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DAY 1 – WEDNESDAY JULY 6

S.1. Neuromechanics of Human Locomotor Stability: Theoretical Insights and Clinical Applications

Inter-limb cutaneous feedback in walking balance: Early responses at the ankle to rapid light touch displacement at the fingertip during walking

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[1]University of Alberta

BACKGROUND AND AIM: Light touch of a stable reference prevents subjects from drifting off of a treadmill when walking with eyes closed. In addition, corrective reactions to balance disturbances during walking are modulated when subjects touch a stable reference. Therefore, feedback from the fingertips is suggested to be involved in control of stability during walking. We asked if tactile inputs from the fingertips can initiate, or trigger, balance reactions during walking. Recently, we demonstrated that rapid displacement of a touch surface can induce a balance reaction during standing. However, these reactions were only observed on the first trial suggesting that the expression of these responses were context dependent. Presently, we hypothesized that rapid displacement of a touch surface would trigger similar balance reactions during treadmill walking and that these responses would be observed more frequently than the first trial alone, given the importance of the touch reference to the task of walking with eyes closed. METHODS: 20 participants walked on a treadmill. EMG activity was recorded from 9 muscles including the right tibialis anterior (TA) and soleus (SOL). Electrogoniometer records were obtained from the right elbow, knee and ankle, along with foot contact from both feet. Participants walked at a consistent self-selected speed in 4 conditions: a) eyes open, b) eyes open while touching, c) eyes closed, and d) eyes closed while touching (ECT). Conditions a-c were used as a deception. During ECT participants walked while lightly touching (<1 N) a touch plate for 1 min before touch plate displacements (12.5 mm, 124 mm/s) were unexpectedly introduced at right heel-strike. Displacements were separated by at least 20 steps. Participants received a block of 10 displacements in a single direction (forward or backward). Half received forward perturbations. RESULTS: All participants responded to the touch plate displacement at heel-strike with activation of ankle muscles in at least two trials. Typically, TA activation was observed following a forward displacement, with a median rate of 7 responses per participant across all 10 trials. SOL activation was typically observed following backward displacement, with a median rate of 6.5 responses per participant across all 10 trials. Response latencies in TA and SOL did not vary from the first [133.75 (±39.05); 125.65 (±46.66) ms] to last responses [136.15 (±43.93); 128.35 (±40.62) ms]. CONCLUSIONS: These findings confirm that light touch sensory cues from a single fingertip are able to generate responses in distant muscles, consistent with a balance reaction during walking. The evoked responses continued to be expressed even when repeated perturbations made the touch reference unreliable. This suggests that cutaneous input from the hands is an important sensory cue in the control of walking balance, particularly when other senses are impaired or the task is challenging.

Perturbation Based Gait Training May Improve the Tradeoff of Stability and Maneuverability in Patients with Lower Limb Injury

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BACKGROUND AND AIM: Lower limb trauma (LLT) significantly impairs walking stability. As a result, individuals with LLT adopt a cautious gait pattern that includes wider step widths (SW). However, maneuverability is an important aspect of community living with many everyday tasks, like navigating a crowded sidewalk, requiring rapid lateral movements. While a wider, less variable SW is considered to be more stable during walking, a narrower, more variable SW is related to greater maneuverability during dynamic movements creating a tradeoff. We present two studies that identify the relationship between stability and maneuverability in individuals with LLT and determine if that relationship can be improved with training. METHODS: To investigate the tradeoff between stability and maneuverability, individuals with LLT and healthy controls navigated a virtual obstacle course which required rapid lateral lane changes through a series of arches. We measured SW mean and variability and the number of transitions where the participant hit an arch. In a separate study, an individual with a unilateral, above-knee amputation

completed an intervention utilizing walking surface pitch and roll oscillations in a virtual environment. We measured SW mean and variability pre and post intervention. RESULTS: Individuals with LLT had more failed transitions in the virtual obstacle course than healthy controls. During the transition movements they maintained wider and less variable SW. Following the intervention, the patient reduced their SW mean and variability, closer to or within normal ranges. This change was accompanied by greater patient reported confidence in their balance and walking ability. CONCLUSIONS: Individuals with LLT maintained wider and less variable steps during the transition movements, suggesting that stability is prioritized over maneuverability, which likely contributed to their reduced performance. This bias toward stability and adoption of a cautious gait pattern likely arise from reduced balance confidence and not having developed appropriate responses to walking perturbations. However, an individual with a unilateral, above-knee amputation was able to normalize their stepping pattern and perceived balance following the perturbation based intervention. This suggests that, although individuals with LLT present with decreased stability leading to cautious gait patterns and a bias towards stability over maneuverability, it appears that perturbation training and exposure to destabilizing situations can assist these individuals in improving their stability and likely their maneuverability as well. ACKNOWLEDGEMENTS NIH 1-R01-HD059844 and DoD/CDMRP/BADER W81XWH-11-2-0222 DISCLAIMER The views expressed herein are those of the authors and do not reflect the official policy or position of Brooke Army Medical Center, U.S. Army Medical Department, U.S. Army Office of the Surgeon General, Department of the Army, Department of Defense or the U.S. Government

Post-stroke deficits in a mediolateral gait stabilization strategy (and a possible intervention)

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BACKGROUND AND AIM: Individuals who have experienced a stroke often exhibit gait instability, as evidenced by an increased fall-risk and fear of falling. Unfortunately, recent large-scale rehabilitation interventions have failed to substantially impact fall-risk, likely due to these interventions not being targeted

toward the mechanisms underlying post-stroke gait instability. The aim of the present study was to identify post-stroke deficits in a control strategy that allows neurologically intact adults to generate a stable gait pattern seemingly so easily. In the longer term, we seek to use these results to design a novel rehabilitation intervention. METHODS: In previous work (and consistent with the work of others), we found that neurologically intact controls (n=16) used a consistent strategy of adjusting their step width based on the mechanical state of the pelvis at the start of a step. We quantified this relationship by calculating the partial correlations between step width and mediolateral displacement of the pelvis relative to the stance foot (r_disp) and mediolateral velocity of the pelvis (r_velocity) at the start of a step. For the present study, we performed the same analysis on data collected from chronic stroke survivors (n=24) walking on a treadmill at their self-selected speed, with the goal of determining whether individual stroke survivors use a similar stabilization strategy. Based on the results (described below), we developed an elastic force-field with the goal of retraining mediolateral foot placement while not interfering with anteroposterior progression. Briefly, our device creates a force landscape in which mediolateral deviations from an adjustable "channel" are resisted by mediolateral forces. In initial proof-of-concept experiments, we tested whether our force-field can be used to strengthen the relationship between step width and pelvis displacement (r_disp) on a step-by-step basis. RESULTS: Among controls, the partial correlation values during normal walking fell within a relatively narrow range. In contrast, most stroke survivors exhibited substantially lower correlation values (see Figure), indicating post-stroke deficits in the normal control strategy of adjusting step width based on the mechanical state of the body. Among uninjured controls (n=8), walking in the force-field consistently increased r_disp (by 0.23 ± 0.11), indicating that step width became more responsive to variance in pelvis displacement. Similarly, in two chronic stroke survivors, the force-field caused increases in r_disp of 0.27 ± 0.07 for paretic steps and 0.19 ± 0.09 for non-paretic steps. CONCLUSIONS: Many stroke survivors lack the normal stabilization strategy of adjusting their steps to account for the body's mechanical state. Future work will investigate whether our force-field has beneficial effects on the use of this strategy with training over a longer time scale.

The effect of balance perturbations after myelopathy related sensory deficits on cortical oscillations during walking

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BACKGROUND AND AIM: The objective of this study was to examine the effect of a balance perturbation on cortical movement related oscillations during walking. Brain activity was recorded using electroencephalography (EEG) while participants were walking on a treadmill and delivered a medial-lateral pull to the waist. We hypothesized that these cortical oscillations, shown in previous studies to be strongly associated with motor control, would shift in magnitude and spatial orientation as a function of sensory integration and motor planning in response to the balance perturbation. METHODS: Ten myelopathy subjects in addition to ten young, healthy, neurologically intact volunteers participated in this study. Participants began each trial standing at rest for 10 s, until a visual cue notified the start of the treadmill up to a self-selected comfortable walking speed. A balance perturbation composed of a medial to lateral pull normalized to 5% of bodyweight was delivered to the subject's waist using a custom cable motor setup. Electromyography (EMG) signals were recorded from the tibialis anterior (TA) and medial gastrocnemius (MG), along with kinematic data from an eight camera Vicon motion capture system. EEG data recorded from a 64 channel active electrode cap setup was preprocessed and analyzed using the Fieldtrip, EEGLAB, and Brainstorm toolboxes. Independent component analysis (ICA) was used to remove blink, EMG and motion artifact. Time frequency decompositions of the cleaned trials were calculated using Mortlet wavelets, time warped to gait events and smoothed in time, before being averaged across epochs. Power values were referenced to the baseline period of standing rest as a percent change in power. RESULTS: Balance perturbations while walking were associated with cortical power modulations in theta, alpha, and beta frequency bands. A large increase in theta and alpha band power was observed throughout the cortex immediately after the balance perturbation, followed by significant beta band power increases identified in frontal, motor areas of the brain (Fz, FCz, $p < 0.05$). Parietal areas of the brain exhibiting this beta band increase were observed to precede the corresponding increase of beta band activity in frontal areas of the cortex. These cortical power increases were observed to be delayed in time in our myelopathy subjects. CONCLUSIONS: The large increase in cortex wide theta band power immediately following the balance perturbation may indicate the escalation of

cortical executive functions in response to the pull. The posterior to anterior sequence of beta band modulation in the cortex suggests an association with sensory integration of the balance perturbation, followed by the creation of a motor plan to prevent falling. The time delay observed in myelopathy subjects may reflect slower processing of the balance perturbation resulting from lower limb sensory deficits caused by compression of the spinal cord.

Cortical Correlates of Locomotor Adaptation to Perturbations of Symmetry

James Finley[1]

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BACKGROUND AND AIM: Walking in the real world often requires us to adapt our walking pattern to changes in the environment. For example, walking on a moving walkway or walking in ski boots each require that we recalibrate our locomotor pattern to maintain balance and move through our environment efficiently. This process, termed locomotor adaptation, is mediated in part by subconscious processes that rely on neural circuits within the cerebellum. Recent studies in the upper extremity have also demonstrated that explicit, strategy-based processes controlled by the prefrontal cortex (PFC) also contribute to adaptation. Whether strategic processes contribute to locomotor adaptation remains to be seen. Since walking typically requires very little conscious effort, one might expect that locomotor adaptation is mediated almost exclusively by cerebellar or spinal circuits. Alternatively, explicit strategies may be used for top-down specification of control objectives related to factors such as balance or energetic cost. Here, we use adaptation to walking on a split-belt treadmill to test the hypothesis that activity in the PFC is associated with responses to perturbations of symmetry. METHODS: Participants walked on a dual-belt treadmill in one of three conditions: a Tied condition when both belts moved at 1.0 m/s, a Right Split condition when the right belt moved at 1.5 m/s and the left belt moved at 0.5 m/s, and a Left Split condition when the right belt moved at 0.5 m/s and the left belt moved at 1.5 m/s. The Split conditions were presented in a quasi-random order in a series of 20, 30 second walking trials separated by 30 seconds of standing. This prevented the participants from anticipating the direction of the impending perturbations and allowed us to obtain robust estimates of cortical activity due to perturbations of symmetry. The average, normalized difference in step lengths (step length asymmetry) during each walking trial was used as the primary kinematic outcome measure. A continuous wave functional near-infrared spectroscopy system (NIRx Nirsport) was used to measure cortical hemodynamic responses in the PFC during adaptation. RESULTS: By presenting the split-belt perturbation in a randomized order, participants maintained significant levels of step length asymmetry despite minor adaptation within each trial. The participants' response to the perturbations was associated with an increase in activity in the PFC relative to baseline trials when the belts moved at the same speeds. CONCLUSIONS: These results provide evidence that the cortex is indeed involved with monitoring, and possibly mediating, locomotor adaptation to perturbations in the environment. Ultimately, identification of the brain areas mediating adaptation may provide targets for non-invasive brain stimulation techniques to improve the acquisition, reacquisition, or retention of motor skills in pathological conditions such as stroke or Parkinson's disease.

System Identification of the Human Locomotion Control System and Energy-optimal Feedback Control

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[1]The Ohio State University, [2]Caterpillar

BACKGROUND AND AIM: Although engineers have built robots that walk and run stably (if barely stably), the control system used by a human to uses to walk and run in a stable manner has not yet been well characterized. Here, we will present three complementary approaches to examining the human walking control system. MEHODS: (1) We fit linear dynamical models to natural variability during steady state walking data to characterize how humans modulate their leg forces as well as foot placement to get back to steady state. (2) We perform 'perturbation experiments' in which human subjects walking steadily are perturbed by unforeseen pulls. We fit similar dynamical models to this data to again characterize how humans modulate their leg force and foot placement. (3) We hypothesize that humans recover from perturbations in a manner that minimizes the effort it takes to get back to steady state. We computed such energy optimal recoveries from various perturbations for two simple models. In addition to walking, we also present results on running, specifically using the first and third approaches, namely fitting models to steady state variability and obtaining optimal feedback control. RESULTS: We find that the linear dynamics inferred from steady state variability and perturbation experiments are qualitatively similar with small quantitative differences, perhaps due to nonlinearity of the controller. We find that small deviations in sideways foot placement during steady walking as well as large corrective steps after perturbations are mostly explained by deviations in the torso state during the previous step, suggesting that foot placement is indeed a significant stabilizing response. We also find that energy-optimal recovery transients are indeed predictive of many aspects of the human response, specifically the sideways foot placement in response to sideways perturbations, in which even simple models give quantitatively accurate results. For running, we obtained mappings from deviations in upper body state during flight and found that such deviations were predictive of the leg force impulse on the step, in a manner that state deviations were reduced, although not completely, suggesting that it takes many steps to kill a perturbation. CONCLUSIONS: Our hope is that these insights into the human walking and running control system can be used toward developing either as diagnostic metrics for quantifying stability and informing the development of control systems for prostheses and exoskeletons that work better in concert with the human walking dynamics. Supported by NSF grants 1254842 and 1538342, and a Schlumberger Foundation Faculty for the Future Fellowship. The first four authors (Joshi, Clark, Seethapathi, and Wang) contributed equally to this work and are joint first authors.

S.2. Motor Unit Control

Synchronization studies require accurate motor unit firings and robust statistical tests

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[1]Delsys, Inc

BACKGROUND Over the past four decades, various methods have been implemented to measure synchronization of motor unit firings. Some assume the firings have a

Gaussian distribution, but never test their assumptions. Others claim synchronization indicates the motoneurons depend on common inputs without testing for statistical correlations indicative of dependent firing behavior. And almost all synchronization studies decompose the EMG signal to extract motor unit firing instances using various manual or automated methods that are subject to errors; yet the degree to which these errors distort measurements of synchronization remains a concern. In this work we show that all of these factors can result in incorrect estimates of motor unit synchronization that provide misleading physiological interpretations such as the existence of universal common inputs to all motoneurons. METHODS We developed a statistically-based method (SigMax) for computing synchronization and tested it with data from 17,736 motor unit pairs containing 1,035,225 firing instances from the First Dorsal Interosseous and Vastus Lateralis muscles - a data set an order of magnitude greater than that reported in previous studies. Motor unit firing instances were obtained using our surface EMG signal decomposition algorithms. Identification and location errors that resulted during the decomposition were evaluated and mitigated using a new error reduction algorithm designed to improve the accuracy of the decomposition result. Only firing data obtained with greater than 95% accuracy were used in the study. The data were not subjectively selected in any manner. RESULTS SigMax incorporated three distinct tests to rigorously assess the physiological incidence of synchronization: 1) test for statistically non-stationary motor unit action potential trains; 2) test for statistically dependent firing instances among pairs of motor unit action potential trains that passed the stationarity test; 3) test for the most statistically significant peak in the cross-correlation among the motor unit action potential trains that passed the dependence and stationarity tests. The synchronization peak provided the latency, peak width, and amplitude of synchronization between the motor units. Because of the size of our data set, the reduction of errors in the decomposition result and the statistical rigor inherent to SigMax the synchronization values we calculated provide an improved estimate of physiologically-driven synchronization. CONCLUSIONS When compared with other approaches used to measure synchronization, ours revealed two major findings: 1) unmitigated decomposition errors can lead to false detections and incorrect estimates of synchronization; and 2) methods that assume motoneurons depend on common inputs result in falsely ascribing synchronization to 100% of motor unit pairs studied. SigMax revealed only 50% of motor unit pairs actually manifested statistically significant synchronization.

Assessing Motor Unit Pool Control Properties in Aging using Surface Electromyography

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[1]University of North Carolina-Chapel Hill, [2]Rehabilitation Institute of Chicago

BACKGROUND AND AIM: A high-yield surface electromyogram (sEMG) decomposition system has been developed, which allows us to examine motor unit (MU) pool control properties noninvasively. Motor unit action potential (MUAP) shapes with corresponding motor unit threshold properties can be derived. METHODS: In this study, we first quantified the reliability of the estimated MUAP waveform features (amplitude and shape) by assessing the stability of the waveforms in relation to the accuracy of the decomposed spike timings. We then quantified the estimated action potential amplitude in relation to the recruitment threshold of motor units, obtained from the first dorsal interosseous muscle of young and elderly (50-70 age range) populations. RESULTS: Our results show that the stability (both amplitude and shape) of the waveform average was sensitive to small (i.e., standard deviation of 1 ms) spike timing errors, indicating that the estimated motor unit action potential amplitudes are reliable based on the waveform stability measures. We also found that there is orderly recruitment of motor units based on the amplitude of action potentials across different age groups. However, the strength of the orderly recruitment tends to be weaker in the elderly, especially at higher muscle contraction levels. Specifically, as shown in Figure 1, the regression slope was more shallow and the goodness-of-fit also reduced, in the elderly group. CONCLUSIONS: Our findings suggest that there is age-associated modification of the recruitment order based on motor unit size. The shallow slopes could also be a function of fiber atrophy, especially in the larger units recruited at higher thresholds.

Motor unit coherence and synchronization in response to sustained isometric contraction of the first dorsal interosseous muscle

Lara McManus[1], Xiaogang Hu[2], William Rymer[3], Nina Suresh[4], Madeleine Lowery[1]

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BACKGROUND AND AIM: Sustained isometric fatiguing contraction is known to induce changes in motor unit (MU) firing rate and recruitment [1]. In addition, it has been suggested that fatigue results in alterations in synchronization and correlation between the firing times of simultaneously active MUs. This is supported by indirect estimates of MU synchronization derived from surface EMG parameters [2]. Direct evidence of increased motor unit synchronization or beta-band coherence as a result of fatigue, however, has not yet been shown. The aim of this study was to examine alterations in MU coherence during and after sustained submaximal isometric fatiguing contraction of the first dorsal interosseous (FDI) muscle. METHODS: Surface EMG was recorded using a surface sensor (Delsys, Inc., Natick, MA) comprised of five 0.5 mm diameter electrodes. Data were recorded during isometric abduction of the FDI in 15 subjects (8 female) before, during and directly after sustained contraction at 30% maximum voluntary contraction (MVC) to task failure. A series of 10 s contractions at 20 % MVC were performed pre- and post-fatigue, and following 10 mins recovery. Individual MU spike trains were extracted from the surface EMG signal using the decomposition algorithm described by Nawab et al., [3] and acceptance criteria outlined in [4]. MU spike trains for each subject under each condition were divided into two groups and spike trains within each summed to yield composite spike trains. Mean squared coherence was estimated pre and post fatigue. Changes in coherence during the fatiguing contraction were similarly estimated using wavelet coherence. Short-term MU synchronization during the first and second half of the fatiguing contraction was also estimated. RESULTS: MU wavelet coherence increased in the delta (1-4 Hz), alpha (8-12 Hz) and beta (15-30 Hz) frequency bands during the fatiguing contraction, accompanied by an increase in MU synchronization($p < .001$). A significant increase in MU coherence was also observed in the delta, alpha and beta frequency bands post fatigue($p < .0001$), and recovered following rest. CONCLUSIONS: The results provide direct evidence of a fatigue-induced increase in correlated motor unit activity in the delta, alpha and beta-frequency bands. Though the origin of the coherent activity is not clear, it may reflect an increase in correlated presynaptic inputs to the motoneuron pool. Beta-band EMG coherence in particular has been shown to exhibit similar task-dependency as corticomuscular coherence,

indicating a likely cortical origin. The ability to infer information about oscillatory cortical and sub-cortical processes from surface EMG provides novel insight into the adaptations taking place in the central and peripheral nervous system during fatigue.

[1] McManus et al. J Neurophysiol, 2015. [2] Holtermann et al. J Electromyogr Kinesiol, 2009. [3] Nawab et al. Clin Neurophysiol, 2010. [4] Hu et al. J Neurophysiol, 2013.

Homogeneity of the Relationship between Motor Unit Recruitment Thresholds versus Derecruitment Thresholds across Force Levels and the Lifespan

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[1]Texas Tech University

BACKGROUND AND AIM: During voluntary contractions, motor units are recruited and derecruited in an orderly fashion according to their recruitment thresholds. While violations to this well-ordered pattern have not been reported in young adults, it is unclear if the processes associated with aging affect the motor unit recruitment versus derecruitment threshold relationship. The purpose of this study was to examine this relationship across the lifespan and for moderate and high force levels. METHODS: Eight boys (mean ± SD age = 12 ± 2 yrs), six young men (age = 27 ± 3 yrs), and seven old men (age = 71 ± 4 yrs) participated. Subjects were free from disease, had a healthy mass, and were not engaged in an exercise program. At least 48 hours following a familiarization session, the subjects performed isometric, constant-force contractions at force levels corresponding to 50% and 80% of their maximal voluntary contraction (MVC) while bipolar surface electromyographic (EMG) signals were detected from the vastus lateralis. Force steadiness was quantified as the coefficient of variation of each plateau region. A Precision Decomposition algorithm was used to decompose the EMG signals into their motor unit action potential trains. Motor units with decomposition accuracy levels < 93.0% were removed. For each contraction, motor unit recruitment and derecruitment thresholds were quantified. Linear regression analyses were used to examine the slope coefficient (recruitment threshold % MVC/derecruitment threshold % MVC), y-

intercept (recruitment threshold % MVC), and R2 of each relationship. RESULTS: Boys demonstrated the poorest force steadiness (marginal means = 3.43% [boys], 2.09% [young men], 2.12% [old men]). Each age group revealed steadier force at 50% (2.90%) versus 80% MVC (2.12%). Each age group and force level showed highly linear recruitment versus derecruitment threshold relationships (R2 >.79). Similarly, the subjects showed similar slope coefficients (mean = 1.47 %/%), with boys and young men showing greater mean values at 80% MVC compared to 50% MVC. The y-intercept demonstrated a significant main effect for force, with lower values demonstrated for 80% MVC (-30.0%) versus 50% (-4.8%). At 50% MVC, the subjects demonstrated equivalency of recruitment and derecruitment thresholds or motor units were derecruited at higher force levels than which they were recruited. At 80% MVC, a crossover effect was noted for the boys and young men, with motor units derecruited at low force levels. CONCLUSIONS: The relationship between motor unit recruitment versus derecruitment thresholds remains linear across force levels and the lifespan. While additional analyses are required to confirm our findings, older adults may recruit and derecruit motor units at similar force levels, particularly during contractions near the MVC. This phenomenon may be related to altered force-twitch potentiation or fatigability due to an age-related loss of high threshold motor units.

Transposed firing activation of motor units during oscillatory contractions

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BACKGROUND AND AIM: The majority of studies on the behavior of motor units during voluntary contractions have been performed during linearly-varying or constant force contractions. In these force paradigms, the recruitment and firing rate of motor units are organized in a strict hierarchical structure that determines their participation in the force generation process. Motor units are activated in a hierarchical order, with the earlier-recruited motor units being activated at lower forces and exhibiting greater firing rates than the later-recruited ones [1]. We performed this study to investigate whether this hierarchical firing rate organization of motor units can be altered during isometric oscillatory-force contractions. METHODS: Six healthy young (23.8 ± 2.0 yr) subjects were asked to track a target

force profile at 20% of their maximal voluntary contraction (MVC) force with a superimposed oscillation of amplitude ±2.5% MVC and frequency increasing from 0.2 to 0.4, 1, 2, 3, and 4 Hz. The first dorsal interosseous muscle was tested while the hand was secured to restrain the index finger to isometric contractions. RESULTS: We found that the normal pattern of activation observed during linearly-varying or constant force contractions can be altered by performing oscillatory contractions at frequencies ≥ 2 Hz. We identified the following surprising alterations in the firing behavior of motor units with increasing oscillation frequency: 1) the firing rates of lower-threshold motor units decreased when the force began to oscillate, and returned to their pre-oscillation level when the oscillation terminated; 2) the firing rate decrease was progressively less pronounced for higher-threshold motor units; 3) the firing rate decrease was progressively more pronounced at greater oscillation frequencies; and 4) additional higher-threshold motor units were recruited when the decrease in the firing rate of the lower-threshold motor units was noted. CONCLUSIONS: Our results demonstrate that the hierarchical regulation of motor unit firing can be manipulated to preferentially activate specific motoneuron populations, providing an opportunistic access to increasing the activation requirement of higher-threshold motor units while decreasing that of lower-threshold ones. This finding can be exploited to develop new forms of physical therapies and exercise programs that enhance muscle performance or that target the preferential atrophy of high-threshold motor units that occurs with aging or motor disorders such as stroke and amyotrophic lateral sclerosis. [1] De Luca CJ et al. J Physiol, 329: 129-142, 1982. Support: NIH/NICHD Grant HD-050111; Neuromuscular Research Foundation.

Biomechanical Benefits of the Onion-Skin Scheme of Motor Unit Firing

Carlo De Luca[1], Paola Contessa[2]

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BACKGROUND AND AIM: Muscle force is modulated by varying the number of active motor units and their firing rates. Over the past five decades, the notion that higher-threshold shorter-after-hyperpolarization (AHP) motoneurons have greater firing rates than lower-threshold longer-AHP ones has been commonly accepted. This notion was derived from electrically stimulated motoneurons in cats, and supports the assumption that the firing rates of motoneurons match their mechanical properties to optimize force generation [1]. That is, lower-threshold motor units have wider and smaller force twitches that require lower firing rates to tetanize. In contrast, we have provided evidence that earlier-recruited motor units maintain higher firing rates than later-recruited ones at any time and force during voluntary isometric contractions, resulting in an inverse orderly hierarchy of firing rate curves named the Onion-Skin scheme [2]. We applied a model of muscle force generation [3] to compare the force characteristics produced by the APH and the Onion-Skin schemes in the First Dorsal Interosseous (FDI) and Vastus Lateralis (VL) muscles. METHODS: The model describes a hierarchical inverse relationship between the recruitment threshold and the firing rate of motor units at any time and force during a voluntary contraction to formulate the Onion-Skin scheme. An opposite arrangement where both the minimal and maximal firing rates of motor units are directly related to recruitment threshold formulates the AHP scheme. RESULTS: Our results show that the Onion-Skin scheme has distinct advantages over the AHP scheme: 1) lower-threshold motor units fire faster and produce more force at low levels. Thus, a fewer number of low-threshold units, in most part oxidative and able to sustain force for extended time, are required for low force production. 2) High-threshold motor units never fully fuse, maintaining the potential for a force "reserve capacity" that is not normally accessible but might be available in extraordinary circumstances. 3) It produces smoother force, especially at the low force levels that are used for normal daily activities. 4) It provides more sustainable contractions by producing lower forces at maximal excitation. CONCLUSIONS: In summary, the Onion-Skin scheme is not designed to maximize muscle force, as proposed for the AHP scheme, but to generate force more quickly when force is initiated, and to provide lower maximal force with the capacity to sustain it over longer time. Smoother force production also enables accurate performance of daily tasks. These features support the flight-or-fight reflexive response in the presence of danger and are more conducive to evolutionary survival. [1] Eccles et al. J Physiol, 142: 275-291, 1958. [2] De Luca et al. J Physiol, 329: 129-142, 1982. [3] Contessa and De Luca. J Neurophysiol, 109: 1548-1570, 2013. Support: NCMRR/NICHD Grant HD-050111; Neuromuscular Research Foundation.

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O.1. Rehabilitation Technologies I

O.1.1 *A new wearable exoskeleton device that controls knee motion in individuals after stroke*

Shihomi Kawasaki[1], Koji Ohata[1], Tadao Tsuboyama[1], Yuichi Sawada[2], Yoshiyuki Higashi[2]

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BACKGROUND AND AIM: Abnormal knee movement patterns were reported as common characteristics of gait abnormality in individuals after stroke. Previous reports have selected knee movement during walking as a critical observational point for gait pattern classification. (De.Quervain IAK, 1996, Mulroy S. 2003). Moreover, the reduction of knee flexion during swing phase was known as a factor increasing mechanical energetic costs (Chen G, 2005). Thus, improving abnormal knee movement is necessary to recover the gait function in this population. Recently, robot rehabilitation is expected to facilitate training for individuals after stroke. However, many of the robots have to be combined with treadmills and wearable robots for overground use are not popular yet in clinical settings. We developed a device that assists knee movements during gait and can be used overground. The aim of this study was to clarify the change of knee motion using the device.
METHODS: Three subjects with left hemiplegia after stroke with an average age of 43.7y (SD 22.5y) participated in this study (male/female: 2/1, Brunnstrom Recovery Stage IV/V: 1/2). They walked with the new device to control the knee movement during gait with an attached actuator at the knee joint. This actuator was controlled to assist the knee motion in appropriate timing and power, using a programmed algorithm corresponding to their gait cycle. The subjects walked at their own preferred speed on a 7-meter walkway in two conditions: with no assist or with a 6N assist on the paretic knee. The knee joint angle during gait was measured by an electric goniometer attached to the paretic knee. The maximum knee flexion angle during swing, knee flexion angles during loading response and knee extension angles during mid-stance were compared between the 2 conditions. Temporal information of the gait was obtained from an accelerator on the paretic heel.
RESULTS: With the assist, all subjects increased the maximum knee flexion angle

during swing (31.3 to 35, 32.4 to 44.3, 29.3 to 33.4 degrees in knee flexion). In loading response, two subjects with normal knee motion during stance showed reduced knee flexion (21.7 to 17.3, 15.3 to 9.8 degrees in knee flexion). On the other hand, one subject with recurvatum-knee motion during stance decreased the peak knee extension angle (-2.6 to 4.2 degree in knee flexion). However, changes in gait speed and gait cycle proportion were inconsistent. CONCLUSION: This preliminary study supported the hypothesis that this new device improves the knee motion in hemiplegic gait. The device probably has a potential to change the common problem such as stiff knee gait and recurvatum knee gait. Future study is needed to examine the effect of this device and to optimize the algorithm for the improvement of the gait function in individuals with hemiplegia after stroke.

O.1.2 ***A Novel Device for Functional Strength Training during Gait: Evidence from Healthy and Stroke Subjects***

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[1]University of Michigan

BACKGROUND AND AIM: Many patients with neurological injury such as stroke or cerebral palsy have significant limitations in walking, which can affect their mobility and quality of living. Facilitating gait recovery, therefore, is a key goal in rehabilitation. Task specific training is frequently applied for rehabilitation of these individuals, but this fails to directly address muscle strength and impairment, which are also critical for motor recovery. For this reason, functional strength training — task-specific loading of the limbs — is becoming increasingly popular when rehabilitating these patient groups. Typically, the resistance necessary for functional strength training of gait is provided using cable robots or weights that are secured to the distal shank of the subject. However, there exists no device that is wearable and capable of providing resistance across the joint, allowing over ground gait training. Therefore, the goal of this study was to develop a gait-training device that is capable of providing variable levels of resistance across the knee during walking and to test the biomechanical effects of this device on the user. METHODS: We first created a benchtop viscous damping device in the form of an eddy current disc brake, and characterized its resistive torque profile using an isokinetic dynamometer. After characterizing the resistive properties of the device, we tuned the parameters

(magnet size, number, etc.) to optimize wearability while maintaining a high resistance. The device was then fitted to an orthopedic knee brace (T Scope Premier Post-Op Knee Brace, Breg, Grand Prairie, TX) that can fit across a wide range of patient sizes (5' to 6'7").The entire assembly weighed 1.6 kg and cost about $2100 for fabrication (including the brace). We then validated the device by having subjects (healthy and stroke) wear it during a walking task through varying resistance levels. Electromyography and kinematics were collected to assess the biomechanical effects of the device on the wearer. RESULTS: Results from benchtop testing indicated that eddy current braking provided resistance levels suitable for functional strength training of leg muscles in a package that is both lightweight and wearable. Human subjects experiment indicated that applying resistive forces at the knee joint during gait resulted in significant increases in muscle activation of many of the muscles tested. A brief period of training also resulted in significant aftereffects once the resistance was removed. Additionally, preliminary results gathered while testing on stroke subjects showed similar changes in muscle activation and substantial aftereffects that translated to their over-ground walking. CONCLUSION: These results support the feasibility of the device for functional strength training during gait. However, future research is warranted before the device is applied in the rehabilitation setting. ACKNOWLEDGEMENT: NIH Grant#R01EB019834

O.1.3 *Gait Rehabilitation in Paediatric Population through a Novel Robotic Platform: Pilot study*

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[1]CSIC

BACKGROUND AND AIM: Cerebral Palsy (CP) is a disorder of posture and movement due to a defect or lesion in the immature brain. New strategies are needed to help to promote, maintain, and rehabilitate the functional capacity, and thereby, diminish the dedication and assistance required and the economical demands that this condition represents for the patient, the caregivers and the society. This study presents the development and preliminary clinical evaluation of a new robotic platform called CPWalker for gait rehabilitation and training in patients with CP, and its applicability with CP children. METHODS: CPWalker is a robotic platform that allows the infant to start experiencing autonomous locomotion in a rehabilitation environment. This robotic platform consists of a smart walker with body weight support and a wearable exoskeleton robot for joint range of motion support. CPWalker control strategies provide the infant with a force field to rehabilitate his/her gait to physiological patterns. The device was evaluated in three children with spastic diplegia aged between 12 and 14-years-old. These children went through the individual robotic-based rehabilitation programme during five weeks. For the outcome measures, 3D motion capture system was used to calculate kinematics and kinetics parameters in pre and post studies (before and after the experiment period respectively). RESULTS: After five weeks of robot-based training with CPWalker system, the three children improved the mean velocity, cadence and step length after robotic-based therapy (Table I). Post studies revealed that the trajectories for right and left lower limbs are closer to the normal values when compared with pre studies (Figure 1). CONCLUSIONS: Preliminary results show the potential of the novel robotic platform to serve as a rehabilitation tool. CPWalker enables overground training of walking with controlled body-weight support in children with Cerebral Palsy. The ability to provide autonomous locomotion to the children improved their participation during the therapy, with positive effects. The system is robust and safe for the children. Such device is a powerful tool to evaluate and compare different robotic-based therapies for gait rehabilitation of children with CP. [1] Bayón et al. CPWalker: Robotic Platform for Gait Rehabilitation in Patients with Cerebral Palsy. IEEE Int. Conf. Robot. Autom., 2016. doi:10.1007/s13398-014-0173-7.2.

O.1.4 *The kinematic change for inverted pendulum during stance phase with assist of hip movement in individuals after stroke.*

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Background: The inverted pendulum model during stance phase is crucial principle to reduce the energy cost during walking in human (Kuo, 2007). This model can explain the conservation of mechanical energy of walking due to effective exchange between kinetic and potential energies. Hemiplegic gait was previously reported to perform inadequate way to exchange between energies (Olney, 1986) and to need high energy cost during walking (Waters, 1999). The assist of hip movement using wearable actuator generated supportive power to the thigh during walking has potential to be useful as one of the assist technology in robot assisted gait training (RAGT). Previous study has reported that the device controlling the thigh movement improved cost of walking (Kitatani, 2014) and symmetry (Buesing 2015). However, kinematic parameters that indicated the change in movement of the inverted pendulum were not investigated. Aim: The aim of this study was to clarify the kinematic change concerned with inverted pendulum model by controlling the hip movement in individuals after stroke. Methods. 17 ambulatory individuals after stroke participated in the study. They walked with assist of hip movement using the device attached actuators on 7m-walkway at self-selected speed in two conditions, i.e., turn-on and turn-off the actuator of the device conditions. Gait kinematics was assessed using 3D gait analysis (MAC3Dsystem, USA). Gait trials on each condition were performed 4-6 times. 5 or more gait cycles were used to calculate parameters in analysis. A gait parameter concerned with inverted pendulum (IP) was defined as the rotation angle of a line connecting between center of ankle joint and the center of gravity (COG) during the single stance phase. Moreover, general gait parameters such as gait speed, stride and step length, cadence, gait temporal and spatial asymmetry were measured. The relationships between IP and various parameters were tested using Pearson correlation coefficient and the changes with hip assist were examined using paired t-test ($p<0.05$). Results: IPs on both sides showed highly positive correlations with gait speed, stride, and step length and negative correlations with spatial asymmetry. The assist of hip significantly increased IP on non-paretic side and significantly reduced temporal asymmetry. Improvements in gait speed and stride length with the assist showed significant positive correlation with increase of IPs on both sides. Change of temporal asymmetry also significantly correlated with changes of IPs on both sides. Conclusion: The results of this study suggested that IPs on both side were essential parameters of gait function in hemiplegic gait. The assist of hip movement using actuators improved the IP on non-paretic side with reducing their asymmetry. However, general gait parameters did not change perhaps of limited change in IP on paretic side.

O.1.5 *Measuring balance control on a treadmill: no need for shear forces*

Ingrid Schut[1], Jolanda Roelofs[2], Jantsje Pasma[1], Herman van der Kooij[1], Vivian Weerdesteyn[2], Alfred Schouten[1]

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BACKGROUND AND AIMS People who sustained a stroke often undergo impaired balance. To give insight into the neurophysiological mechanisms underlying impaired balance, system identification techniques in combination with perturbations can be used in which the body is perturbed using motion platforms. However, a motion platform is a dedicated and large device, which is unavailable in most labs and clinics. Treadmills are becoming more popular and affordable and are used to train gait in neurological patients. This study investigates the possibilities of measuring balance control using a treadmill and what the minimal set of signals might be. Therefore, we first investigate which forces and moments are necessary to identify the neurophysiological mechanisms. METHODS In this study, 2 healthy women (age 20-30 years) were asked to maintain their balance while standing on a dual force plate treadmill (GRAIL), while the belt speed was perturbed in both directions around an equilibrium position. A multisine perturbation containing frequencies in the range of 0.05-5 Hz was applied on the belt resulting in peak-to-peak translations of 23 cm with a duration of 20 seconds. Three trials consisted each of 5 repetitions of the perturbations signal, resulting in three trials of 100 seconds. Horizontal and vertical ground reaction forces (i.e. shear forces and gravitational forces) were measured to calculate the corrective ankle torque consisting of the shear force induced torque component and the gravitational force induced torque component respectively. Body kinematics were measured using a motion capture system to calculate the body sway. Corrective ankle torque and body sway were used for system identification techniques to calculate the frequency response function (FRF) of the neuromuscular controller. To investigate the contribution of the shear forces on the FRF, the corrective ankle torque was calculated both with and without incorporating the shear forces. The mean of the difference in torque was calculated in percentage and the difference in magnitude of the resulting FRF was calculated for all frequencies in percentage. RESULTS Preliminary results show that the mean difference in torque calculated with and without shear forces is between 0.01-9% for all subjects. All subjects show that the variation in FRFs between repeated trials is larger than the variation in FRFs calculated with and without shear forces (averaged standard deviations of 0.24 and 0.04 respectively). The difference in FRF increases as the frequency increases and does not exceed 5%. CONCLUSION This study shows that the shear force induced torque component is negligible to the ankle torque during stance on a treadmill and could be ignored for simplifying measurements of balance control. The calculated FRFs are comparable with previous studies, in which motion platforms were used. This is a promising result for system identification techniques on treadmills to measure balance control.

O.1.6 *The Effect that Joint Mobilization has on Propriospinal Reflexes and Pain*

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INTRODUCTION: Individuals diagnosed with chronic pain (ChPa) display a range of unexpected neurologic and muscular changes. Patients report lower pain thresholds and display heightened flexor withdrawal responses. Despite evidence for more widespread changes, the current consensus is that ChPa conditions are manifestations of central hypersensitization. The finding that joint mobilizations (JM) diminishes the flexor withdrawal reflex supports the hypothesis that proprioceptive information may also influence central pathways. To our knowledge no studies have looked at the effect that JM has on spinal proprioceptive reflexes and descending neural drive in people with ChPa. This study therefore investigated the effect that JM has on the H-reflex and the V wave in people with ChPa. METHODS: Thirty subjects (18-65 years-old) experiencing ChPa at or below the knee volunteered for this study. ChPa was defined as pain that has been present for at least six months that was not attributable to any physical trauma or pathology. People with osteoarthritis of the knee or ankle were also included. The experimental protocol was a two group, random selection, Pre-test, Post-test design where reflex recordings were taken before and after a treatment intervention to the ankle. Subjects were randomly subdivided into a treatment (txG) and a sham group (SG). The txG received JM while the SG did not. H-reflexes and V waves were elicited by stimulating the skin directly over the tibial nerve unifocally with a 1ms rectangular pulse at a frequency of 0.1 Hz. The myoelectric signal was band pass filtered at 10-10,000 Hz, digitized at 5,000 Hz and displayed and analyzed on a computer screen. The experiment began by taking pain measurements (1-10 on a 10 point visual analog scale for resting pain, and a second score for pressure pain threshold) and recording 10 H-reflexes and V-waves. These values served as baseline values with which all other recordings were compared. Subjects then received either JM or sham treatments. JM consisted of large amplitude, posterior-to-anterior direction movements to the talocrual joint at a rate of approximately 45 oscillations/minute. The sham intervention was similar to the JM setup in every way except that no talocrual joint posterior-to-anterior displacement took place. Treatments lasted for six minutes. Immediately after joint/sham mobilizations the experimental procedure was repeated. RESULTS: A 2x4 repeated measures ANOVA showed no significant difference between or within the two treatment groups for either reflex and/or pain measurements. CONCLUSION: Talocrual JM did not affect lower limb proprioceptive spinal reflexes or on the descending neural drive converging onto motoneurons. In addition, talocrual JM did not have a generalized effect in lowering pain levels. This finding suggests that JM may be only useful in decreasing pain levels specifically to the joint being mobilized.

O.2. Neuromechanics I

O.2.1 *Task dependancy in Sensorimotor Training: Influence of free bipedal and unipedal stance on variance of soleus H-reflex amplitudes*

Gunnar Wahmkow[1], Tilman Engel[1], Steffen Müller[1], Eduardo Martinez-Valdez[1], Kaplick Hannes[1], Frank Mayer[1]

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BACKGROUND AND AIM: Sensorimotor training was shown to be effective for postural control and improved balance in rehabilitation and prevention. The H-reflex is often used to identify spinal adaptation after sensorimotor training. Recruitment curves are commonly evaluated in prone position or fixed bipedal stance, to either serve as a direct outcome for adaptation after intervention through the Hmax/Mmax -ratio or as orientation for stimulus intensities during other measurement tasks. As adaptational effects of sensorimotor training on H-reflexes were shown to be highly task specific, conditions during H-reflex assessments should match sensorimotor training demands. Therefore, the purpose of this study was to assess H-reflex amplitudes and their variance in free bipedal compared to unipedal stance. METHODS: 14 healthy subjects (8f/6m, 171±8cm, 65±12kg, 29±2yrs) performed free bipedal and unipedal stance in a randomized order on a force plate (AMTI Netforce). Subjects were advised to stand as still as possible with their hands on the pelvis and viewing straight forward. After COP was measured 3x25s in bipedal and unipedal stance, a recruitment curve of M-Wave and H-reflex was recorded from the soleus muscle for both conditions. Afterwards another 10 stimuli per condition were applied with an individual consistent current at Hmax from the assessed recruitment curve. Statistical analysis was performed with a one way ANOVA (α=0.05) of means for COP path length [mm], Hmax/Mmax -ratio and the coefficient of variation [%] of 10 stimuli at Hmax from the recruitment curve. RESULTS: Findings showed a significant increase of postural sway from bipedal (241±63mm) to unipedal (856±263mm) stance (p<0,05) in all subjects. No significant differences between bipedal (0.52±0.32) to unipedal (0.54±0.32) stance (p>0,05) were found for the values of the Hmax/Mmax -ratio. The coefficient of variation in Hmax amplitudes was significantly lower in unipedal (20±14%) than in bipedal (57±24%) stance (p<0,05). CONCUSIONS: Unipedal stance is a common position for functional tasks in sensorimotor training. It increases limb loading as well as task difficulty as shown by differences in COP displacement compared to bipedal stance. However, unchanged Hmax/Mmax -ratio suggest that differences in task difficulty between bipedal and unipedal stance are not strong enough to provoke alterations in reflex modulation at the spinal level. Nevertheless, the lower variation of Hmax reflex amplitudes in unipedal stance suggests that a more unstable task with higher COP displacement does not lead to more variation of Hmax reflex amplitudes. The findings of the present study indicate a great usefulness for more training related measurement tasks in the assessment of task specific adaptations via H -reflex method.

O.2.2 *Trunk Muscle Reflexes Are Elicited by Small Continuous Perturbations*

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BACKGROUND AND AIM: Low-back pain (LBP) has been recognized as the leading cause of disability worldwide. Lumbar instability has been considered as an important mechanism of LBP and one potential contributor to lumbar stability is trunk muscle reflex activity. Indeed, it has been shown that some LBP sufferers display delayed reflex responses. However, it remains unclear as to what extent this reflex pathway contributes to overall lumbar stability. Numerous studies have quantified the

mechanical stiffness of the trunk as a surrogate measure for lumbar stability. However, these studies use continuous small stochastic perturbations to quantify lumbar stiffness, whereas reflexes are commonly elicited using single large perturbations. Thus, it remains unknown whether reflexes are elicited in the studies that use small continuous perturbations to quantify lumbar stiffness, and hence, whether these paradigms could properly quantify the reflex contribution to overall lumbar stiffness. In this study, we determined to what extent reflexes of various trunk muscles were elicited by the small continuous perturbations normally used to quantify the lumbar stiffness. METHODS: Thirty six subjects, 19 with no history of LBP, and 17 suffering from chronic LBP stood upright with their chests' attached to a linear motor via an adjustable harness at the T8 level while perturbations, which consisted of a 4 mm pseudo-random binary sequence (PRBS) with a switching rate of 150 ms, were applied. Electromyographic (EMG) activity was measured from 3 trunk extensor muscles-longissimus (LO), illiocostalis (IL) and multifidus (MF)-and 3 trunk flexor muscles-rectus abdominus (RA), internal oblique (IO) and external oblique (EO). EMG activity in response to each perturbation was separated based on the direction of the perturbation (i.e. forward or backward), aligned and averaged. Reflex activity for each direction was computed as the mean rectified EMG activity at four times: 25-50 ms (M1), 50-75 ms (M2), 75-100 ms (M3) and 100-125 ms (long-latency reflex-LLR) following the perturbation. RESULTS: The small continuous perturbations were capable of eliciting reflexes, as reflex activity was seen in all muscles. 34 of the 48 muscle-epoch combination showed a significant reflex response to either perturbations in the forward or backward direction. Though it is impossible to classify one muscle as having the largest reflex responses, 4 muscle-epoch combinations (M1 & M2 in IL, M1 in IO and LLR in EO) were larger than the rest. Though not the primary objective of this experiment, we found no group differences between healthy and LBP populations. There were group differences between males and females, as males tended to have larger short latency reflex responses, while females had larger LLR responses. CONCLUSION: Reflexes are elicited by small continuous perturbations, and should contribute to the measured mechanical lumbar stiffness by this and similar type of experiments.

O.2.3 ***Heteronymous models are needed to describe shoulder stretch reflexes***

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BACKGROUND AND AIM: Healthy shoulder function requires the humeral head to remain secure in the glenoid cavity. Stretch-sensitive feedback may be critical for glenohumeral stability, and it is known that pathologies impairing feedback (e.g. stroke or spinal cord injury) often lead to severe shoulder insta-bilities. However, little is known about stretch reflexes at the shoulder due to challenges with measuring them reliably. We developed a manipulandum to study 3D shoulder mechanics, and the underlying neural control. This study investigated the coordination of stretch reflexes elicited by rotations of the gleno-humeral joint, as a step towards understanding their role in maintaining shoulder integrity. We hypothe-sized a heteronymous organization whereby shoulder reflexes in any muscle would be sensitive to the background activity of multiple muscles crossing the shoulder. METHODS: We recorded electromyograms (EMGs) from 8 shoulder muscles in response to random dis-placements in 6 directions spanning the degrees of freedom of the glenohumeral joint. Reflexes were quantified by average rectified EMG in short- (20~50 ms), medium- (50~75 ms), and long-latency win-dows (75~100 ms) after perturbation onset; background activity was computed -100~0 ms before each perturbation. Reflexes were elicited as subjects (n=11) generated isometric torques (10 or 20% maximum contraction) in the 6 measurement directions, and when relaxed. These volitional torques created rich pat-terns of background activity, providing a means to test our hypothesis. This was done using a linear mixed-effects model between the background activity of all muscles and the stretch reflexes elicited in each muscle. Separate models (n=144) were constructed for the reflexes in each muscle, each perturbation direction, and each response window. A simulated log-likelihood ratio was used to determine if models considering background activity in all muscles (heteronymous) were significantly better than those con-sidering only background activity in the muscle in which the reflex was measured, reflecting a homony-mous organization. RESULTS: The heteronymous model was significantly better than the homonymous model for 96% of the tested conditions. These results did not differ across measurement windows (p=0.16). The magnitude of the improvement was generally greatest for the largest reflex responses, which typically resulted from perturbation directions that caused the largest change in muscle length. For these conditions, the heteron-ymous models had an average $R^2 = 0.63$

± 0.18, and explained 18 ± 15% more of the total measured variance than the homonymous models, demonstrating a wide range of improvements. CONCLUSIONS: Our results demonstrated clear and strong stretch reflexes in muscles crossing the glenohumeral joint. The vast majority of these reflexes were explained best by a heteronymous model in which the response in any one muscle was modulated by the background activity in multiple muscles.

O.2.4 *Nonlinear connectivity in the human stretch reflex revealed by nonlinear phase coherence and multisine perturbations*

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ACKGROUND AND AIM: Reflexes are fast involuntary motor reactions with various latencies in response to unexpected perturbations. A common way to investigate reflexive behavior is to use mechanical perturbations (Kearney & Hunter, 1989). Previous studies used multisine perturbations (sums of sinusoids) for system identification of the human reflex system involving muscle spindles, Golgi tendon organs, the spinal cord and supraspinal systems (Abbink et al, 2011; Schouten et al, 2008). These studies mainly assessed linear input-output relations in human stretch reflexes, though several basic elements in the nervous system, such as muscle spindles, have been shown to be highly nonlinear (Gielen & Houk, 1987). This study explores nonlinear connectivity in the human stretch reflex using multisine perturbations and our recently developed nonlinear measure, namely multi-spectral phase coherence (MSPC) (Yang et al, 2016). MSPC is a nonparametric nonlinear phase coherence measure capable of assessing nonlinear input-output interactions and time delays in the nervous system. Since the multisine perturbation contains only a limited number of frequency components (fi, i = 1, ..., N), nonlinear connectivity can be detected by calculating nonlinear coherence between the stimulation frequencies and their harmonic (k*fi) and intermodulation frequencies (sum(ki*fi)) in the EMG. METHODS: Eleven subjects exerted an isotonic wrist flexion (1 Nm) while a manipulator imposed a multisine position perturbation to the same wrist. The multisine signal consisted of the sum of three sinusoids (7, 13 and 29 Hz, period: 1s, 1320 periods in total) with random phases. These frequencies allow for the

assessment of all second and third order nonlinearities without overlap in the output spectrum. Differential EMG signals were recorded from the flexor carpi radialis and the extensor carpi radialis muscles. The EMGs were digitally filtered by high-pass (35 Hz) and notch (50 Hz) filters to remove movement artefacts. Afterwards, the EMGs were full-wave rectified. We computed the nonlinear connectivity and time delay from the perturbation to EMG using MSPC. RESULTS: Nonlinear connectivity from the perturbation to EMG signals was detected in both second and third order harmonics and intermodulations of the stimulation frequencies. The estimated time delay from the multisine perturbation to EMG was 33 ± 6 ms, in accordance with the reported latency of the spinal stretch reflex at distal arm muscles to transient perturbations (Gorden et al, 2000). CONCLUSIONS: This study provides new evidence of nonlinear neuronal connectivity of the stretch reflex, in terms of nonlinear phase coherence. The estimated time delay indicates a major contribution of the spinal reflex loop to the nonlinear connectivity, in comparison with the transcortical component of the reflex which would result in longer delay. Our approach provides a useful tool to study nonlinear connectivity in the reflex system.

O.2.5 *Peri-patellar taps elicit regional stretch reflexes in the human vastus medialis*

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BACKGROUND AND AIM: Due to regional variations in fiber orientation and broad attachments, many human muscles have the potential to produce forces along different directions. The activation of these muscle regions may be regulated regionally based on local feedback from muscle spindles (Windhorst et al, 1989). While experiments with animal models provided some evidence for the regionalization of stretch reflexes (Cohen, 1953), experiments on the human tibialis anterior did not reveal such regionalization (McKeon et al, 1984). Because of its anatomy, the tibialis anterior has low potential for producing force in different directions; for this reason, we have investigated the regionalization of stretch reflexes in a human muscle with known region-specific directions of force production: the vastus medialis (VM). METHODS: Nine healthy individuals participated in this study. Using a custom-made hammer with an embedded load cell, taps were applied manually in steps of 10 mm to multiple regions along the VM insertion on the patellar edge. Thirty taps with varying intensity were applied to each location. A high-density surface EMG grid (5 columns by 13 rows spaced 8 mm) was placed across the VM, proximally to the innervation zone. In 3 participants, intramuscular recording electrodes were also inserted in 3 regions of the VM under the electrode grid. For the surface EMG, only trials where action potential propagation could be observed were included in the analyses. To standardize the input force applied across locations, 5 taps with comparable peak force were selected for each location. For each channel, the amplitude of the response was calculated as the magnitude of the largest negative peak occurring 15-45 ms after the tap. The amplitude distribution of the EMG response across the muscle was calculated by averaging the amplitude values for each row, resulting in an array of 13 amplitude values that formed a cross-section of the VM. The barycenter of the channels with amplitude larger than 70% of the peak of the distribution was used to describe the location of the response across the grid. RESULTS: Taps applied with similar input force (coefficient of variation: 3.42 ± 1.85%) resulted in localized, discrete responses of the stretched fibers only (3-5 regions for each participant). The location of the elicited responses was dependent on the location of the tap (ANOVA, $P < 0.001$; figure). Recordings with intramuscular electrodes confirmed the regional activation of the VM at different tap locations. CONCLUSIONS: These results indicate that motor neurons innervating fibers located in different muscle regions may be independently activated at the spinal level. As VM motor units located in different muscle regions have potential for producing force along different directions (Gallina and Vieira, 2015), these results suggest that these motor units can be recruited, at the spinal level, based on the mechanical efficiency of their muscle fibers.

O.2.6 *Evidence of Invariance in the Lower Leg Muscle?s Response due to Stretch Reflex Excitation during Movement.*

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Joint dynamic stiffness defines the relation between joint position and torque and dictates the joint response to unexpected perturbations. At the ankle, it is composed by the intrinsic, given by the viscoelastic and inertia properties of the joint, connective tissue and muscle, and the reflex component, given by the involuntary muscle activation due to the excitation of the stretch reflex mechanism. These two components act and change together so that estimating their relative contribution to the joint stiffness is a challenging problem. Several methods have been proposed for this task, among those, an analytical method that describes the joint dynamic stiffness by a parallel cascade structure where the intrinsic and reflex stiffness are given by a linear system and a series connection of a delay, a differentiator, a static nonlinearity and a linear system respectively, and estimates the system parameters from joint position and torque records, has been successfully used in our laboratory to separate the joint dynamic stiffness components. Using this method, it has been shown that joint stiffness model parameters change significantly with discrete changes in the joint position and torque (operating point). Recently, we extended this technique to estimate the joint dynamic stiffness during continuous changes in the operating point. This new method assumes that the parameters of the model are time-varying (TV) and can be described as linear combinations of predefined basis functions. An experimental study that involved an imposed ramp-and-hold movement with constant muscle activation showed that the novel joint stiffness model and identification algorithm were able to appropriately describe the intrinsic and reflex component during movement. It was observed that all the elements of the intrinsic stiffness changed significantly as a function of the joint position. Conversely, only the static nonlinearity in the reflex pathway showed significant changes with as the joint position changed. However, as the stretch reflex system, composed by the muscle spindles, neural connections and muscles, is lumped in a single non-linear system in our model, is difficult to dissect the response of each individual element. The stretch reflex response can also be modelled as the relation between rectified reflex EMG and torque. This relation bypasses the muscle spindle and neural connections, modelling only the relation between the electrical activity at the muscle and the produced torque. Provided this, we modified our algorithm to estimate the relation between joint position, reflex EMG and torque as a MISO, linear, TV system. Experimental results showed that the system representing the reflex EMG-torque does not change as function of the joint position. This indicates that the muscle?s response to the stretch reflex activation is invariant during the movement, and so, the source of the reflex modulation should be located in another component of the system

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O.3. EMG: modeling

O.3.1 *Comparison of EMG Feature Projection Techniques for Force Estimation*

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BACKGROUND AND AIM: In a process of extracting useful and meaningful information from the electromyogram (EMG) signal, feature reduction is considered as a valuable processing step to remove redundancy in the future space. This study investigates the effect of seven feature projection techniques on the estimation of force from EMG signals. METHODS. In this study we used previously recorded data during single and combined movements; see Kamavuako et al. (2013) for more details about the experimental protocol. From the six surface EMG channels, 11 time and frequency domain features (variance, mean absolute value, modified absolute value, mean absolute value slope, root mean square, Wilson amplitude, zero crossings, slope sign change, waveform length, mean frequency and mean power) were extracted from overlapping (by 50 ms) windows of 200 ms. We compared the following techniques: locality preserving projections (LPP), linear graph embedding (LGE), principal components analysis (PCA), orthogonal locality preserving projections (OLPP), isometric projections (IsoP), neighborhood preserving projections (NPE), uncorrelated linear discriminant analysis (ULDA) and orthogonal linear graph embedding (OLGE) at different number of retained features. The association between the reduced features and force was investigated using a linear regression model, with the coefficient of determination R^2 as performance measure. RESULTS: The coefficient of determination without any dimensionality reduction analysis (0.76±0.20) was used as the baseline, and compared to projection techniques where the turning point before the plateau was quantified. Performance was: LGE (0.87±0.20), LPP (0.86±0.33), PCA (0.78±0.19), NPE (0.85±0.20), OLPP (0.76±0.18), OLGE (0.77±0.21), ULDA (0.83±0.23) and IsoP (0.81±.22) averaged across all subjects. Performance measure approached maximum at the following reduced dimensions: LPP (8), LGE (6), PCA (18), ULDA (23), NPE (10), IsoP (12), OLGE (24) and OLPP (20).

IsoP was the most computationally complex technique. CONCLUSION: Results showed that in case of high dimensionality, LGE and LPP could improve performance and may be used as an alternative to PCA based techniques. REFERENCE: Kamavuako EN, Scheme EJ, Englehart KB. J Neurophysiol. 2013, 109(11):2658-65.

O.3.2 ***Periods of non-stationarity indicate motor unit recruitment in the tibialis anterior muscle of young healthy adults***

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BACKGROUND AND AIM: The orderly recruitment of motor units according to the Henneman size principle allows for efficient force generation. Recent studies have shown that periods of non-stationarity in the rat diaphragm electromyography (EMG) signal during ventilatory and non-ventilatory behaviors correspond with motor unit recruitment (Seven, et al. 2013). Furthermore, this non-stationary period was shorter during activities that required higher force production rates (e.g. sneezing) compared to activities that required lower force production rates (e.g. eupnea), indicating greater central drive. The specific aim of this study was to investigate the non-stationarity in surface EMG signals collected from the human tibialis anterior (TA) muscle during ramped isometric contractions. We hypothesized that higher rates of force generation would result in a shorter non-stationary period compared to lower rates of force generation. We also hypothesized that higher force generation rates would have a right shifted frequency spectrum compared to lower force generation rates, indicating the recruitment of fast-twitch motor units. METHODS: Eight young healthy adults (5 males; 26±2 years old; BMI: 22±2 kg/m^2) participated in this study. A bipolar stainless steel surface electrode was placed over the right TA muscle belly parallel to the muscle fibers. Ankle dorsiflexion force and surface EMG were simultaneously acquired at 2500 Hz per channel as subjects performed ramped isometric contractions at rates of 5%, 10% and 15% of each subject's maximum voluntary contraction (MVC) per second. Each force rate was repeated fifteen times. The stationarity of each signal was assessed in 20 ms segments over a 360 ms moving average window using the reverse arrangement test. Power spectral analysis was performed on stationary segments and the median power frequency (MedPF)

was calculated. A repeated-measure mixed model was used to test for differences, and Tukey-Kramer post-hoc analyses were used when appropriate ($\alpha<0.05$). RESULTS: Inter-individual differences accounted for 64% of the total variance in the non-stationary period and 30% of the total variance in the MedPF. The mean period of non-stationarity was 1268 ms, 980 ms, and 683 ms ($p<0.05$) for the 5%, 10% and 15%MVC/second force rates, respectively. The mean MedPF was 98 Hz, 86 Hz, and 125 Hz ($p<0.001$) for the 5%, 10% and 15%MVC/second force rates, respectively. CONCLUSIONS: The shortening of the non-stationary period with increasing force generation rate is consistent with greater neural input and more rapid recruitment of motor units. The shift of the MedPF to higher frequencies as force generation rate increased also suggests the additional recruitment of fast-twitch motor units. Collectively, these results indicate that non-stationarity analysis of surface EMG signals may be used to evaluate motor unit recruitment in human muscles.
References: Seven, YB, et al. (2013). Respir Physiol Neurobi: 185(2).

O.3.3 *Two Degrees of Freedom EMG-Force at the Wrist in Able-Bodied Subjects Using a Minimum Number of Electrodes: Pilot Testing of Limb-Absent Subjects*

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BACKGROUND: Traditional hand-wrist prostheses provide proportional control of only 1 degree of freedom (DoF) at a time, requiring the user to mode-switch between them. Research using large numbers of electrodes on able-bodied subjects has related the EMG of the forearm muscles to two degrees of freedom at the wrist. Initial evaluation in limb-absent subjects also shows this relationship, albeit with higher errors. However, using such large numbers of electrodes in a commercial prosthesis is not presently practical. Hence, we studied the ability to extract EMG-force information using a minimum number of electrodes. METHODS: For 10 able-bodied subjects, 16 conventional bipolar electrodes were mounted transversely about the proximal forearm. The hand was secured to a load cell which measured forces generated during wrist extension-flexion, radial-ulnar deviation and pronation-supination. A screen target produced slowly-moving (quasi-static) force targets along one of these three contraction dimensions per trial, and also produced targets with equal levels of co-contraction for pairs of dimensions (2-DoF tasks).

Effort ranged over 0-30% MVC. Linear, static, 1-DoF and 2-DoF models relating EMG amplitude to force were then trained, using regularized linear least squares. Initially, all 16 electrodes were used as inputs. Thereafter, backward stepwise selection of the training data sequentially reduced the number of electrodes. RMS error on a separate test trial was evaluated at each step. RESULTS: For 1-DoF models, stepping down to fewer than two electrodes was unacceptable; and retaining more than two electrodes provided limited benefit. This result was expected and consistent with existing prosthesis practice. With 2 electrodes, the 1-DoF average error ranged from 6.5-9.5%, depending on the DoF; pronation-supination exhibited the highest errors. For 2-DoF tasks, there was little or no change in error stepping from 16 down to 4 electrodes. Errors generally increased progressively as the number of selected electrodes decreased from 4 to 1. With 4 electrodes, the 2-DoF error averaged 6.3-8.1%, depending on the DoFs. Minimum errors occurred when combining flexion-extension with ulnar-radial deviation. This experiment was piloted with 4 unilateral limb-absent subjects. Force was measured from their sound side and mirrored contractions produced on the limb-absent side. Electrodes were mounted on the limb-absent side. For 1-DoF models using 2 electrodes, errors ranged from 12.8-18.3%, depending on the DoF. For 2-DoF models using 4 electrodes, errors ranged from 13.8-16.1%. Result trends matched those of the able-bodied subjects, but with higher errors overall. CONCLUSION: These results are encouraging that as few as 4 conventional electrodes, optimally located about the forearm, could provide 2 DoFs of simultaneous, independent and proportional control with error rates similar to the 1-DoF approach currently used for commercial prosthesis control.

O.3.4 *A comparison of Spike Shape Measures from Surface and Indwelling Electromyography during Elbow Flexion Isometric Ramp Contractions*

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BACKGROUND AND AIM: Surface EMG provides a global estimate of muscle activity, however the signal must pass from the muscle through fascia, fat, and skin, which acts as a physiological low-pass filter. Alternatively, indwelling EMG has the ability to identify individual motor units, however, only the few motor units located closest to the needle are recorded. The use of spike shape measures, rather than traditional amplitude and frequency measures, may provide a better comparison between surface and indwelling EMG recordings. The purpose of this research was to compare five spike shape measures obtained from surface and indwelling EMG of the biceps during a slow ramp contraction to 100% maximal elbow flexion force. METHODS: Eleven participants completed ramp contractions to 100% maximal force at a rate of 10%/sec. Electromyography was recorded from the medial head of the biceps brachii. Surface EMG was recorded in a bipolar electrode configuration. Indwelling EMG was recorded using a quadrifilar needle consisting of a 25-gauge stainless steel cannula housing 4 platinum-iridium wires 50 μm in diameter. Surface and indwelling EMG data was assessed across 22 epochs, 500 ms in duration, starting from the onset of the contraction. For each 500 ms epoch traditional (root-mean-square amplitude and mean power frequency) and spike shape measures (see Figure; mean spike amplitude, duration, slope, frequency, and number of peaks) were calculated for both surface and indwelling EMG. RESULTS: All measures had a significant interaction between electrode types across epochs. However, inspection of the amplitude measures (RMS, MSA, and MSS) shows that each of the three measures, calculated from both surface and indwelling EMG, followed the same general pattern across epochs. Alternatively, the frequency measures (MPF, MSF, and MSD) had different patterns depending on the electrode type and across the three measures. The amplitude traces can be characterized as a curvilinear pattern beginning with a linear increase until approximately 75-80% maximal force was reached, followed by a slight plateau and subsequent decrease as the end of the contraction neared. CONCLUSIONS: The similarity of patterns between surface and indwelling is explicable since wave cancellation has been shown to affect the magnitude but not the shape of amplitude measures (Keenan et al., 2005). The three measures of frequency; MPF, MSF, and MSD; demonstrated a nearly identical pattern across the three measures for surface, but not indwelling, recordings. Analysis of the data suggests that the selection of the threshold for spike detection may be the primary cause of the differing patterns. It is evident that EMG measures can be affected by physiological changes (force gradation across epochs) as well as methodological differences between the types of electrodes (surface vs indwelling) and types of analysis (interference pattern vs spike shape). This work was supported by NSERC

O.3.5 *On the Usability of Rejection Capable Support Vector Machines in an Online Virtual Targeting Task*

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BACKGROUND AND AIMS: Myoelectric prosthetic control - the use of electromyographic (EMG) signals to control an artificial limb - has been under investigation for decades. A major active area of research is in pattern recognition (PR), in which EMG signals are classified based on sample contractions representing common hand and wrist motions. While PR carries tremendous promise for intuitive and realistic control of prostheses, it remains underused outside of laboratory settings due to poor robustness. The support vector machine (SVM) classifier is more accurate in offline testing than the current standard, linear discriminant analysis (LDA), and produces a more granular confidence metric, which should allow more robust rejection of misclassified contractions. Thus, the objective of this study was to determine the usability of an SVM rejection classifier as compared to LDA. METHODS: Ten subjects (six male, 26.0 ± 4.7 years) participated in two experimental sessions. In each session, they first provided sample contractions which were used to train four classifiers: LDA, LDA with rejection (LDAR), SVM, and SVM with rejection (SVMR). The subjects were then presented with a Fitts' Law-based virtual targeting task; all four classifiers were used for this task, presented in random order. In the first experimental session, the cursor moved according to a class-normalized proportional control system; in the second, a standard mean-intensity proportional control system was used. RESULTS: SVMR outperformed LDA in all six Fitts' Law measures ($p < 0.05$), SVM in three (path efficiency, overshoot, and stopping distance), and LDAR in two (path efficiency and overshoot). Proportional Control showed a significant main effect in two measures (path efficiency and stopping distance), with the standard proportional control performing better than the normalized control in both cases. The fact that proportional control had a significant effect on the measures that SVMR excelled in prompted a deeper investigation. It was found that the SVMR predominantly outperformed the LDAR at low intensity levels, leading to improved performance with smaller targets, particularly with respect to stopping. The normalized proportional control scheme, however, was found to restrict these low-intensity movements, mitigating the benefits. This appears to be due to differences in the way classifier boundaries are calculated: SVM boundaries are calculated at the margins of the data, and are thus more sensitive to thresholding effects than LDA boundaries, which are based on the centroid and covariance matrix. CONCLUSIONS: While the SVMR generally outperformed the LDAR, the improvement was not as substantial as found in previous offline analyses. To better understand this, ongoing work is looking further into the interactions between classifier characteristics and proportional control schemes.

O.3.6 *Towards Improving the Training of Pattern Recognition Based Myoelectric Control*

Kadie Wright[1], Kevin Englehart[1], Erik Scheme[1]

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BACKGROUND AND AIM: Pattern recognition based myoelectric control has recently begun to see deployment in clinical use. One major challenge, however, is the need to conveniently and effectively train and retrain these systems. Even with prosthesis guided training, which allows the users to decouple from a training screen, the process remains cumbersome and unintuitive. The purpose of this research is to improve the training of these systems by better understanding the effects of user errors, and integrating more intelligent data processing and segmentation techniques. By looking at the effects of simulated mistakes (delayed response to prompts, or incorrect motions) that commonly occur during training, the challenges associated with different training methods can be better understood. These initial findings are being used to better understand the dynamics of training, and to develop new training algorithms. METHODS: To simulate training mistakes, 15 subjects were fitted with a flexible cuff with eight bipolar electrodes and were asked to elicit contractions corresponding to common prosthetic functions (such as wrist rotation or hand open). Offline analysis of motion classification accuracy was performed while artificially delaying the data onset, as well as swapping out specific training repetitions with incorrect motions. RESULTS: Figure 1a shows the drop in classification accuracy with increasing delay in user response to prompted motions (using a using linear discriminant analysis (LDA) classifier). Figure 1b shows the effect on classification accuracy as one training motion (wrist pronation) is replaced with that of a different motion (wrist supination) from 0 to 100 percent of that training repetition. CONCLUSIONS: These initial results indicate that the accuracy of a myoelectric classifier is greatly impacted by even minimal simulated errors during

training. Ongoing work is investigating alternative training modalities that could reduce the incidence of training errors. Additionally, we are developing a novel unsupervised segmentation algorithm that will be able to detect and compensate for the effects of these common mistakes during classifier training.

O.4. Rehabilitation Technologies II

O.4.1 *Cranial Nerve Non-Invasive Neuromodulation for Symptomatic Treatment of Mild and Moderate Traumatic Brain Injury - Effects on Muscle Coordination Patterns during Walking*

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BACKGROUND AND AIM: The objective of this on-going study is to investigate the influence of a cranial nerve non-invasive neuromodulation (CN-NINM) on gait in individuals with chronic symptoms of chronic mild to moderate traumatic brain injury (mTBI). CN-NINM is used to enhance neuroplasticity during rehabilitation, thereby improving the brain's ability to functionally compensate for neural tissues damaged or compromised by mTBI. The aim of this study was to investigate whether CN-NINM can fundamentally alter the underlying muscular coordination patterns observed during treadmill walking. METHODS: We have developed a portable electrotactile stimulation system (PoNS) to stimulate cranial nerves V and VII via an electrode array placed on the human tongue. We are currently conducting a double-blind clinical trial to assess the efficacy of the PoNS device for enhancing neurorehabilitation of gait and balance. The study enrolls 44 subjects: 22 with an active PoNS, 22 with a sham device. All subjects perform rehabilitation exercises 3x per day with the assigned device for 2 weeks in the clinic. Clinical metrics of gait and balance are obtained prior to training and at 2, 14, and 26 weeks. We collect electromyogram (EMG) data during gait as a metric of neuromuscular coordination. Surface EMG during walking was collected on a treadmill for 60 seconds at each subject's baseline preferred speed for six muscles on each leg (Tibialis Anterior, Medial Gastrocnemius, Soleus, Vastus Lateralis, Rectus Femoris, Semitendinosus). All EMG was bandpass

filtered (1-350Hz), rectified, and then low-pass filtered at 10Hz. EMG was averaged over all gait cycles and normalized to the muscle's rms EMG activity. The protocol was repeated on 8 healthy young adults. We cross-correlated individual mTBI muscle activation patterns with the healthy controls to assess the regularity of the muscle activations both before and after 2 weeks of rehabilitation. The Dynamic Gait Index (DGI) was also performed. RESULTS: The mTBI subjects entered the study with an average DGI of 18 (±6), putting them at an increased falls risk. There was a significant (p=0.006) improvement in the DGI to 21 (±6) following 2 weeks of rehabilitation. A number of individual mTBI subjects exhibited improved phasing of plantarflexor muscle activities. Univariate correlations revealed a significant (p=0.04) improvement in the consistency of soleus activation patterns, and a tendency (p=0.095) toward improvement in the gastrocnemius. CONCLUSIONS: CN-NINM is a new integrative therapeutic intervention that used the tongue to stimulate cranial nerves for the purpose of enhancing neuroplasticity during rehabilitative exercises. With 17 subjects enrolled, we are already seeing a significant improvement in clinical gait metrics. While we remain blind to which subjects are receiving active PoNS devices, there is an inconsistent effect across subjects with 4 individuals exhibiting remarkable (>4) improvements in the DGI.

O.4.2 *What does the CNS see during electrically stimulated muscle contractions?*

Patrick Crago[1]

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BACKGROUND AND AIM: Muscle stimulation is applied for therapeutic or neuroprosthetic benefit, including pain or spasticity reduction, and rehabilitation or augmentation of impaired motor control. Stimulation generates centrally conducted action potentials in both motor efferents and muscle receptor afferents, and the stimulated action potentials are mixed with ongoing neural activity supporting muscle control. To what extent are the resulting action potential patterns analogous to those evoked by normal muscle activity? Action potential patterns that result from muscle stimulation have not been well characterized. During stimulation via intramuscular, muscle nerve, or skin surface electrodes, action potentials propagating to the CNS are elicited in large diameter (low threshold) axons including motor efferents and proprioceptive afferents from muscle spindles (Ia) and tendon organs

(Ib), whose axons are co-located and have similar stimulation thresholds. A stimulus generates a pair of action potentials travelling distally and proximally. Thus, each stimulated axon combines antidromic and orthodromic action potentials generated by the stimulus mixed with action potentials generated by physiological processes. METHODS: This report focuses on the responses of tendon organs to both voluntary and stimulated contractions, including the effects of simultaneous Ib afferent stimulation. Action potential patterns are characterized by numerical simulation of human first dorsal interosseus contractions. The muscle model includes individual motor units and a population of tendon organs. Action potential antidromic-orthodromic interaction models include collision, refractory periods, and resetting of tendon organs by stimulus generated action potentials. RESULTS: Ib firing rates increase with increasing force level, achieved by increasing physiological excitation level, stimulus rate, or stimulus recruitment. Simultaneous Ib stimulation increases the action potential rate in a nonlinear manner. The average rate (calculated as the number of action potentials in a time window) is the lowest integer multiple of the stimulus rate that exceeds the receptor firing rate. Thus, for a fixed stimulus rate, increasing the receptor firing rate increases the Ib rate in a nearly staircase fashion. Low stimulus rates show a greater number of stair steps (i.e., better resolution) than higher rates. The net rate increment of a uniformly distributed population of tendon organs is approximately one half the stimulus rate. Therefore high rates offer the greatest increase in net firing rate. CONCLUSIONS: Stimulation of tendon organ afferents significantly disrupts their force coding accuracy. Increasing the stimulus rate increases the average firing rate but lowers resolution. Similar effects on sensory coding would be expected from stimulation of any afferent axon.

O.4.3 *Does the distance between electrodes markedly affect the knee extension torque elicited in tetanic, stimulated contractions?*

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BACKGROUND AND AIM: The parameters considered in functional electrical stimulation protocols are well described in literature. However, regarding the quadriceps muscle, indications on the positioning of stimulation electrode are missing [1,2]. In this study we specifically ask: does electrically elicited knee extension torque increase with the proximo-distal distance between cathode and anode electrodes positioned on rectus femoris (RF), vastus medialis (VM) and lateralis (VL) muscles? Considering the extensive, proximo-distal distribution of motor points within these muscles [3], we expect greater inter-electrode distances to elicit greater knee torque. METHODS: We measured the knee extension torque elicited by stimulating the femoral quadriceps of ten subjects (500 μs rectangular pulses; 20 pps). Adhesive stimulation electrodes were positioned to obtain current lines directed longitudinally to the each muscle. By taking as reference the femoral length (FL), defined as the distance between the patella apex and the anterior superior iliac spine, we tested four inter-electrode distances: 12.5%FL (L1), 25.0%FL (L2), 37.5%FL (L3) and 50.0%FL (L4). The position of the cathode electrode was fixed at 20%FL. For each configuration tested, we progressively increased current intensity at 10 mA steps, from 0 mA to the maximally tolerated intensity. Non-parametric Friedman ANOVA was used for the multiple comparisons and Wilcoxon test for the paired comparison, with Bonferroni correction. RESULTS: As expected, electrode positioning affected markedly the maximally elicited, knee extension torque. For the L1 and L2 configurations, knee extension torque did not increase after the stimulation intensity reached a certain value. In contrast, for L3 and L4, knee torque increased proportionally with the stimulation intensity. The maximal torque values elicited for L3 (interquartile interval: 70-125 Nm; N=10 subjects) and L4 (90-140 Nm) were on average 2-3 times greater ($p<0.05$) than those obtained for L1 (25-40 Nm) and L2 (55-70 Nm). The maximal current tolerated by each participant ranged from 60 mA to 100 mA and did not depend on the inter-electrode distance. CONCLUSIONS Key results revealed that: i) for small inter-electrode distances, increases in knee torque ceased after the current intensity reached a certain value; ii) the maximal extension torque increased dramatically with inter-electrode distance. Collectively, these results indicate the position of stimulation electrodes critically affects the elicited torque, with potential, significant implications for the optimisation of protocols based on functional electrical stimulation. [1] Davoodi R. et al. IEEE Trans Neural Syst Rehabil Eng. (2002); 10: 197-203. [2] Benton L.A. et al. FES - A practical clinical guide, Rehab Eng, Downey, 1980 [3] Botter A. et al. Eur J Appl Physiol (2011); 111: 2461-2471.

O.4.4 ***Sensory and Motor Thresholds for Surface Electrical Stimulation of Median and Ulnar Nerves at Elbow for Sensory Feedback***

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BACKGROUND AND AIM: Loss of the sensory input for trans-radial amputees may lead to maladaptation in the sensory cortex, causing phantom limb pain (PLP). Restoring part of the lost sensory input through sensory feedback evoked by electrical stimulation may induce plastic cortical changes and alleviate PLP to some degree. Sensory and motor thresholds for surface electrical stimulation of ulnar and median nerves at elbow evoking hand sensations in healthy subjects have been investigated. The study aimed to optimize parameters of the electrical stimuli evoking hand sensations without eliciting motor responses in 10 healthy subjects. METHODS: For each nerve, one pair of round PALS electrodes with diameter of 32 mm was placed at elbow. To stimulate the ulnar nerve, one electrode was placed just above the cubital tunnel, with reference to the medial epicondyle of the humerus and the olecranon of the ulna, and the other was placed proximal towards the median side of the humerus. One electrode was placed lateral to the biceps tendon and the other was placed distal along the ulna when stimulating the median nerve. Current controlled biphasic stimuli of increasing amplitude of 0.5 mA, frequency of 10 and 50 Hz, and pulse duration of 100, 200, and 300 msec were delivered by the Inomed neurostimulator to both nerves during one session of approximately 3 hours. The subjects reported location of evoked sensations in areas of the palmar side of the hand corresponding to innervation by median and ulnar nerves. RESULTS: Sensation thresholds of 5.88 %2B/- 1.04 mA and 8.16 %2B/- 1.75 mA and motor thresholds of 8.01 %2B/- 1.76 mA and 11.65 %2B/- 1.74 mA were obtained for the median and ulnar nerve, respectively. Stimuli with frequency of 50 and 10 Hz and pulse duration of 200 and 300 msec evoked sensations without motor response in 27.9 and 32.3 % of the area of palmar side of the hand for ulnar and median nerve, respectively. The pulse duration and frequency showed a modulating effect on the sensory and motor thresholds for both nerves ($p < 0.05$, 3-way ANOVA). CONCLUSIONS: Hand sensations were consistently evoked by surface electrical stimulation of the median and ulnar nerves at elbow for sensory feedback.

O.4.5 *The effect of rehabilitation with the neuromuscular electrical stimulation after femoral neck fracture surgery -Short term intervention reports-*

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Background and Aim: Following femoral neck fracture treatment, lower leg muscle atrophy and weakness were caused by immobilization and inflammation. It is important that patients start to rehabilitation during early post-operative period in order to prevent muscle atrophy and maintain muscle strength, which is often used the neuromuscular electrical stimulation (NMES). Past researchers studied the effectiveness after total knee arthroplasty or femoral fracture treatment. However, there were few studies about the comparison of the effect by using the NMES after the Bipolar hip arthroplasty surgery. Our purpose of this study was to compare the differences of the clinical results between the Bipolar hip arthroplasty (BHA) with the NMES and control group. Methods: Eighteen patients were randomly divided in 2 groups: BHA with NMES (9 patients) and no NMES group (control, 9 patients). There were no differences about the age, height and weight between BHA with NMES and control group. These patients received both standard rehabilitation and, in the NMES groups, two pairs of adhesive electrodes were displayed the femoral nerve and the quadriceps muscle to mitigate strength loss. The NMES unit we used (ESPURGE, Ito Co., JPN) provides an asymmetric biphasic pulse waveform, pulse duration of 300 μs. The frequency was 80 Hz. NMES was applied 20 minutes per day at the maximal tolerable intensity for 4 weeks after surgery. We analyzed the knee extensor muscle strength by using the hand held dynamometer and Japanese Orthopedic Association Scoring (JOA) at 1 week, 2 weeks, 3 weeks and 4 weeks after surgery. JOA score were consisted of pain, Range of Motion (ROM), gait ability, and Activity of daily life (ADL). Student t test assessed the differences in the muscle strength and JOA among three groups. Results: As for the comparison of muscle strength, the results of BHA with NMES were significantly better than these of control at 1 week ($p<0.01$), 2 weeks ($p<0.01$), 3 weeks ($p<0.01$) and 4 weeks ($p=0.025$). And the JOA score were significantly better in the BHA with NMES compared with the control at 1 week ($p<0.01$), 2 weeks ($p<0.01$), 3 weeks ($p<0.01$) and 4 weeks ($p<0.01$). Conclusions: The inclusion of the neuromuscular electrical stimulation (NMES) program after BHA surgery was more effective at providing rapid improvements in muscle strength than control. And the JOA score of BHA with NMES were significantly higher than that of control. We suggest that the difference in muscle strength between BHA with NMES and control after surgery was brought about by the prevention muscle atrophy by NMES using for 4 weeks. Furthermore, our data also supported the increased muscle strength were influenced on JOA score. In the future, it should be further followed up the patients to investigate the long-term outcomes.

O.4.6 *The cortical adaptation monitoring system for leg press machine with FES induced biofeedback*

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BACKGROUND AND AIM: For the purpose of effective training of paralysis, Functional Electrical Stimulation(FES) provides both muscular training and sensory stimulation for the brain. Combination of muscular synergy effect and the brain plasticity is new key issue of robotic rehabilitation. The conventional FES system is applied mainly for the tentative training, however it has been disturbed for long term recovery of motor function, since the difficulties of keeping motivation. FES system required long time trial and error training without any feedback. This boring process is one big reason for losing motivation. Therefore, evaluations of training effect are desired to provide feedback to the trainees to keep motivation. FES has shown its effectiveness in the recovery of motor function. It can promote recovery of muscular force and induce brain plasticity by somatosensory feedback. This study investigated the generality of brain responses during voluntary exercise associated with FES which has the effect of training (motor learning). METHODS: The subjects were separated into two groups. One group performed leg press training while undergoing FES. We stimulated subject's left quadriceps muscle with the FES device for one second. The subjects controlled the timing of FES to provide FES induced biofeedback. We thought that FES is assist for leg press training. The other group only performed voluntary leg press training. The subjects were seated in the chair of the leg press device(Fig.1). The subjects were required to control the position quickly and accurately during high-intensity exercise. The NIRS measurement covered the primary motor cortex and the somatosensory cortex with transmitters and receivers. Receiver No.5 was positioned on the Cz of the international 10-20 system. The

subjects performed leg press training twenty times per experiment. RESULTS: We constructed a measurement system for leg press training with FES induced biofeedback. Both knee joint angle and brain activity during training are measured and synchronized by an external signal. We monitored the brain activity of healthy subjects with NIRS over a three-month period (once per day) during which the knee joint movement was induced by FES. The motion performance results showed that the dispersal of position error was smaller with FES(Fig.1 left and right). CONCLUSIONS: The experiment results suggested that FES has efficacy as power assist in motor training. This monitoring system might well be able to evaluate training effects during FES induced biofeedback. Further research will examine patients suffering from paralysis to determine the optimum stimulation parameters for brain activation to involve brain plasticity.

O.5. Neuromechanics II

O.5.1 *Effect of Lower Extremity Efforts on Involuntary Upper Extremity Activity in Chronic Hemiparetic Stroke: Preliminary Findings*

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INTRODUCTION: Following hemiparetic stroke, individuals often manifest altered interlimb coupling patterns. High efforts in the lower extremities can cause involuntary upper extremity movements, which interfere with gait, balance reactions, activities of daily living, and have negative cosmetic effects. Abnormal interlimb coupling is hypothesized to be due to an upregulation of brainstem motor pathways (reticulospinal and vestibulospinal tracts), which branch extensively in the spinal cord. While abnormal coupling patterns within both the upper and lower extremity have been previously quantified, coupling patterns between limbs are poorly understood. The aim of this project was to quantify the effect of lower extremity tasks on involuntary activation of the upper extremity in individuals with chronic stroke. METHODS: 12 individuals with chronic stroke and 7 age-matched controls were recruited for this study. A novel robotic application was used to support the upper

extremity with haptic springs. This approach allowed for the quantification of upper extremity kinematics and kinetics, while negating the weight of the upper extremity and preventing participants from using their upper extremity as a rigid ground to gain biomechanical advantage. Participants performed maximal and submaximal (25, 50, and 75%) voluntary isometric knee flexion and extension contractions while instructed to relax their upper extremity. In a separate condition, participants were asked to suppress their upper extremity activity. Both paretic and non-paretic upper extremities were tested with each leg. In control participants, the non-dominant arm was tested with both legs. RESULTS: Control participants were able to isolate the lower extremity efforts, with no significant upper extremity activity. In individuals with chronic stroke, lower extremity efforts resulted in involuntary upper extremity activity that was dependent on the level of effort in the lower extremity. Both paretic and non-paretic knee flexion and extension elicited involuntary upper extremity movement. While the involuntary movement was greater in the paretic arm, the non-paretic arm also had activity that was greater than in control participants. Shoulder adduction was elicited in the majority of stroke participants regardless of the lower extremity task, while there was a trend for knee extension resulting in elbow extension and knee flexion causing elbow flexion. When asked to suppress the upper extremity motion, stroke participants were unable to significantly reduce their arm motion or produce the same level of lower extremity torque.
DISCUSION/CONCLUSIONS: The results of this study show that individuals with chronic stroke have altered interlimb coupling patterns that are dependent on the level of descending motor drive. The findings suggest that the underlying mechanism for altered interlimb coupling is an increased use brainstem pathways with increased task demands.

O.5.2 *Variability in neuromotor control of the musculoskeletal system dynamics: a stochastic modelling approach.*

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Introduction The number of muscles in the human motor system exceeding the number of kinematic degrees of freedom (DOF) [1] allows the motor control system to select one neuromotor control strategy from many options. Even when pursuing the same strategy, however, structured variability exists in the muscle activations and end-effector forces recorded [2]. A stochastic method (Metabolica) has been used to sample the space of possible muscle force patterns that balance the net joint moments throughout a movement [3]. Static optimization techniques have been used to separately determine the boundaries of the corresponding space of muscle activation patterns [4]. The aim of this study is to compare the boundaries of the spectrum sampled using Metabolica for an increasing sample size with corresponding boundaries calculated using static optimization. This information is necessary towards the design of a probabilistic framework for studying subject-specific control strategies. Methods Gait analysis data were collected for one gait cycle of one healthy subject (male, age: 28 yr., height: 1.90 m) and net joint moments and muscle lever arms were estimated using the Opensim Gait2392 model with 13 DOF and 92 muscles [5]. The force each muscle could produce was constrained by its tetanic isometric force at optimal fibre length. The solution space of the constrained equilibrium equation at the joints was sampled using Metabolica with the following sample sizes: 1e5, 2e5, 3e5 and 1e6. The reference boundaries of the solution space were calculated through static optimizations that separately minimized and maximized the force of each muscle. The ranges of muscle force identified by the two methods were compared. Results and discussion For a sample size of 1e5, the sampled muscle force ranges grossly underestimated the optimized force ranges. For 2e5 samples, the samples covered the whole range for most muscles, while for some muscles (including gluteus maximus, vasti and soleus) the range sampled with Metabolica was smaller than the optimized range, as shown by non-red areas in Figure 1, indicating extreme forces to be highly improbable. Following increases in sample size did not generate evident changes in the results. This is likely to be attributed to the fact that a change in the force of certain muscles constrains the possible force contribution of other muscles. Future studies will focus on using EMG and kinematic data from repeated movements in order to define a layer of probability associated with the sampled force patterns to represent individual variability. Acknowledgement This project was funded by the EPSRC Frontier Engineering Awards, Grant Reference No. EP/K03877X/1. References [1] Bernstein NA. Oxford: Pergamon Press 1967 [2] Valero-Cuevas FJ, et al. J Neurophysiol 2009;102:59-68 [3] Martelli S, et al. J Biomech 2013;46:2097-2100 [4] Simpson CS, et al. J Biomech 2015;48:2990-2997 [5] Delp SL, et al. IEEE Trans. Biomed. Eng. 2007;54:1940-1950

O.5.3 *From muscle-tendon to whole-body dynamics: towards a multi-scale empirical understanding of human movement biomechanics*

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BACKGROUND AND AIM: A grand challenge in the field of biomechanics is to develop a cohesive, multi-scale understanding of human movement that links muscle-tendon, joint and whole-body dynamics. Musculoskeletal simulations have been developed to help bridge these gaps; however, these computational models are difficult to validate due to parameterization complexity and anatomical/physiological uncertainties. Empirical methods could potentially overcome these limitations by more directly measuring human biomechanics, but the challenge remains to improve quantitative agreement between our various experimental estimates. Using traditional 3D analysis, biomechanical estimates at one scale often do not agree with estimates at another. For instance, net mechanical work computed about the joints when a person climbs a set of stairs overestimates the work performed to raise the center-of-mass against gravity (Duncan et al. 1997). Even for level ground walking, work discrepancies of 25-35% have been observed (Zelik et al. 2015). Likewise, muscle-tendon work estimates derived from ultrasound and force transducers may not be fully consistent with joint work estimates from inverse dynamics. It is critical to resolve these discrepancies in order to develop a comprehensive, multi-scale understanding of movement. This abstract summarizes our recent efforts to coalesce multi-scale estimates. METHODS: In one study we integrated various empirical estimates of work and energy in order to synthesize whole-body dynamics (from Fenn 1930, and Cavagna et al. 1963 traditions) with joint- and segment-level kinetics (from Braune and Fischer 1895, and Elftman 1939 traditions). In a second study we focused on developing and validating an EMG-driven musculoskeletal analysis to partition joint kinetics into contributions from individual muscle-tendon units. We are now working to parse muscle fiber vs. tendon work by incorporating ultrasound. RESULTS AND CONCLUSIONS: We demonstrated, for the first time, that joint-segment estimates could fully capture whole-body gait

dynamics (work done on/about the center-of-mass, Zelik et al. 2015). We found that the key to resolving work discrepancies was using 6 degree-of-freedom (rotational and translational) analysis of the hip, knee, ankle and foot. Next, we demonstrated that a new EMG-driven analysis could reproduce inverse dynamics sagittal ankle power with high fidelity during walking (R^2=0.98, Honert and Zelik 2016, in review), while providing estimates of individual muscle-tendon contributions. Future work remains to validate this approach for different joints, activities, and planes (non-sagittal). The next challenge is to parse muscle fiber vs. tendon work. Although historically difficult, advances in medical imaging (e.g., ultrasound) offer promise. We will discuss ongoing efforts to reliably quantify muscle-tendon length changes and forces during movement, and to synthesize these with our multi-scale biomechanical understanding.

O.5.4 *The same library of muscle synergies are shared across diverse locomotor tasks*

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BACKGROUND AND AIMS: Previous research has suggested that human movement is controlled by a "mixed" modular strategy that includes both shared (task-independent) and specific (task-dependent) muscle synergies (i.e. consistent time-synchronous multi-muscle coordination patterns). However, prior studies have been insufficient to fully characterize how muscle synergies are recruited across a range of locomotor tasks because of the limited number and diversity of the tasks they examined. It is possible that the muscle synergies considered task-specific are recruited during other non-measured behaviors. The aim of this study was to investigate muscle synergies across a large number of diverse locomotor tasks. We hypothesize that locomotor tasks are controlled by a library of task-independent muscle synergies. METHODS: One healthy, young adult (M, 25 years old) performed 18 diverse locomotor tasks that included walking at a range of speeds/directions, with different stepping patterns, turning with different radii, and maneuvering around obstacles and across uneven terrain. EMG was collected from 16 leg and trunk muscles on the right side. We identified the set of unique muscle synergies recruited across all tasks using a two-step process. In step one, muscle synergies were extracted separately from each task using non-negative matrix factorization (NMF). The number of muscle synergies for each task was chosen such that the overall variability accounted for (VAF) of the reconstructed EMG was ≥ 90%. Then in step two, the muscle synergies extracted from each task in step one were pooled together and grouped using a hierarchical cluster analysis (CA). The number of unique muscle synergies was determined by identifying the minimum number of clusters such that each cluster did not contain multiple muscle synergies from the same task. As a secondary validation, we also extracted a set of unique muscle synergies from a data matrix containing all data from all tasks (joint extraction, JE), where the number of unique muscle synergies was chosen such that overall VAF for each task was ≥ 90%. RESULTS: We found a total of 13 unique muscle synergies using the CA method that could describe the muscle activity from all 16 muscles during all 18 locomotor tasks. 6.8±1.0 (mean±SD) of these muscle synergies were recruited per task and each muscle synergy was recruited in more than one task (mean number of tasks per muscle synergy: CA=9.4±4.8, range 5-17). The JE method identified an equivalent number of muscle synergies, 12, which were found to be similar in structure to those identified using the CA method (Pearson's R=0.83±0.12), and were also recruited across multiple tasks (12.6±2.7). CONCLUSIONS: By examining a large number of locomotor tasks encompassing diverse functional demands we found that all muscle synergies were recruited across multiple tasks, supporting our hypothesis that locomotion is controlled by a library of task-independent muscle synergies.

O.5.5 *Decreasing the lumbar flexion moment induces earlier onset of flexion relaxation*

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BACKGROUND AND AIM: Flexion relaxation (FR) is characterized by a reduction in lumbar erector spinae (LES) muscle activation near end range of trunk flexion. FR is believed to occur as passive spine structures (ligaments, discs, and passive muscles), which are slack in a neutral spine position, become engaged and support the lumbar moment. The engagement of passive structures allows lumbar muscles to cease active force production. Consistent with this theory, increasing the lumbar moment

by adding mass to the torso has been shown to delay the onset of FR [1]. The purpose of this study was to determine if experimentally decreasing the lumbar moment produced the opposite effect, inducing FR to occur earlier. A secondary purpose was to characterize how the lumbar moment affected thoracic and abdominal muscle activity during trunk flexion. METHODS: Ten healthy males (25 ± 2.5 years, 181 ± 5.8 cm, and 82 ± 11.2 kg) performed four trunk flexion conditions; lumbar moment was reduced by attaching 0, 5, 10, or 15 lb counterweights to the torso with a pulley. Muscle activity was recorded using fine wire electromyography (EMG) from lumbar multifidus and surface EMG from LES, thoracic erector spinae (TES), latissimus dorsi (LD), rectus abdominus (RA), and external (EO) and internal oblique (IO). Kinetic and kinematic data were input into a custom two dimensional, dynamic rigid linked segment model to determine the lumbar moment. Lumbar moment, lumbar flexion angle (between T12 and S1 spinous processes) and trunk inclination angle (between T12 and horizontal) at the critical point when LES became inactive (CPLES) were compared between conditions. RESULTS: Counterweights decreased the lumbar moment and lumbar flexion angle at CPLES ($p < 0.0001$ and $p = 0.0029$, respectively); however, there was no effect on trunk inclination at CPLES. Multifidus demonstrated FR similar to LES, while TES and LD remained active throughout trunk flexion. RA, EO, and IO activated at the same instant that LES inactivated, except in the 15 lb condition where abdominal muscles became active approximately 1 s before CPLES. CONCLUSIONS: The hypothesis that FR would occur earlier when the lumbar moment was reduced was accepted. This provides further evidence that FR occurs when the lumbar moment is equilibrated by passive structures. Thoracic and abdominal muscles actively produced force at end range of trunk flexion. As both thoracic and abdominal muscles affect the lumbar spine moment, changes in mechanics or activation of these muscles may affect presentation of FR. REFERENCES: [1] Howarth SJ, Mastragostino P (2013). J Biomech Eng.135(10); p1-6.

O.5.6 ***Estimation of Ankle Impedance During Walking on a Slippery Surface***

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BACKGROUND AND AIM: Walking safely on a slippery surface is a difficult task and failure to do so can result in falls and injuries. This challenge is increased for lower-limb amputees, as their ability to change gait patterns is constrained by the dynamics of the prosthetic leg, which typically do not adapt to changing surfaces. We previously demonstrated that able-bodied subjects reduce slip potential in part by reducing ankle muscle activity, which has been linked to a reduction in joint impedance. This finding could be used to program the impedance of robotic prostheses, which are becoming more prevalent. However, we do not yet know how the observed reduction in muscle activity influences the net impedance of the ankle. The objective of this work was to quantify ankle impedance for able-bodied subjects walking on a non-slippery and slippery walkway. Based on previous work, we hypothesized there would be a reduction in the stiffness component of ankle impedance on the slippery walkway. METHODS: Three able-bodied subjects completed a protocol in which they walked across a non-slippery walkway (coefficient of friction (COF) > 0.4) and a slippery walkway (COF $= 0.17 \pm 0.01$). Embedded halfway down the walkway was the Perturberator Robot, a device that can be used to estimate ankle impedance during the stance phase of gait. When subjects stepped onto the robot, it randomly delivered a 2-degree ramp-and-hold perturbation. Perturbations occurred randomly in either the plantarflexion or dorsiflexion direction at 150, 300, or 450 ms after heel contact. Perturbations occurred in 67% of the trials. System identification techniques were used to estimate ankle impedance, modeled as a second-order system with stiffness, damping, and inertia. Electromyograms (EMGs) were recorded from select ankle muscles, including medial gastrocnemius (MG) and tibialis anterior (TA). EMG was quantified using root-mean-square over the same range of data used for impedance estimation. RESULTS: Even though there was a reduction in EMG on the slippery walkway, there was no concurrent reduction in joint stiffness. MG EMG was significantly reduced ($p=0.004$) by 18% and TA EMG was significantly reduced ($p=0.027$) by 13% on the slippery walkway. There was, however, no difference in stiffness between the walkways ($p=0.406$). CONCLUSIONS: These results suggest that the muscles recorded in this study, which are easily accessible using surface EMG, cannot be used as a proxy for joint stiffness. This is in direct contrast to what has been shown for isometric contractions, implying that joint impedance is modulated differently during static tasks compared to time-varying dynamic tasks. Other parts of the joint, such as the tendon, might be setting the stiffness level under these conditions. Follow-up studies should be conducted to determine the parts of the joint that contribute to impedance modulation during locomotion.

O.6. Motor Units I

O.6.1 *Motor units in the human medial gastrocnemius muscle are not spatially localized or functionally grouped*

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BACKGROUND AND AIM: There is evidence from surface electromyography (EMG) studies of regional medial gastrocnemius (MG) muscle activation in humans, which may allow for more controlled and efficient torque generation. In line with these findings, MG motor units (MUs) are thought to occupy small muscle territories (2.5-4 cm), with low-threshold units preferentially located distally. However, the presence of regional activation in the MG muscle has been questioned. In the present study we used indwelling wire and needle EMG recordings to estimate the size and location of MG MU territories and determine whether they were grouped based on recruitment threshold or joint action. METHODS: Subjects (n = 8) performed ramped and sustained isometric contractions (ankle plantar flexion and knee flexion; range: ~1-40% maximal voluntary contraction) and we measured MU territory size with spike-triggered averages from fine-wire electrodes inserted along the length (seven electrodes) or across the width (five electrodes) of the MG muscle. RESULTS: Of 69 MUs identified along the length of the muscle, 32 spanned at least half the muscle length (≥ 6.9 cm), 11 of which spanned all recording sites (13.6-17.9 cm). Distal fibres had smaller pennation angles ($P < 0.05$), which were accompanied by larger territories in MUs with fibres located distally ($P < 0.05$). There was no distal-to-proximal pattern of muscle activation in ramp contraction ($P = 0.93$). Of 36 MUs identified across the width of the muscle, 24 spanned at least half the muscle width

(≥ 4.0 cm), 13 of which spanned all recording sites (8.0-10.8 cm). MUs were not localized (length or width) based on recruitment threshold or contraction type, nor was there a relationship between MU territory size and recruitment threshold (Spearman's rho = -0.20 and 0.13, P > 0.18). CONCLUSIONS: MUs in the human MG have larger territories than previously reported and are not localized based on recruitment threshold or joint action. In line with these observations and similar to what has been reported in the cat, we found that many MUs in the human MG muscle have territories that extend over a large portion of the muscle, with no evidence that these MUs are grouped by recruitment threshold or joint action. Together, these results lead us to propose that the human MG muscle is uniformly activated by the CNS and, more cautiously, that previous reports of regional muscle activation may reflect methodological limitations and between- and within-subject variability. Finally, these results indicated that the CNS does not have the means to selectively activate regions of the MG muscle based on task requirements.

O.6.2 ***Motor Unit Action Potential Clustering***

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Motor Unit Action Potential Clustering Michael J. Asmussen, Vinzenz von Tscharner, Benno M. Nigg Background & Aims: This study aimed to understand motor unit action potential synchronization and clustering using a modelled electromyography (EMG) signal. The power spectrum of an electromyography (EMG) signal can be sensitive to changes in the shape of motor unit action potentials (MUAPs) and MUAP firing patterns. For instance, the EMG signal from a fatiguing muscle is often associated with a shift of the mean power frequency to lower values. Dynamic tasks, such as squatting, result in similar mean power frequency shifts. The mechanism underlying this shift, however, has yet to be determined. Previous literature suggests that this low frequency shift could be attributed to the phenomenon of motor unit action potentials arriving together in a very short time window (i.e., clusters). The purpose of this study was to determine, using a modelled EMG signal, whether clustered motor unit action potentials can create differences in the corresponding power spectrum characteristics. Methods: The EMG signal was modelled by

convolving a single MUAP with a randomly distributed impulse train (EMG-rand). A second EMG signal was modelled with the same MUAP and a "clustered" train of impulses that occurred in windows varying in duration from 1 to 80 ms (EMG-clust). To form the final modelled EMG signal, the EMG-clust was added to the EMG-rand with varying ratios ranging from 1:1 to 1:10. Results: The results from this study revealed that adding clustered MUAP (8 to 40 ms) to an EMG-rand signal caused a substantial low frequency shift (i.e., ~30 Hz) in the mean power frequency with the largest shift occurring with a cluster window of 16 ms. Further, the magnitude of the greatest mean frequency shift in the power spectrum was larger when the ratio of EMG-clust to EMG-rand was higher (i.e., 100% clustering: 26 Hz; 50% = 17 Hz; 33% = 13, ratio 25% = 7 Hz; 10% = 3 Hz). Conclusions: The changes in mean frequency of the modelled EMG signal in this study were similar to the frequency shifts seen experimentally during dynamic tasks. Therefore, the model created in this study potentially explains the mechanism of the mean frequency changes in the power spectrum observed in dynamics tasks such as running. While the applied model is a simplification of a typical measured surface EMG, it seems to be able to describe the phenomenon of power spectra changes in dynamic tasks.

O.6.3 *EMG envelope and tension oscillations during steady fine motor control*

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Introduction At the beginning of motor unit (MU) recruitment, the inter-spike interval shows relatively large variability. This phenomenon can be related to large force fluctuations (Tracy et al., JAP, 2005). Studies dealing with the relation between the steadiness in muscle mechanical output and the fluctuations in the drive from the spinal motoneurons usually do not focus on the first transient phase. For this reason, there are relatively few data investigating the force transients and motor unit activity in the time interval time interval needed to reach the force target. This study aims at shedding light on this aspect of motor control, using experimental recordings of torque, bipolar EMG (SD-EMG), reflecting the overall stream of MU commands, and high density surface EMG (HD-EMG), from which a direct information on MU activity can be obtained by decomposition (Negro et al., 2016). Methods Two experiments were performed. In the first, bipolar EMG signals (SD-EMG) were recorded from 20 subjects. In the second, HD-EMG using arrays of 64 surface electrodes were recorded in 5 subjects. In both experiments, the tension (T) was recorded during a 20-s abduction of the First Dorsal Interosseous (FDI) muscle, with target force set to 2.5% of the maximal voluntary contraction (MVC). SD-EMG study. The fluctuation of the EMG envelope (eEMGf) and of the T (Tf) were obtained by bandpass filtering the two signals (0,5-5 Hz). Average rectified values (ARV) of eEMGf and Tf was calculated second by second. HD-EMG study. Individual MU spike trains were identified through decomposition and analyzed according to Negro et al. (2009). Results SDEMG study. Through exertion, the eEMGf and Tf ARV decreased up tp 40%±5.35 and 15%±1.84yy from their initial value, respectively. The difference was statistically different. The steady state in the Tf and eEMGf ARV reduction was reached always within 4 s. HDEMG study. During the transiet to target force, the interspike interval variability for individual MUs was greater than in the steady part of the contraction (its coefficient of variation changed from about 1.2 to 0.3 from the first seconds to the steady state) . Moreover, a continuous recruitment and de-recruitment of MUs was observed. Conclusion The results from HDEMG study support the hypothesis that the initial phase of tension variability may be related to a large variability in MU firing and recruitment (this is mirrored in high eEMGf and Tf ARV values in the first 4-5 s of exertion). After this interval the motor control system provides a more stable flow of motor commands and the tension oscillations are reduced. These events can influence the mechanical output more than the eEMGf variability because of the different summation properties of MU twitches and MUAPs.

O.6.4 ***Using the Size Principle to Model Peripheral Muscle Fatigue***

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BACKGROUND AND AIM: Peripheral muscle fatigue is the decrease in the force output of motor units, and the whole muscle, for a given excitation. Fatigue models in the literature range from regression equations to complex representations of motor neuron pools and metabolic dynamics (see Dideriksen et al, 2010). An accurate, but easy to implement, fatigue model would have many applications in ergonomics, exercise, and rehabilitation. This paper describes the development and

validation of such a model, which uses size-principle based simulations to predict motor unit (MU) firing rates, MU and whole muscle force production, and their subsequent fatigue time-histories. METHODS: We used the model of Fuglevand, Winter & Patla (1993) to determine instantaneous firing rates and forces for 120 MUs, as excitation was increased from 0 to 100% MVC. We then assumed that each MU's instantaneous fatigue rate (FR) was proportional to its current force, such that higher threshold (and stronger) MUs had higher maximum FRs, and individual MUs approached their own maximum FR as they approached their maximum force. During sustained isometric contractions, each active MU was ascribed a reduction in its maximum force, over each 0.10 s epoch, according to its current exerted force and corresponding FR. In the subsequent epoch, the model determined the necessary excitation to meet the target force given the resulting force loss for each MU recruited at that excitation. Endurance time was then determined as the time, since the outset of the contraction, at which simulated muscle force could no longer match or exceed the target force, despite maximal excitation of the MU pool. Simulated endurance times were compiled for a wide range of target forces (20 to 80%, in 5% increments) and compared to those estimated from non-linear regression of measured endurance times from numerous experimental studies on human subjects. RESULTS: Overall, the model predicted endurance times remarkably well over a wide range of target forces. Across all 13 target conditions, the RMS difference between simulated and experimentally observed endurance times was 6.5%. For example, for a 20% MVC target, the model predicted an endurance time of 486 s, whereas that estimated from empirical data was 513 s (-5.3% difference). Likewise, for a 60% MVC target, the model predicted an endurance time of 79 s whereas the estimate from empirical data was 72 s (9.7% difference). CONCLUSIONS: This modelling approach shows great promise for tracking peripheral muscle fatigue during sustained, isometric efforts. The model has the added benefit of providing powerful insights into the fatigue time-histories of individual MUs during a range of constant effort demands. Further adaptations will also allow for the model to track individual motor unit and whole muscle recovery, so that any type of effort pattern can be evaluated.

O.6.5 ***Features for tracking spatial intra-cortical, electrophysiological changes in a rat model of ischemic stroke***

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ISEK ORAL ABSTRACT BOOKLET
This is a searchable PDF of all oral presentations in chronological order

[1]Sensory-Motor Interaction

BACKGROUND AND AIM: Ischemic stroke occurs as a cascade of events from energy depletion to cell death and involve a series of pathophysiological events that evolve over time and space. To increase the complexity several of the pathological processes are ?janus-faced? in nature with both beneficial and detrimental effects. Today MRI is used as the primary tool in the acute phase in the clinic to assess anatomical and hemodynamic changes but at a relatively low temporal and spatial resolution. Preclinical animal studies have focused on histological infarct volume and sensorimotor function tests to evaluate the effects of stroke. Microwire electrode-arrays inserted in the cortex enable direct analysis of electrophysiological properties of neural networks at high spatial and temporal resolution, however the analytic focus is often on single-channel responses. The objective of the present study was therefore to establish features to quantify the spatial progression of ischemic stroke over time in an animal model of ischemic stroke. METHODS: Eight male Sprague-Dawley rats were instrumented with a 28-channel Intracortical (IC) electrode-array and a cuff electrode around the sciatic nerve. Photothrombosis intervention was performed within the hind limb area of the left sensorimotor cortex and the pathophysiological changes were assessed by analysis of the IC responses to stimulation of the sciatic nerve. We recorded the IC responses immediately before and up to 7 hrs. after induction of the ischemic stroke. Based on peri-stimulus time histograms we identified the peak neural response (PNR) for each electrode. Based on the PNR we interpolated the signals to generate 2D neural activity maps for the entire electrode array. To assess the spatial progression of the ischemic stroke over time we calculated two features; 1) the Area, as the fraction of the cortical region that responded to the sciatic nerve stimulation, and 2) the Center of Gravity (COG) of the responding area. RESULTS: Ischemic stroke led to an expansion of the sensory cortical area that responded to sciatic nerve stimulation. The Area kept expanding until 330 min post stroke where an average of 155% increase of activity was reached in comparison to the activity level before stroke, where after it plateaued. The neural response to sciatic nerve stimulation gradually redistributed uniformly around the ischemic core following photothrombosis intervention, since the COG moved towards the ischemic core. CONCLUSIONS: Our observations are in line with the general consensus that the most dramatic phase of damage occurs within the initial hours following ischemic stroke. Our results may provide insight into optimization of new rehabilitation interventions.

S.3. *Muscle mechanics and neural control determining fine hand-motor tasks*

Mechanical factors limiting finger independence

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BACKGROUND AND AIM: During several tasks, we need precise movement and/or force control of our fingers. However, the extent in which we can independently control individual fingers is limited. Voluntary movement or force exertion by a single finger is generally accompanied by involuntary movement or force exertion by the non-target fingers. Such limited independence can be attributed to neural and mechanical factors. In this presentation, the focus will be on the latter. Muscle fiber forces can be transmitted to the tendon of non-target fingers via connections between the tendons of the extrinsic finger flexors and extensors. Force can also be transmitted between muscle-heads of adjacent fingers via the intramuscular connective tissue network. Recent studies from our lab strongly suggest that such mechanical constraints play an important role, especially for tasks in which fingers move relative to each other. METHODS: Young healthy subjects performed active single finger flexion through the full range of movement with all other fingers free to move. Kinematics of index, middle, ring and little fingers was measured to assess movement in the non-target fingers and the range of independent movement. Simultaneously, we assessed displacements of the flexor digitorum superficialis tendons using speckle tracking on B-mode ultrasound video's. During flexion of the instructed finger, all non-instructed fingers showed some movement. RESULTS: During flexion of the instructed finger, all non-instructed fingers showed some movement. Most movement was found in the fingers adjacent to the instructed finger. Each finger showed a range of independent movement (between 13% and 61% of the full movement until the tip of the finger touched the palm of the hand),

which was highest for the index finger. The start of non-target finger movement was asymmetrical for adjacent fingers. Finger interdependence was found also at the tendon level. Similar to the joint angle results, initially little or no tendon displacement was found which was followed by a steep increase in tendon displacement. CONCLUSIONS: Our results indicate that no finger can move independently through the full range of finger flexion, but some independent movement is possible for each of the fingers. The range of independent movement both at the tendon and joint level is a result that is in agreement with effects of known mechanical linkages between the muscle-tendon units corresponding to each finger. Although neural factors cannot be excluded, a range of independent movement are less likely the result of neural mechanisms. We propose that mechanical connections between the muscle heads or tendons are initially slack and need a certain relative finger displacement to be pulled taut. The asymmetry of non-instructed movements may indicate a preferential direction of such connections. Funded by EC grant MOVE-AGE.

Neuromuscular control of extrinsic flexors and extensors during single finger movements

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BACKGROUND AND AIM: The human hand is an indispensable instrument essential for performing a large variety of daily actions. When moving one finger the neighbouring fingers commonly move to some extent as well, a phenomenon called enslaving. To understand how finger movements are produced and why they cannot be moved independently, more insight into the neural control of the extrinsic finger muscles is required. The aim of the present study was to assess the activation patterns of finger specific flexor and extensor muscle regions during single finger flexion movements. METHODS: Nine right-handed subjects (22-29 years) performed single finger flexion movements with the hand held palmside up in a 45 degree supination angle. They were instructed to move each finger separately and to not actively resist potential movements of the non-instructed fingers. Muscle activation

was assessed using a grid of 90 surface electromyography electrodes (sEMG) placed over the flexor digitorum superficialis (FDS) and the extensor digitorum communis (EDC) muscles. Kinematics of four fingers, excluding the thumb, was recorded using an instrumented glove. Finger specific muscle regions were found by cross-correlation of the EMG envelopes and the angle of the instructed finger. EMG signals were normalized to the maximum EMG amplitude found for each finger throughout all tasks for the flexor and extensor muscles separately. RESULTS: During index and middle finger flexion, the EMG amplitude of the instructed finger flexor muscle region was higher than that of one or more of the neighbouring fingers ($p<0.05$). Only during little finger movements there were no significant differences found between the finger flexor muscles. For the extensor muscles, differences between muscle regions were found only during middle finger flexion, where the EMG amplitude of the middle finger was lower than that of the non-instructed fingers ($p<0.01$). For the non-instructed fingers, most movement was observed in the fingers closest to the instructed finger. This enslaving effect was highest for the ring finger and lowest for the index finger ($p<0.05$). CONCLUSIONS: During finger flexion, not only the FDS region of the instructed finger is activated but some activity is found also in the regions of the other fingers. Some of this flexor activity seems to be counteracted by activation of the specific regions of the EDC. Since our results show that in most cases the non-instructed fingers did move, this coordination pattern is at least partly ineffective. These results indicate that the movements of the neighbouring enslaved fingers cannot be fully explained by the activation patterns of the extrinsic extensor and flexor muscles. This suggests that also mechanical factors, such as tendon interconnections and myofascial force transmission, mediate limited finger independency.

The Effect of the Subsynovial Connective Tissue in the Carpal Tunnel On Finger Motion In Health And Disease

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BACKGROUND AND AIM: Carpal tunnel syndrome (CTS), a compression neuropathy affecting the median nerve at the wrist, is the most common surgically treated problem in the hand, with a prevalence of roughly 3% in the adult population. Aside from the neuropathy itself, the most common associated finding is fibrosis of the subsynovial connective tissue (SSCT) within the carpal tunnel. While most cases of CTS are considered idiopathic, one hypothesis is that the SSCT fibrosis may cause CTS, by altering the mechanics of tendon and nerve movement, thereby producing the pressure elevation which ultimately compresses the nerve. For the past decade my laboratory has studied this hypothesis, and has produced evidence that SSCT pathology may indeed be a common cause of CTS. METHODS: See citations below for methods. RESULTS: Normally, the SSCT is a filmy multilayer areolar tissue, interspersed among the 9 tendons within the carpal tunnel[1]. As the tendons move, successive SSCT layers are recruited, providing a limit to differential movement of adjacent tendons, beyond that which would be theoretically possible given normal tendon and joint excursions[2]. When the tendon moves beyond this limit the SSCT fails, in both cadavers and animal models[3]. Increasing tendon velocity increases the stiffness of the SSCT and may predispose to injury with more rapid hand movements[4]. In an animal model we have shown that this SSCT damage leads to progressive fibrosis and neuropathy[5], as is seen in human CTS. Clinically, this fibrosis restricts both tendon and nerve motion within the carpal tunnel in CTS patients[6]. Importantly, this impedes the normal ability of the median nerve to 'move aside' when the tendons are loaded, which causes the tendons to translate anteriorly and contact the carpal tunnel ligament. CONCLUSIONS:This observation may explain the pathogenesis of the nerve compression in CTS: the SSCT is damaged by differential finger motion, perhaps from a high velocity repetitive activity; this results in SSCT fibrosis with restricts nerve movement, which in turn facilitates nerve compression and thereby CTS. A finite element model has been developed[7] to help study the effect of various hand movements on SSCT stress and strain, and may help to identify potentially hazardous activities, which may then be modified to reduce the risk of developing CTS. 1. Ettema, A.M., et al., J bone joint surg. American volume, 2004. 86-A(7): p. 1458-66. 2. Vanhees, M., et al., J orth res, 2012. 30(11): p. 1732-7. 3. Yamaguchi, T., et al., J biomech, 2008. 41(16): p. 3519-22. 4. Filius, A., et al., J orth res, 2014. 32(1): p. 123-8. 5. Sun, Y.L., et al., J orth res, 2012. 30(4): p. 649-54. 6. Filius, A., et al., J orth res, 2015. 33(9): p. 1332-40. 7. Matsuura, Y., et al., J biomech, 2015.

Wrist posture and force effects on finger control

Peter Keir[1], Stephen May[1]

ISEK ORAL ABSTRACT BOOKLET
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BACKGROUND AND AIM: When asked to move or apply a force with an individual finger, movements and/or forces tend to occur in the other fingers. The anatomical structure of the extrinsic finger muscles suggests that wrist posture may play a role in the involuntary "enslaving effect" (EE) seen in the non-task or "slave" fingers. The rate of motion has been shown to affect enslaving [1], as has changing force levels in isometric contractions [2]. The purpose of this study was to determine the effect of (i) wrist posture on enslaved finger forces during ramp and isotonic exertions, and (ii) the rate of force development on enslaved forces and accuracy. METHODS: Twelve male participants performed 3 submaximal finger flexion and extension actions with the index and ring fingers at 30° wrist flexion, neutral, and 30° wrist extension. Trials consisted of a 5 second isotonic contraction at 25% of maximum, and two ramp contractions. Ramp contractions were performed at 25% MVC/s and 10% MVC/s up to 50% MVC, a 0.5 second hold, and decreased to zero at the same rate. Surface electromyography was recorded from the compartments of extensor digitorum and flexor digitorum superficialis and analyzed at 25% of maximum. Each condition was repeated 3 times for a total of 108 trials. Surface EMG was recorded from each compartment of extensor digitorum (ED 2-5) and flexor digitorum superficialis (FDS 2-5). The EE was defined as the normalized force in the non-task (slave) fingers. Enslaved forces and EMG were analyzed at 25% MVC for isotonic, ascending and descending contractions. Repeated measures ANOVAs were followed up with Tukey's HSD. RESULTS: There was a significant posture x direction x slave finger interaction as seen by greater EE of the fingers adjacent to the task finger in extension exertions with wrist extension. Thus, for extension exertions, enslaving was higher at shorter muscle lengths. There was a significant posture x compartment interaction for muscle activity for extension exertions and flexion exertions of the ring finger, where non-task fingers were significantly more active at shorter muscle lengths. Both rate and phase significantly affected EE for both index and ring finger ramp exertions (all $p < 0.001$). In adjacent fingers, EE was higher with the slower force rate in the descending phase; however, muscle activity was not significantly increased in this phase. CONCLUSIONS: Wrist posture significantly affected enslaving, particularly in fingers adjacent to the task finger in extension exertions at shorter muscle lengths. In these conditions, there was also a concurrent increase in muscle activity across all compartments. The rate of force production and type of contraction (isotonic,

increasing or decreasing force) significantly increased enslaving, without increasing muscle activity. References 1. Kim et al., 2008. Human Movement Science 27; p. 408-422 2. Sanei and Keir, 2013. Human Movement Science 32 (3); p. 457-471.

Correlated deficits in bi-lateral hand function following unilateral stroke

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The impairments in skilled movements of the contralateral hand due to stroke have previously been well characterized. Recent evidence, however, suggests that motor deficits due to stroke are not purely limited to the contralateral hand, with early deficits also being observed in the ipsilateral hand (Noskin et al., 2008). To date, it is unclear whether motor deficits in either hand follow similar time-courses or similar patterns of recovery. Here we show that following a unilateral stroke, individuals do indeed show correlated deficits in skilled finger movements of either hand. Furthermore, these deficits follow similar recovery trajectories over time. 48 first-time ischemic (unilateral) stroke patients and 14 healthy age-matched controls performed a finger individuation task while their behavioral task performance was assessed longitudinally at 5 time points (weeks 1, 4, 12, 24 and 52 immediately after stroke onset). Subjects made individuated force presses with an instructed finger (Fig 1a-b) at four different force levels (20%, 40%, 60%, 80% of MVC), and the patterns of involuntary forces produced by the passive fingers of the instructed hand (enslaving, Fig 1c), and by all fingers of the uninstructed hand (mirroring Fig 1d) were quantified. We found that both the enslaving and the mirroring patterns for either hand were highly reliable within both patients and controls (enslaving, $r = 0.871$, $SE = 0.008$, mirroring, $r = 0.790$, $SE = 0.011$). Furthermore, we found no dominant and non-dominant hand differences for the healthy controls (repeated measures MANOVA, $\chi 2 = 13.9$, $p = 0.17$). A stroke caused an increase in the magnitude of the enslaving, which was restricted to the paretic hand (Fig 2a). Although the enslaving magnitude decreased over time, patients still had higher enslaving in comparison to healthy controls after a year. Similarly, a high degree of mirrored movements on the non-

paretic hand were observed for movements of the paretic hand following stroke. Again, the magnitude of mirrored movements decreased with time but not to the level of healthy controls. Throughout recovery, the enslaving and mirroring magnitudes for movements of the paretic hand were highly correlated, r=0.79, suggestive of a single underlying cortical mechanism responsible for both phenomenon. Finally, while the overall magnitude of enslaving was not increased for both hands, we found that the patterns of enslaving were disrupted similarly across paretic and non-paretic hands. Healthy controls showed stereotypical patterns of enslaving (Fig 3a). After stroke, the enslaving patterns for both hands were similarly disrupted (Fig 3b), and recovered back towards the enslaving patterns for healthy controls. Our findings that the onset and recovery of enslaving and mirroring are tightly coupled, as well as that the enslaving patterns for both hands are similarly perturbed after stroke is highly suggestive of bi-hemispheric cortical reorganization during recovery.

Base vectors in complex finger movements

Sigrid Dupan[1], Naveed Ejaz[2], Dick Stegeman[1], Joern Diedrichsen[2]

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Fine hand motor control of the fingers is part of daily activities as grasping and writing. Most common movements involve simultaneous use of multiple fingers, and analysis shows that fingers do not move independently (1). Isolated single finger presses, commonly used to study fine hand motor control, are rare in daily life. Rather, we string together multiple single finger presses into more complex movements as sequences - for example in typewriting -, or we combine a small amount of fingers together - for example forming chords while playing a musical instrument -. How does our brain build a representation of these movements? Does it generate these complex movements as a combination of isolated single finger presses, or is it constrained by muscle synergies? Neural and mechanical constraints may simplify the control of certain movements, but also enforce limitations on single finger mobility. Involuntary force production by non-intended fingers - enslaving -, has been related to both these neural and mechanical factors. On the level of the primary motor cortex (M1), fine finger movements are controlled by the neuronal activity in the hand area. Studies based on multiple methods - microstimulation, transcranial magnetic stimulation (TMS), and functional magnetic resonance imaging (fMRI) - show a lack of isolated somatotopy for the different fingers (2-4). Moreover, it is shown that stimulation of different regions in M1 results in coordinated movements related to natural movements performed on a daily basis (2). The muscle patterns recruited in these movements might limit the possibility of performing arbitrary complex finger movements. This study combines force data of individual fingers with EMG data of both the intrinsic and extrinsic hand muscles. Data is collected during different types of movement: involuntary movement due to TMS on multiple stimulation sites of the motor cortex, and voluntary movement of single finger presses, combined finger presses, and sequences. To investigate whether muscle synergies constrain the way we perform complex movements, the EMG patterns are predicted based on the force data through linear models. The fit of different models, based on the single finger presses and involuntary TMS movement, are compared. Although muscle force and EMG amplitude approximately have a linear relationship, modelling complex movements based on single finger movements reveals non-linearities. These are included in the model through the inclusion of parameters for between-finger interaction. To summarize, our study will show the distributions of EMG activity after stimulating with TMS at different M1 sites as building blocks for the EMG distributions generated during voluntary complex movements. (1)Ingram, J.N., et al. (2008). Exp Brain Res 188(2): 223-226. (2)Overduin, S.A., et al. (2012). Neuron 76(6): 1071-1077. (3)Gentner, R. and J. Classen (2006). Neuron 52(4): 731-742. (4)Ejaz, N. et al. (2015). Nat Neurosci 18(7): 1034-1040.

S.4. *Neuromodulatory Strategies for Improving Motor Control after CNS Damage*

Novel neuromodulation strategies for Parkinson's disease

Robert Chen[1]

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Deep brain stimulation (DBS) is an accepted treatment for Parkinson's disease (PD) but its mechanisms of action are not fully understood. Many studies have examined the use of non-invasive brain stimulation such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation as treatment for Parkinson's disease. The talk will review evidence for abnormal plasticity in Parkinson's disease as revealed by non-invasive brain stimulation and how non-invasive brain stimulation can be used to study the mechanisms of action of deep brain stimulation. Studies that used paired associative stimulation have found impaired cortical plasticity in PD, particularly in patients with levodopa-induced dyskinesia. Dopaminergic medications alone did not restore cortical plasticity in PD patients with levodopa-induced dyskinesia but was restored by subthalamic nucleus DBS together with dopaminergic medications, suggesting that DBS and dopaminergic medications may have synergistic effects. Moreover, subthalamic nucleus DBS increased cortical excitability at specific intervals of about 3 ms and 23 ms after DBS pulse. Cortical plasticity could be induced by repeated pairing of subthalamic nucleus DBS and TMS at these specific intervals. These findings suggest that modulation of cortical plasticity could be a mechanism of action of DBS. Many studies have tested repetitive TMS (rTMS) as a treatment for PD but there are no large, randomized controlled trials to proof its efficacy. Meta-analysis of published studies suggested that high frequency rTMS may benefit PD motor symptoms. A recent randomized controlled trial (MASTER PD study) that involved 61 patients confirmed benefit for motor symptoms with higher frequency rTMS of the bilateral motor cortices but found no improvement in mood symptoms with stimulation of the left dorsolateral prefrontal cortex. Further studies of rTMS for treatment of Parkinson's disease are needed. Many studies aimed to improve DBS as a treatment for PD. These include novel electrode designs that can target multiple brain areas, adaptive stimulation and combination of DBS and non-invasive stimulation. Adaptive or closed-loop stimulation is also being developed. As the clinical status of PD patients fluctuates rapidly, one approach is to measure local field potentials from the target areas that reflect the clinical state of the patient, and then automatically adjust stimulation parameters to optimally treat the fluctuating symptoms to improve the efficacy of DBS. Since repeated pairing of DBS with TMS at suitable intervals can induce cortical plasticity, combined DBS and rTMS may be further explored as a novel treatment.

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Changing a reflex to improve walking: operant conditioning of the soleus h-reflex in people with chronic incomplete spinal cord injury

Aiko Thompson[1]

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BACKGROUND AND AIM: People can learn to change a spinal reflex through operant conditioning (J Neurosci 29: 5784-5792, 2009). Several months of exposure to a reflex operant conditioning protocol modifies specific spinal pathways and can thereby affect behaviors that use these pathways. Previously, we showed that down-conditioning the soleus H-reflex during standing can markedly improve walking in people with spastic hyperreflexia and impaired walking due to chronic incomplete spinal cord injury (SCI) (J Neurosci 2013;33:2365-2375). Based on this success, we are currently testing the hypothesis that H-reflex conditioning during a specific phase of walking can further improve reflex modulation and walking. Specifically, the protocol aims to shape the locomotor reflex activity toward a more normal pattern by reducing the soleus H-reflex size during the swing-phase of walking, where the H-reflex is very small or absent in normal subjects but abnormally large in people with spastic hyperreflexia due to chronic SCI. METHODS: Ambulatory individuals with spastic hyperreflexia are studied with either the conditioning or the control protocol. Conditioning protocol consists of 6 baseline and 30 down-conditioning sessions that occur over 12 weeks (i.e., 3 sessions/week). In each baseline session, the subject completes 3 blocks of 75 control H-reflex trials, in which soleus H-reflex size is measured without feedback. The H-reflex is elicited every other step by tibial nerve stimulation at just above M-wave threshold during the late swing-phase of walking. In each conditioning session, the subject completes 3 blocks of 75 conditioning trials, during which s/he is asked to reduce H-reflex size with the aid of visual feedback. Control protocol consists of 6 baseline and 30 control sessions, throughout which the subject is exposed to treadmill walking without H-reflex elicitation for the number of steps comparable to the conditioning protocol. Before and after the 30 conditioning or control sessions, 10-m walking speed and swing-phase H-reflex are assessed. RESULTS: To date, 10 (5 conditioning and 5 control) subjects with spasticity due to chronic (1-14 yrs) incomplete SCI have participated. In 4 of 5 conditioning subjects, H-reflex down-conditioning was successful; their final swing-phase H-reflex size was 48±18(SEM)% of the baseline value. Their 10-m walking speeds increased by

13±4(SEM)%, and the clonus diminished substantially. In control subjects, the final swing-phase H-reflex size was 155±58(SEM)% of the baseline and the final 10-m walking speed was 100±5(SEM)% of the baseline. CONCLUSION: These results suggest that operant conditioning of the swing-phase H-reflex is possible and can improve walking in people with incomplete SCI. Beneficial effects of swing-phase H-reflex conditioning do not appeared to be caused by just walking. Analysis of locomotor kinematics and EMG to better understand the impact of the swing-phase H-reflex conditioning is underway.

Acute Intermittent Hypoxia Enhances Neuroplasticity In Incomplete Sci

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BACKGROUND AND AIM: Restoration of function after incomplete spinal cord injury relies on three factors. The first is spontaneous recovery, which is progressive and linked to reduction of inflammation and to recovery of neural conduction in damaged spinal circuits. The second factor is the emergence of compensatory strategies in which required movements are performed in different ways from those utilized prior to injury. The third and potentially most appealing approach is the use of neural plasticity as a therapeutic tool in which appropriate neural circuits are reestablished allowing optimal restoration of function. Although neural plasticity has the greatest appeal, it is the most difficult to implement and typically requires extended task repetition, training and practice. METHODS: This presentation will describe an alternative approach, which relies on the administration of acute intermittent hypoxia to persons with incomplete SCI. In this approach, inspired air is switched intermittently to a mixture with sharply reduced levels of oxygen (9.5%). Because the hypoxia exposure is very brief, there is no risk of damage to neural or other tissues, yet the hypoxia can still trigger striking neural plasticity, sufficient to induce tangible improvements in voluntary force generation. This is manifested in performance of standard movements, of the lower extremity (in paraplegic patients) or in the upper extremity in patients with incomplete cervical spinal damage inducing quadriplegia. RESULTS: We have been able to show that brief sequences of intermittent hypoxia (9.50% for 90 seconds, repeated 15 times) for several repeated sequences can produce striking improvements in locomotor function, and in function

of the upper extremity in patients with cervical cord injury. These improvements manifest as changes in gait speed and endurance for the lower extremity, or in strength and dexterity of the upper extremity. CONCLUSIONS: The beneficial effect of hypoxia after spinal cord injury appears to depend upon the existence of hierarchical rescue mechanisms that have emerged through evolution to protect the life of an animal when breathing apparatus or the controlling innervation is damaged. While these mechanisms were historically most visible in the neural control of breathing, they are also applicable in the neural control of limb musculature, and can potentially be harnessed to provide useful therapy in persons with incomplete SCI.

Stimulation-induced plasticity in corticospinal transmission to motoneurones

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BACKGROUND: In humans, the corticospinal pathway provides important input to the motoneurones for the control of timing and strength of voluntary contractions. With stroke or spinal cord injury, corticospinal input can become inadequate to recruit sufficient motoneurones to produce forceful contractions. One way to counteract this impairment in voluntary drive to the motoneurones would be to increase the strength of synapses or number of synapses between the remaining corticospinal axons and their spinal targets. Such changes at a spinal level would mean that the same cortical output would provide more effective input to the motoneurones. Stimulation protocols offer possible ways to influence spinal transmission of corticospinal signals. METHODS AND RESULTS: In the elbow flexor muscles of able-bodied participants, we have shown that paired corticospinal motoneuronal stimulation (PCMS), in which transcranial magnetic stimuli (TMS) are repeatedly paired with maximal motor nerve stimuli at specific interstimulus intervals, can increase muscle responses evoked through stimulation of the corticospinal axons and can also increase the muscle force produced for a given level of descending drive (Taylor & Martin 2009). Increases in responses last for at least 1 hour after 100 pairs of stimuli (Fitzpatrick et al 2016). We postulate that these changes reflect plasticity at the corticospinal-motoneuronal synapses. For the hand muscle, adductor pollicis, 100 pairs of stimuli (TMS paired with ulnar nerve stimuli) resulted in small

increases in voluntary activation (4±5%; mean±SD; n=14), measured with twitch interpolation during isometric maximal voluntary contractions. That is, there was a small improvement in the ability of these able-bodied participants to drive the muscle maximally after PCMS compared to after TMS alone. This suggests that changes in the transmission of corticospinal input are effective for high threshold motoneurones as well as those recruited in weak contractions. CONCLUSION: Although PCMS produces reproducible effects in individuals (Fitzpatrick et al 2016) and has shown potential to enhance motor output in people with incomplete spinal cord injury (Bunday & Perez 2012), its effect is not reliable across the population. Therefore, the clinical utility of the technique depends on identification and control of factors that underlie these inter-individual differences. REFERENCES: Bunday KL, Perez MA (2012) Motor recovery after spinal cord injury enhanced by strengthening corticospinal synaptic transmission. Curr Biol 22: 2355-2361. Fitzpatrick SC, Luu BL, Butler JE, Taylor JL. (2016) More conditioning stimuli enhance synaptic plasticity in the human spinal cord. Clin Neurophysiol. 127: 724-731. Taylor JL, Martin PG (2009). Voluntary motor output is altered by spike-timing-dependent changes in the human corticospinal pathway. J Neurosci. 29: 11708-11716.

Using targeted neuroplasticity for rehabilitation

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An operant-conditioning protocol that bases reward on the amplitude of the electromyographic (EMG) response produced by a specific central nervous system (CNS) pathway can target activity-dependent plasticity to that pathway. For example, in monkeys, rodents, and people, an operant-conditioning protocol can increase or decrease the spinal stretch reflex or its electrical analog, the H-reflex. Reflex change begins quickly and then continues at a slow rate over days and weeks. It is associated with neuronal and synaptic plasticity in the pathway of the reflex itself as well as with plasticity elsewhere in the spinal cord and brain. This multi-site plasticity appears to function as a hierarchy, in which the plasticity in the brain guides and maintains the plasticity in the spinal cord that is directly responsible for the reflex change. Because the modified spinal neurons and synapses serve many behaviors, the plasticity produced by reflex conditioning can change other behaviors. In the normal CNS, additional compensatory plasticity prevents the plasticity underlying reflex change from disrupting important behaviors, such as locomotion. In contrast, when CNS trauma or disease (e.g., partial spinal cord injury) has impaired an important behavior such as locomotion, the spinal cord plasticity produced by appropriate reflex conditioning can improve the behavior. Furthermore, in this situation, appropriate reflex conditioning can trigger widespread beneficial plasticity that further improves the behavior. This wider plasticity is hypothesized to reflect a process in which each of the multiple behaviors in an individual's repertoire repeatedly induces plasticity that improves its key features. The aggregate process is a negotiation among the behaviors; they negotiate the properties of the spinal neurons and synapses that they all use. This process maintains spinal cord properties in a "negotiated equilibrium" that serves all the behaviors in the repertoire. The operant conditioning protocol adds a new behavior to the negotiation; the targeted plasticity it produces moves the state of the spinal cord away from its previous location in the multidimensional space composed of the values of all spinal neuronal and synaptic properties. Thus, the new behavior (e.g., a modified H-reflex) can enable the old behavior (e.g., locomotion) to escape an inferior solution (i.e., a local minimum) reached prior to the operant conditioning, and can thereby more nearly restore the key features of the old behavior. Operant-conditioning protocols constitute a promising new therapeutic method that could complement other rehabilitation methods and enhance functional recovery.

Plasticity in the Corticospinal Pathway after Human Spinal Cord Injury

Monica Perez[1]

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The corticospinal tract is an important target for motor recovery in humans with spinal cord injury (SCI). Here, I will discuss a novel paired stimulation protocol aiming at enhancing corticospinal transmission and residual voluntary motor output in humans with partial paralysis due to cervical incomplete chronic SCI. Paired-pulse transcranial magnetic stimulation (TMS) of the human primary motor cortex results in consecutive facilitatory motor evoked potential (MEP) peaks in surface electromyography (EMG) in intact humans. These peaks can be used to make inferences about the physiology of indirect (I) waves from surface EMG recordings.

We recently showed that early and late TMS-induced MEP peaks undergo distinct modulation in humans with incomplete SCI, with late MEP peaks likely reflecting a decreased ability to summate descending volleys at the spinal level. Our results suggested that late corticospinal inputs on the spinal cord might be crucial for recruitment of motoneurons after human SCI. In subsequent experiments, we used repeated paired-TMS pulses at interstimulus intervals compatible with a late MEP peak (I3 interval). This protocol resulted in distinct improvements in aspects of corticospinal transmission and voluntary hand motor output in humans with SCI. Thus, specific tailored stimulation of the corticospinal pathway may present a novel therapeutic tool for enhancing voluntary motor output in motor disorders affecting the corticospinal tract.

S.5. ***Joint ISEK-ISB symposium***

Surface Electromyography Meets Biomechanics or Bringing sEMG to Daily Life

Catherine Disselhorst-Klug

Background: Muscles move you! Their coordinated activation is the basis for human movement and locomotion. Impaired muscular activation is not only related to poor movement performance, it causes pain, disability and loss of quality of life. To prevent and to restore movement performance the information about the subject's individual muscular activation is of high relevance. Because of their non-invasive character, the only way to get deeper insight into muscular activation during freely performed movements is related to surface-electromyographic (sEMG) methods. Technological advances have made possible the development of a variety of equipment to monitor muscular activation. Ready-to-use technologies are increasing rapidly driven by technological innovation. They enable sEMG measurements in several new applications such as a part of regular sports training, monitoring, biofeedback in rehabilitation, control of prostheses, etc.. However, the correct interpretation of sEMG signals remains debated even amongst scientists and potential sEMG users are getting lost when applying sEMG technologies especially in new areas of application. No guidance is given for correct application or data processing and interpretation of the results remains questionable. sEMG meets Biomechanics: One aspect complicating the interpretation of sEMG is related to the fact that in most innovative applications dynamic contractions are analyzed. From biomechanics it is well known that the contraction force of the muscle fiber depends on the fiber length as well as on the contraction velocity. Additionally, recent investigations support hypothesis that due to titin the resulting muscle fiber force is higher during eccentric contractions compared to concentric ones. On a more macroscopic level, the torque generated by a muscle depends on its biomechanical moment and with that on the joint position. Since sEMG reflects the number of motor units activated by the central nervous system to reach a certain force level, it is obvious that in dynamic contractions sEMG amplitude as well as its frequency content is affected by the biomechanical parameters mentioned above. Additionally, due to the redundancy of the musculoskeletal system, central nervous activation strategies have to be taken into consideration, which are rarely known in physiological movement control and are hard to manage in pathology. Bringing sEMG Technologies to Daily Live: To take sEMG out from the research laboratory into everyday life and to implement the knowledge about the subject's individual muscular activation into training, treatment and prevention biomechanical as well as neuromechanical aspects have to be integrated in the interpretation of sEMG signal recorded during dynamic contractions. New and innovative sEMG processing, information extraction strategies are needed to bridge the gap between bench and application for sEMG.

Forearm muscle activity differs during gripping in people with tennis elbow compared to healthy individuals.

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Background and aim: Lateral epicondylalgia (LE), commonly referred to as tennis elbow, is a chronic musculoskeletal injury that presents with pain over the lateral elbow that is associated with altered wrist posture during gripping. Although the underlying pathophysiology involves degenerative changes of the common extensor tendon, from which the extensor carpi radialis brevis (ECRB), extensor digitorum communis (EDC) and extensor carpi ulnaris (ECU) muscles originate, their contribution to altered wrist posture and gripping is unknown. Therefore, the aim of this study was to examine the effect of wrist posture on forearm muscle activation patterns during an isometric grip task in people with LE. Methods: Eleven individuals with LE (age range 32 to 65 years, 8 males, 10 right hand dominant) and eleven age- and sex-matched controls were recruited from the community. Surface EMG was collected from ECRB, EDC, ECU, flexor carpi radialis (FCR), flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU) and anconeus muscles. The tasks in the study were 6 s steady isometric hand grips at 15% of maximal voluntary contraction (MVC) with a neutral wrist posture, 20 degree wrist extension, and 20 degree of wrist flexion. Each muscle EMG amplitude was normalized to the same muscle's peak amplitude during MVC, at each respective wrist posture. Muscle activation was computed as the EMG root mean square in a 25 ms non-overlapping window and averaged from five grip trials at 15% MVC target grip in each wrist posture. Muscle coactivation was calculated as the proportion of each muscle's activity to the net activity of all muscles at each wrist posture. Results: Muscle activation. A main effect of group was detected for overall ECRB activation ($F(1, 20) = 6.22$, $p = 0.021$), where the LE group had significantly decreased activation compared to controls during the 15% MVC target grip force. Pairwise comparisons revealed that LE ECRB activation was decreased in wrist extension ($p = 0.044$) and neutral wrist ($p = 0.043$) posture compared to the controls. Muscle coactivation. A significant main effect of wrist posture was detected for ECRB ($p = 0.048$) and ECU ($p = 0.019$) coactivation, when both groups are combined. However, the post-hoc analyses of wrist posture revealed that ECRB, EDC and ECU coactivation differences ($p < 0.05$) were only present in the healthy controls, with coactivation of forearm extensors unaffected by wrist posture in LE. Conclusion: The results indicate that the forearm muscle activation is altered in LE, most notably in the ECRB which is frequently implicated in this disorder. Absence of significant differences in wrist extensors muscle coactivation between the wrist postures in LE compared to the matched healthy controls indicates the possibility of reduced motor variability due to pain related manifestations of LE. This feature is often seen in other chronic musculoskeletal conditions such as neck-shoulder pain and low back pain.

An electromyographic evaluation of elastic band exercises targeting neck and shoulder pain

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BACKGROUND AND AIM: Specific (Intensive) exercises for the neck and shoulder muscles have been shown to relieve work related pain. To minimize resources for supervision there is a need for simple exercises that are effective and can easily be performed at the workplace during the workday. The aim of this study was to quantify the activity of the neck and shoulder muscles during 6 selected elastic band exercises performed at intensities of 20RM and 12RM. The main hypothesis of this study is that high intensive activation of the neck and shoulder muscles requires specific exercises: Shrugs (SHR) and Reverse flyers (RF) for upper trapezius (UT) activation, Cervical extension (CE) and Lateral flexion (LF) for upper neck extensors (UNE) and Cervical flexion (CF) and Cervical rotation (CR) for sternocleidomastoideus (SCM). METHODS: A group of 11 healthy males (25.9±1.4 years, height 183.6±5.0 cm, body mass 82.1±6.0 kg, BMI 24.3±1.4) with no pain in neck or shoulders (VAS=0) were included. Electromyographic activity was bilaterally recorded from UT, SCM and UNE during the 6 exercises at 12 and 20 RM in randomized order. Electromyographic amplitude was normalized to maximum amplitude obtained during muscle specific maximal voluntary isometric contraction (% MVE). RESULTS: For UT the activity during SHR (100.3±29.8%MVE) and RF (91.6±32.8%MVE) was significantly higher than in the remaining exercises (<20%MVE). For UNE activity during CE (67.6±29.8%MVE), SHR (61.9±16.8%MVE) RF (55.4±16.3%MVE) and LF (45.5±14.6%MVE) was higher than for CR and CF (<20%MVE). For SCM activity was higher during CF (51.7±16.4%MVE), CR (42.5±11.6%MVE), and LF (41.5±14.6%MVE) than during the remaining exercises (<30%MVE). Both SHR and CE produced an activity >60% MVE during 12RM in UNE. Both 20RM and 12RM SHR and RF induced >60% MVE in UT. No exercises induced an activity >60%MVE in SCM. Overall %MVE was during 12 RM about 8-10% larger than for 20 RM. A detailed analysis comparing activity in the concentric and eccentric phases showed higher activity in the concentric than in the eccentric phase, most pronounced for UT. CONCLUSIONS: SHR and FR were highly effective exercises as they induced high muscle activity of both shoulder and neck muscles. These findings have practical implications for the choice

of exercises for workplace suited training programs targeting muscle specific pain and disorders.

Factors affecting smoothness of head movements

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Background: Human head and neck movement is a complex action based on a fine interaction between the musculoskeletal, visual, auditive and vestibular system. An effective movement is typically smooth with one acceleration phase and one deceleration phase. In the presence of pain, the movement may become irregular, with several acceleration and deceleration phases. For persons with neck pain with a traumatic cause, flexion and extension movements are shown to be less smooth compared to controls. The movements were also slower. Are these differences also present in persons with persistent neck pain without a traumatic cause and in other directions? We also examined movement qualities in head rotation to explore if irregularity and slower movements constitute a generalised movement property among these persons. Methods: 14 persons with persistent neck pain and 14 age and gender matched neck pain free controls were included (13 females and one male). All persons trained on the entire test protocol to familiarize with the test laboratory and technical equipment 7-14 days prior to testing. ROM, speed and smoothness were measured during rotations and flexions/extensions based on position data from six motion sensors attached to the head and trunc (Liberty, Polhemus Inc). The persons were instructed to first use their preferred pace, therafter a slow and maximum pace. A generalized mixed-effects model was used for analysis. Results: Persons with neck pain moved their head with a slower self selected pace than pain free controls in both rotation and flexion/extension. They had significantly lower ROM in 5 of 8 movement directions. Using the mixed-effects model, pain status had no impact on smoothness but speed and ROM had (â -0.64 and 0.59 respectively). Trunc movement and tilting of the head out of the main direction during movements, do not affect irregularity (table 1). Rotations were faster than the flexions and extentsions; overall approximately 25% difference (data not given). Increased movement speed and ROM gave more smooth movements (table 1). Conclusions: These preliminary results suggest that smoothness depend on movement speed and the distance of movement/displacement. All group differences disappeared when controlling for these factors. Therefore, neck pain does not seem to have a principle influence on smoothness. The more jerky movements are due to differences in speed and ROM.

The additional value of electromyography in system identification and parameter estimation to assess the contribution of underlying systems in standing balance

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BACKGROUND AND AIM: Impaired balance is a common complaint reported by elderly due to the degeneration of underlying systems involved in standing balance (i.e. motor system, sensory systems and nervous system) with chronological age, specific diseases and medication use. The involvement of several underlying systems in controlling standing balance and strategies to compensate for each other's deterioration makes it difficult to diagnose the underlying cause of impaired balance. System identification and parameter estimation (SIPE) is an upcoming method to disentangle the contribution of underlying systems in standing balance, which enables early detection of impaired standing balance. In this study, we investigated the additional value of including electromyography (EMG) data of the lower leg muscles in SIPE to reliably estimate the contribution of the underlying systems in standing balance. METHODS: Both simulated data obtained with a comprehensive balance control model and experimental data of healthy young participants were used. A sensory perturbation of the proprioceptive information was applied by rotation of the support surfaces (SS) with a pseudorandom ternary signal with a maximum peak-to-peak amplitude of 1 degree. The dynamic behavior of both the simulation model and healthy young participants were estimated by Frequency Response Functions using system identification representing the sensitivity functions of the ankle torques, body sway and EMG of the lower legs to the SS rotation. A simplified balance control model was fitted on the sensitivity functions to estimate parameters describing the underlying systems with several combinations of the 3

sensitivity functions. For model fits on each combination of sensitivity functions the reliability was described by the mean absolute difference between the estimated values and the values used in the simulation in percentage, by the mean goodness of fit (mGOF) and by the mean relative standard errors of the mean (mSEM) of the estimated parameters. RESULTS: In the model simulations, the results show that including the sensitivity function of the EMG reduced the mean differences between the parameter values used in the simulation and the estimated parameters from 42.65-46.48 % to 7.94-9.33%. Furthermore, the mSEM reduced from 6.924-10.224 to 0.265-0.281. No differences in mGOF were found. Similarly, the results of the fitting procedure on the experimental data show a decrease in mSEM when EMG was included. No differences in mGOF were found between the combinations of sensitivity functions. CONCLUSIONS: Including EMG data of the lower leg muscles in SIPE improves the reliability of the estimated parameters both in simulated and experimental data. Therefore, it is recommended to include EMG in the assessment of the underlying systems involved in standing balance using SIPE to estimate reliable parameters, which gives the opportunity to improve the diagnosis of impaired balance.

Intrinsic foot muscle activity in response to different loading conditions

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[1]The University of Queensland

BACKGROUND AND AIM: The human foot is an adaptive structure that can conform to the conditions and ground we stand, walk and run on. The foot's complex architecture consists of 26 bones, 33 joints, 107 ligaments and 19 muscles. It is characterised by a prominent longitudinal arch (LA) that compresses and recoils under load, absorbing and returning elastic strain energy [1] through the cycle. Our aims, over a series of experiments, were to characterise how the three largest intrinsic foot muscles, abductor hallucis, flexor digitorum and quadratus plantae are activated in response to different loads and forms of loading, as well as how their activation influences LA compression. METHODS: Vertical loads up to 150% of body weight were incrementally applied to the foot, through the tibia, while recording LA motion and intramuscular electromyographic activity from the foot intrinsic muscles, named above. These muscles were also-involuntarily and independently activated via

indwelling electrical stimulation electrodes while loaded at 50% and 100% of body weight. The spring-like function of the foot and electromyographic activity of the same foot muscles was also assessed while running on a force-instrumented treadmill during shod and barefoot conditions. The latter experiment was performed in response to recent suggestions that running shoes may actually impede LA function, possibly reducing the effectiveness of intrinsic foot muscle function [2]. RESULTS: A decrease in LA height and an increase in foot intrinsic electromyographic activity was observed as the foot was incrementally loaded to 150% body weight. Involuntary electrical activation of the intrinsic foot muscles resulted in a significant decrease in LA compression (increase in arch height) when loaded at either 50% or 100% body weight. All intrinsic foot muscles, as well as muscles of the triceps surae (medial gastrocnemius and soleus), increased their activation when running with shoes as compared to barefoot. The increased muscle activity was accompanied by a reduction in LA compression during the period of maximum loading. CONCLUSIONS: These findings verified our hypothesis that abductor hallucis, flexor digitorum and quadratus plantae have the potential to control foot posture and LA stiffness, particularly during the type of loading that is associated with standing and locomotion. The ability for the foot intrinsic muscles to actively stiffen the arch is likely to have important implications for how forces are transmitted during these types of activities. This is particularly important when running at different speeds, over different terrains and perhaps whether shod or barefoot. For the latter point, our results confirm that running shoes do indeed influence the mechanical function of the foot. Overall our findings support the notion that LA stiffening, through passive and active mechanisms, is important for how forces are transmitted between the foot and ground during locomotion. [1] Ker RF at al (1987) The spring in the arch of the human foot. Nature 325, 147-149 [2] Lieberman DE et al (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 463, 531-535

S.6. *Stepping out of the lab: EMG in daily life*

Fully-Integrated Stretchable Epidermal Electronics and Biosensors

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Background Existing classes of electromyography and motion tracking systems have many important capabilities, they lack the mechanical properties necessary for achieving intimate contact, robust signal quality, and maximum comfort for patients. These limitations are due in large part to the bulky and packaged components with terminal connections to wires and rigid circuit boards, which typically do not bend, stretch or adjust with the dynamic curvilinear motions of the human body. Aim A different approach relies on electronics and biosensors configured in ultrathin formats that achieve intimate coupling in ways that are mechanically invisible to the subject [1, 2]. Here we describe new mechanical and electrical design strategies for achieving these medical systems with physical properties that approach that of a soft bandage worn on the epidermis. Methods These 'epidermal electronics' (Fig. 1) are fabricated using flexible electronics and roll-to-roll manufacturing processes using packaged and unpackaged chipsets. The integrated biosensors measure linear motion, angular motion, temperature and electrophysiological activity. Results The sensors and associated circuitry (i.e. microcontroller, memory, voltage regulators, rechargeable battery, wireless communication modules) are all embedded within an ultrathin, highly stretchable elastomeric substrate. Quantitative analyses of system mechanics during cyclical exposure to tensile and bend stresses illustrate the ability of the epidermal electronics to mechanically couple with soft tissues, in a way that is mechanically invisible to the user. These results highlight the soft and stretchable form factor achieved and multimodal sensing, which is ideally suited for monitoring physiological signals from different regions of the body in patients. Conclusions Epidermal electronics provide quantitative biometric information to physicians in a continuous manner over a broad range of clinical applications, with implications for clinical trials and home monitoring. This platform has been validated in the clinical setting and thus serves as a powerful alternative to self-reporting and other conventional clinical screenings.

A Wireless Surface EMG System for Daily Activity Measurement

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BACKGROUND AND AIM: The surface Electromyography (sEMG) is a technique used for recording and extracting neuromuscular information produced by skeletal muscles. During voluntary muscle contractions a number of motor units trigger signal activations which can be detected using sensors placed on the surface of the skin. sEMG is intuitive and convenient in revealing not only single muscle activity, but also the coordination of different muscles during a movement. While sEMG applications in the past mostly focused on clinical studies and rehabilitation, in recent years commercial products that focus on human computer interaction have been emerged. However, most commercially available sEMG systems are limited due to large size, power consumption, and device placement factors. This study presents a portable wireless sEMG system that addresses these limitations and can be used for daily activity measurements. METHODS: The 35mm diameter wireless sensor module presented in this study offers 8 differential sEMG channels and 9-axis motion information. Enclosed in a plastic case (Figure 1), the integrated system is composed of four units: sEMG electrodes, sense electronics, and motion processor and communication unit. Muscle activity acquired by electrodes are amplified and digitized by the sense electronics on the integrated sensor board. sEMG data can be pre-processed on board for noise reduction and transmitted to a processing host using Bluetooth Low Energy (BLE) protocol or a proprietary in house protocol. A host application is developed to configure the wireless sensor and display the data collected by the sensors. The system is powered by a rechargeable coin size battery with a lifetime depending on the sensor configurations. RESULTS: The system was tested by attaching electrodes on a subject's forearm Brachioradialis muscle as differential channels and the subject was asked to perform the hold-fist movements. The electrodes used in this experiment were disposable passive Ag/AgCl solid gel electrodes that carefully skin preparation was required. The raw sEMG data was filtered by a bandpass filter with cutoff frequency 10Hz to 250Hz and a notch filter to eliminate power noise (Figure2 (a)). As a comparison, the same experiment was conducted using a commercial wireless system from Delsys (Figure 2 (b)). The signal-to-noise ratio (SNR) of the signal recorded using the Delsys system and the wireless sEMG system presented in this study are 35.4dB and 37.9dB respectively. CONCLUSIONS: A portable wireless sEMG system for daily activity measurement is developed. The system offers 8 differential channels of sEMG recording and 9-axis motion information. The size of the system provides comfort and mobility. The low power consumption enables long-term recordings without recharging the battery. The quality of the sEMG recorded from the proposed system is comparable to commercially available sEMG systems.

Tattoo-like, long-term electromyography sensors for quantifying muscle fatigue and recovery

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When muscle performance degrades, we need a reliable method to tell whether it is because the subject is not trying hard enough or it is actually due to muscle fatigue. When muscle fatigues, we hope to study its recovery over a time scale of days instead of hours. We therefore manufactured tattoo-like, long-term electromyography (EMG) sensors based on stretchable gold nanoribbons via our newly invented "cut-and-paste" method. The EMG measured by our stretchable electrodes are comparable to the gold standard Ag/AgCl gel electrodes. EMG was gathered by both types of electrodes simultaneously, and the signal-to-noise ratios (SNRs) of the two were found to be within 28.5% of one another. Our ESS electrodes are so thin and soft that they are imperceptible and can be worn for a week. We performed synchronous measurements of EMG from the forearm muscles and hand grip force (HGF) using a NeuLog hand dynamometer once a day over the course of a week without changing the stretchable electrode. Each subject was instructed to grip with maximum voluntary contraction (MVC) for two minutes. For the purposes of our experimental results, fatigue was defined as the degradation of the model with respect to the initial model state. Vectorial autoregressive moving average (VARMA) systems are built to model the relationship between EMG and HGF, and Kullbeck-Leibler criterion is used to track degradation of the model as applied to the Forearm-Hand system with time. The stretchable electrodes combined with the VARMA model clearly shows both a departure from the original model up to a Kullbeck-Leibler of 3, and a return to within 5% of the original model after sufficient resting period. These model changes correspond to changes in forearm-hand dynamics as a result of fatigue.

EMG-based Online Intent Recognition for a Powered Lower Limb Prosthesis

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BACKGROUND AND AIM: Pattern recognition has been used to transition powered leg prostheses between locomotion modes seamlessly. Adding EMG signals to mechanical sensor information improves performance, but is not clinically implemented because signal quality degrades over time. We developed a method for detecting detrimental changes in EMG signal quality by comparing new patterns to a model of previous training data. The aim of this study was to evaluate this technique with amputees using an online pattern recognition system to control a powered knee-ankle prosthesis. We investigated whether our method can prevent errors by reverting to using only mechanical sensors to make predictions when EMG changes are detected. METHODS: Two transfemoral amputees were fitted with a powered knee-ankle prosthesis and completed a protocol that included walking on level ground, ramps, and stairs on two different days. On the first day, an experimenter triggered mode transitions at four gait events (heel contact, mid-stance, toe off, mid-swing). Embedded mechanical sensor and EMG information from four residual leg muscles were recorded during ambulation. Signal features were used to train eight classifiers acting within different modes and at different gait events to predict the transitions between standing, level walking, ramp ascent/descent, stair ascent/descent. Gaussian models of EMG features were developed to inform classifiers when to incorporate EMG into mode predictions. In the second session, an online classifier transitioned the prosthesis between modes. Only mechanical sensors were used if new EMG patterns were significantly different (>3σ) from the model of EMG features. The percentage of steps where EMG was used is reported for each classifier. Steady-state and transitional classification error rates for each classifier were calculated. The average classifier error for heel contact and toe-off is also reported. RESULTS: EMG signals from the second day were frequently excluded by most classifiers, and none used EMG signals in 100% of its classifications (Table 1). Classifiers operating in standing mode (ST_HC, ST_TO) and the toe-off classifier (TO) incorporated EMG in most classifications. Subjects could successfully transition between modes with low classification error rates (Table 1). The average error rate for all heel contact classifiers was 1.9% [0.9%], (mean [standard deviation]), for steady-

state steps and 5.4% [2.1%] for transition steps. The average error rates for all toe off classifiers was 1.8% [1.0%] for steady-state steps and 0% [0%] for transition steps. CONCLUSIONS: We determined that most EMG signals from the second day contained changes in signal quality. Changes were likely caused by donning/doffing the prosthesis. These variations would normally cause classification errors, but using only mechanical sensors likely kept error rates low. Future work includes creating an adaptive system that can learn to reincorporate EMG.

NeuroGame Therapy for the Improvement of Ankle Control in Children with Cerebral Palsy

Torey Gilbertson[1], Sarah McCoy[1], Kristie Bjornson[2], Robert Price[1], Chet Moritz[1]

[1]University of Washington, [2]Seattle Children's Research Institute, University of Washington

Background: Neural plasticity and motor-learning research suggest that task-specific practice should control intensity, repetition, timing, difficulty, and salience to have the largest effect (Kleim & Jones, 2008). Based on these principles, 'NeuroGame' Therapy (NGT) was designed and has shown promise in upper extremity rehabilitation in children with cerebral palsy (CP)(Rios et al, 2013). We explored the effects of task-specific practice using NGT for improving activation of ankle dorsiflexion muscles in children with CP. Our portable system provided biofeedback from ankle dorsiflexion (ADF) surface electromyography (sEMG). Successful ADF sEMG activation allowed children to control computer games. Study Design: Our repeated measures case series design utilized 5 assessments, each occurring 3 weeks apart. Intervention occurred between the second to the fourth assessment as a home exercise program. Study Participants and Setting: Nine children (3 male) with bilateral lower extremity involvement and spasticity, Gross Motor Function Classification System level I-III, mean 12.15 yrs (SD 3.36 yrs) completed the study. Materials/Methods: Assessments spanned the ICF dimensions including: sEMG co-contraction, standing balance, muscle contraction force (MCF), spatiotemporal and kinematic motion analysis during gait, ADF range of motion (ROM), Selective Control Assessment of the Lower Extremities (SCALE), falls, and the 6-minute walk test (6MWT). Intervention consisted of using NGT 3-5 times per week followed by a 5-minute walking session to practice ADF during gait. Walking adherence was

documented via a FitBit activity monitor. Results were analyzed descriptively case by case. Results: All children used NGT multiple times per week and reported enjoyment of the game. Results were varied based on child, level of involvement, and amount of game play but all children showed improvement in at least two measures. Children who played the game the most showed the most change in sEMG co-contraction during AROM and walking. Positive changes were also seen in balance (6/9 participants) and MCF (4/9 participants). Two children showed improvements with gait (1 dorsiflexion at initial contact, 1 in stride length). Two children had slight increase with walking velocity. Only one child had increased passive ROM. There were changes with the total SCALE scores in 6 of 9 children, and also changes seen with movement quality. Three children improved with their 6MWT. One child had fewer falls. Conclusions/Significance: NeuroGame therapy was feasible and enjoyable for these children with CP, and facilitated repetition and intensity of intervention. Results of NGT use seem to be highly correlated to the amount of time using this device. Participants improved their ADF muscle activity, which lead to some changes in ankle function. NGT, which leverages neuroplasticity and motor learning principles, appeared to increase participants' motivation to perform therapy at home.

Backyard Brains: Using EMGs as an entry into neuroscience education

Gregory Gage[1]

[1]Backyard Brains

Electrophysiology is an exciting and compelling way to engage the public and generate interest in neuroscience research. For the past 5 years my organization, Backyard Brains, has been developing entry-level electrophysiology kits to explore invertebrate nervous systems. Our open source bioamplifiers (SpikerBox) can record and analyze action potentials from the neurons of cockroaches, worms, grasshoppers, and other insects. In this talk, I will discuss our transition to human electrophysiology and it's impact on neuroscience K12 education. Our goal is to create educationally affordable technologies for teaching neuroscience, a subject that has traditionally been ignored in secondary education. By creating exciting and accessible experiments and demonstrations, we aim not only teach neuroscience, but also spark the public's interest in participating in and contributing to neuroscience research.

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DAY 2, THURSDAY JULY 7

S.7. *Synchrony and frequency in neuromuscular control*

Synchrony and frequency in neuromuscular control

Christopher Laine[1]

[1]Univ of Southern California

Significance: In the nervous system, synchrony implies communication or shared input. As such, quantification of synchrony (e.g. among EMG or EEG signals) is an incredibly powerful tool for understanding neural control of muscles. The origin and functional relevance of different types of synchrony have generated continued interest for many years. It is clear that investigating the strength and frequency content of neural drive holds great potential for probing neuromuscular circuitry and control strategies, guiding rehabilitation, and characterizing disease progression. However, we lack a clear conceptual roadmap for the use of these techniques in targeting specific neural mechanisms, and maximizing their utility for scientific and clinical pursuits. Focus: Defining what novel information can be gained about neuromuscular control through measures of synchrony (e.g. correlation, coherence, phase-locking) between signals recorded from humans (e.g. between motor units, EMG, EEG, and kinematic/kinetic measures). Suggested topics for presentation include, but are not limited to: 1) Insights into neural mechanisms of sensorimotor integration, tremor, fatigue, or motor learning. 2) Potential utility of synchrony/coherence measures as biomarkers of motor dysfunction or as relevant measures within the context of rehabilitation technologies. 3) Coordination between muscles and analysis of muscle synergies 4) Relevant statistical/signal processing methods

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Motor control of upper airway dilator muscles

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BACKGROUND AND AIMS: In order to explore the motor control of upper airway dilator muscles, common oscillatory inputs to the motoneurons of genioglossus (GG), tensor palatini (TP) and palatoglossus (PG), were assessed during wakefulness in human participants using coherence analysis conducted on simultaneously recorded pairs of motor units. METHODS: Results are reported for the frequency ranges 0-5 Hz (common drive) and 10-30 Hz (short term synchrony). Electromyograms were recorded via intramuscular fine wire electrodes. In the first study 201 pairs of single motor units were obtained from GG and TP muscles in 24 male participants. In the second study 148 pairs of motor units were obtained from GG and PG muscles in 17 female and male participants. Finally in study three, 77 pairs of GG motor units were simultaneously recorded before, during and after inspiratory loading in 12 male participants. RESULTS: Consistent with an earlier report (Laine & Bailey, J Neurophysiol, 2011, 105, 380-387), study one demonstrated that GG motor units have moderate common drive (coherence in the 0-5 Hz range) and an absence of short term synchrony (coherence in the 10-30 Hz range). But critically, it was shown that the level of common drive was dependent on the discharge pattern of the pairs of motor units; motor units with a respiratory phasic pattern had very high common drive, while motor units that were without respiratory phasic activity (tonic units) had only moderate common drive. Further, respiratory phasic and tonic units did not share common drive (low coherence of respiratory - tonic motor unit pairs). This pattern was replicated in TP motor units and in study 2 in PG units. Of interest was the observation that GG and TP respiratory modulated motor units shared common drive (GG-TP pairs) with the same strength as both GG pairs and TP pairs, while this was not the case for tonic GG-TP pairs. However, unlike GG and TP respiratory phasic motor units, GG and PG respiratory phasic motor units did not share common drive. Finally, in study three we demonstrated that common drive to respiratory modulated GG motor units increased in response to an increase in respiratory drive. CONCLUSIONS: The results suggest that pre-motor inputs differ between respiratory modulated and tonic motoneurons for each of the muscles studied, with respiratory phasic motoneurons showing stronger common drive; this possibly indicates

different functional significance of motoneurons with different discharge patterns. Further, tonic motor units from different muscles did not appear to share pre-motor inputs, while GG and TP respiratory phasic motor units, but not PG units, were strongly influenced by the same pre-motor input. This pattern of activity raises the possibility that respiratory phasic and tonic motoneurons represent different muscle systems with different functional roles.

Investigating neural strategies for muscle coordination

Christopher Laine[1], Francisco Valero-Cuevas[1]

[1]University of Southern California

BACKGROUND AND AIM: Correlated patterns of muscle activity observed during certain actions have often been interpreted as evidence that the nervous system simplifies the task of muscle coordination by controlling them together as a group, rather than independently. It is not always clear if coordination among muscles implies a simplified neural control strategy, an obligatory co-activation, or simply reflects mechanical requirements of a task. Although co-activated muscles often receive some degree of common neural input, it is not clear if/how the strength and frequency content of such input relates to functional control. This talk will briefly cover two lines of investigation in which intermuscular neural drive is characterized under a variety of conditions. In the first (Laine et al., J Neurosci, 2015), we tested the basic assumption that mechanically synergistic muscles are controlled together through shared neural drive, rather than independently. In a second, recent line of investigation, we studied the flexibility of intermuscular neural drive to muscles whose functional coordination depends on task. METHODS: To investigate neural drive to synergist muscles, motor unit activity was recorded from the vastus lateralis and vastus medialis muscles during isometric knee extension. Partial coherence analysis was used to disambiguate the contribution of shared vs. independent drive sent to the motoneuron pools of each muscle, and to track how their relative proportion changes with force magnitude. To investigate neural drive to mechanically separate muscles, surface EMG signals were recorded from the abductor pollicis brevis and the first dorsal interosseous muscles during a variety of two-fingered pinching tasks. These included static and dynamic isometric force generation, the slow rotation of an object between the fingers, and the compression

of a slender spring which requires dynamic, quasi-isometric force modulation to prevent buckling. RESULTS: We found that the two thigh muscles share most of their neural drive, and that the strength as well as bandwidth of this shared drive increase with total knee extension force. In the hand muscles, we found that beta-band (15-30 Hz) intermuscular coherence was reduced when the spring was compressed nearly to the point of buckling, as compared with coherence recorded during the pinching of a wooden dowel at matched forces. Intermuscular coherence during dynamic modulation of isometric force tended to be similar to that observed during static force production. During object rotation, a shared 'Piper rhythm' of ~40 Hz and a 10 Hz common input became dominant. CONCLUSIONS: These investigations demonstrate the flexible nature of intermuscular neural drive, and emphasize that intermuscular synchrony, when measured within the context of an appropriate task, can provide an important window into muscle coordination strategies.

Investigating the neural substrate of motor coordination using muscle networks

Tjeerd Boonstra[1]

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How the central nervous system coordinates the many degrees of freedom of the musculoskeletal system remains an outstanding question. Neural synchronization may offer a novel window into the neural circuitry underpinning motor coordination. Equivalent to its role in perceptual processes, it is suggested that neural synchrony provides a mechanism for integrating distributed motor systems. However, the role neural synchronization has not been systematically evaluated as mechanism for motor coordination. Here I will use complex network analysis to investigate patterns of intermuscular during postural control. EMG from 40 muscles distributed across the body (whole-body EMG) was acquired from 14 healthy participants during upright standing, while postural stability (no, anterior-posterior or medial-lateral instability) and motor coordination (no, unimanual or bimanual pointing) were experimentally manipulated. Intermuscular coherence was estimated between the EMG envelopes of all muscle pairs (780 combinations) and non-negative matrix factorization was used to estimate the coupling strengths that define the edges of the muscle networks. Complex network analysis was used to assess the patterns of neural synchronization and compare muscle networks across experimental conditions. We observed coherent muscle activity at multiple distinct frequency bands throughout the body. Non-negative matrix factorization revealed four frequencies components centred at 2, 8, 16 and 40 Hz. The lowest frequency component was dominated by connectivity between leg muscles and was affected by postural stability. The higher frequency components revealed more local connectivity that was linked to motor coordination: 8-Hz connectivity in the upper body and arms was observed during the no-pointing conditions while 16-Hz connectivity was observed during unimanual and bimanual pointing. Complex network analysis revealed six modules consisting of (1) bilateral lower leg, (2) left upper leg, (3) right upper leg, 4) upper body, (5) left arm, and (6) right arm muscles. Complex network analysis is ideally suited to analyze the rich patterns of neural synchronization observed between muscles distributed across the body. The significant differences in network topology between experimental conditions suggest that muscle networks are functionally organized. Community analysis revealed six modules corresponding to the major anatomical body parts. By unraveling multiple frequencies components, the contribution of different motor pathways to motor coordination can be investigated.

Motor unit synchronization revisited: Estimating the proportion of common synaptic inputs to population of motor neurons in humans

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BACKGROUND AND AIM: Motor neurons innervating a muscle receive both common and independent synaptic inputs from spinal and supraspinal centers. This observation is classically based on the presence of significant correlation between pairs of motor unit spike trains (Nordstrom et al., 1992). The functional significance of the relative proportion of common input across muscles and conditions is still debated. One of the limitations in our understanding of correlated input to motor neurons is that its robust estimation is still an open problem. Indeed, correlation measures of pairs of output spike trains have several limitations (Negro F & Farina D, 2012; Farina D & Negro F., 2014). In this study, we report a new approach to measure the proportion of common input to a motor neuron pool with respect to the total synaptic input in voluntary contractions in humans. METHODS: We theoretically derived the relation between the common synaptic input and the total amount of synaptic input received by the motor neuron pool. This analytical derivation is based on a simplified motor neuron behavior (LIF model). Using a least-square curve fitting of the estimated values of coherence for cumulative spike trains, we estimated a parameter (PCI, proportion of common input) linearly related to the amount of common synaptic input received by the motor neuron pool. The new index was tested using a model of 300 realistic motor neurons and on experimental data. Experiments were performed on the abductor digiti minimi (ADM), the tibialis anterior (TA), and the vastus medialis (VM) muscles at moderate force levels. Single motor unit action potentials were recorded with intramuscular electrodes in the three muscles and decomposed using EMGLAB (McGill KG, 2005). RESULTS: In both simulated and experimental results, the estimation of the coherence between pairs of composite spike trains showed a tendency to increase faster for greater levels of input correlation, as predicted theoretically. In simulations, the PCI index showed to be robust and independent on the discharge rates. In the experimental recordings, the averaged (total) number of identified motor unit spike trains for a single trial were 9 ± 2 (45) (ADM), 13 ± 4 (51) (TA), and 8 ± 2 (40) (VM). The estimated values of PCI were 75 ± 12 (ADM), 82 ± 17 (TA), and 63 ± 20 % (VM). These results show that the motor pools of these muscles receive a similar and large (>60%) proportion of common low frequency oscillations with respect to their total synaptic input. CONCLUSIONS: In this study, we have provided for the first time a robust quantification of the proportion of common input to motor neuron pools with respect to the total synaptic input. The results suggest that the central nervous system provides a large amount of common input to motor neuron pools, in a similar way for muscles with different functions and control properties.

Sensitivity of intermuscular coherence to identify common oscillatory synaptic inputs to motor neurons

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BACKGROUND AND AIM: Oscillations in the synaptic inputs received by motor neurons have been reported to play a critical role in sensorimotor control. A number of groups are currently developing and improving methods to quantify the

oscillations in common synaptic inputs within and across motor neuron pools and to determine the functional significance of these oscillations. The purpose of the current study was to evaluate the use of coherence analysis between simulated surface electromyograms (EMGs) to quantify common oscillatory synaptic input to two populations of motor neurons. METHODS: Models of two motor-neuron pools were used to simulate surface EMG signals that were detected over both muscles after imposing common oscillatory synaptic inputs across the two motor unit populations. The simulations varied the level of muscle activation, as well as the amplitude and frequency of the common oscillatory synaptic input shared across the two pools of motor neurons. Also, several parameters were varied to examine the influence of crosstalk, motor unit action potential shapes, high-pass filtering, amplitude cancellation, and rectification on EMG-EMG coherence. RESULTS: In general, coherence estimates derived from rectified EMG signals underestimated the level of common input due to the influence of amplitude cancellation and changes in the shapes of the motor unit action potentials. Across several conditions, estimates of coherence obtained from interference EMG signals resulted in a more accurate estimate of the common input than that derived from rectified EMG signals. However, the difference between the two estimates depended on the common input frequency, the cutoff frequency of the high-pass filter, and crosstalk. CONCLUSIONS: As several of these factors above are difficult to assess during experimental conditions, the results indicate that EMG-EMG coherence provides a limited measure of the level of common oscillatory synaptic input received by motor neurons in two muscles.

S.8. *Neuromuscular Electrical Stimulation: Time to Turn the Page*

Maximising the central contribution to electrically-evoked contractions

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BACKGROUND AND AIM: Traditionally it is thought that neuromuscular electrical stimulation (NMES) produces contractions by activating motor axons beneath the

stimulating electrodes, thus through pathways restricted to the peripheral nervous system ("peripheral pathways"). However, contractions can also be generated via "central pathways", by the depolarisation of sensory axons beneath the stimulating electrodes which produces contractions via reflex pathways through the spinal cord. The aim of this presentation is to describe how to maximise this "central contribution" to contractions evoked by NMES and provide an overview of the benefits and weaknesses of generating contractions in this way. METHODS: NMES was applied using surface electrodes to produce contractions of the muscles that flex (tibialis anterior) and extend (triceps surae) the ankle. The stimulation was applied over the muscle belly (mNMES) or peripheral nerve trunk (nNMES) using a range of pulse durations (0.05-1.0ms) and frequencies (20-100). Isometric torque was measured using a Biodex system 3 dynamometer. Electromyographic (EMG) activity was measured from the tibialis anterior and soleus muscles. The extent to which peripheral pathways contributed to the evoked contractions was assessed by the amplitude of M-waves in the EMG signal. The central contribution was assessed by the amplitude of H-reflexes and EMG activity that was asynchronous from the stimulus pulses. RESULTS: The central contribution to electrically-evoked contractions was stronger during nNMES than mNMES and, regardless of NMES type, was stronger in the triceps surae than the tibialis anterior. The central contribution was maximised using relatively wide pulse durations. During constant frequency NMES, H-reflexes were depressed but asynchronous activity was greater when high frequencies were compared to lower frequencies. When the stimulation was delivered in a frequency modulated pattern (20Hz for 2s-100Hz for 2s-20Hz for 3s), H-reflexes, asynchronous activity and torque were elevated after the 100Hz "burst" compared to before it. Torque produced via central pathways was less stable than torque produced by peripheral pathways. Contractions generated through central pathways were more fatigue-resistant than contractions produced through peripheral pathways in individuals with no neurological impairment and in individuals with a spinal cord injury. DISCUSSION: Signals travelling along central pathways recruit motoneurons synaptically, according to Henneman's size principle, thus contractions fatigue less than those produced by the depolarisation of motor axons, which is thought to recruit motor units randomly with respect to type. However, the inherent variability of transmission along central pathways makes torque produced by central pathways less stable than that produced by peripheral pathways and the "central contribution" to electrically-evoked contractions can vary widely between muscles and individuals.

Introduction and Conclusion to the symposium "Neuromuscular Electrical Stimulation: Time to Turn the Page"

Nicola Maffiuletti[1], Marco Minetto[2]

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Neuromuscular electrical stimulation (NMES) involves the application of pre-programmed trains of stimuli to superficial skeletal muscles with the ultimate goal to evoke visible tetanic contractions. Unlike other electrical stimulation modalities such as transcutaneous electrical stimulation (that is commonly used for pain relief), NMES-based treatment programs have long been used to either preserve or restore skeletal muscle mass and function during and after a period of disuse due to injury, surgery or illness. The general (quite provocative) idea of this symposium is to present and critically discuss some of the recent advancements that can promote a better clinical application of NMES in the future. Various emerging modalities of stimulation - such as kHz-frequency alternating currents, wide-pulse NMES, peripheral magnetic stimulation, distributed and multipath NMES - have received considerable attention over the last few years, but their principles, feasibility, acceptability and potential clinical effectiveness are not fully understood. For each of these stimulation modalities, the following points will be addressed: (1) functioning principle (how it works, especially with respect to conventional NMES), (2) rationale (why it should be used/preferred - or not - to conventional NMES); (3) effectiveness and clinical acceptability (always with respect to conventional NMES); and (4) population-specific considerations. Our introductory talk will present the rationale and configuration of the symposium, while the concluding talk will provide a summary of key points that will hopefully initiate a constructive discussion.

Predictors of response to neuromuscular electrical stimulation training

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Neuromuscular electrical stimulation (NMES) represents an effective means for improving muscle weakness in adult patients. However, there is considerable inter-individual variability in response to NMES training, and optimization may relate not only to the parameters of the stimulation paradigm, but also to the characteristics of the subject. The key factor for optimizing NMES effectiveness has been suggested to be the muscle tension which is mainly related to the following stimulation parameters: amplitude of the applied current and frequency of the stimulation busts. Further, recent observations have indicated that the optimization of NMES effectiveness can also be obtained through manipulation of the stimulation paradigm. In fact, the introduction of an interphase interval interposed within the two phases of biphasic pulses enhanced the electrically-evoked contraction force of the quadriceps muscle. In addition, NMES effectiveness is also related to intrinsic anatomical and (patho)physiological properties that should be investigated in stimulated subjects. For instance, individual motor nerve branching, which determines the response of the muscle to the application of electrical current over the skin, should be carefully investigated through the identification of the main muscle motor points. This procedure is essential to establish the proper position of the stimulation electrodes as well as the proper inter-electrode distance, that has recently been found as an important determinant of the torque elicited during electrically-evoked contractions. The proper placement of stimulation electrodes and inter-electrode distance selection enable to maximize the spatial recruitment that is spatially fixed and incomplete during NMES. Another strategy to maximize the spatial recruitment, thus minimizing the extent of muscle fatigue, is to deliver electrical pulses to the nerve trunk. However, as the electrical stimulation of the nerve is not comfortable, a painless approach to stimulate the nerve trunk may be represented by peripheral nerve magnetic stimulation. Consistently, magnetic stimulation of the femoral nerve elicited quadriceps contractions up to 70% of the maximal force and proved to be well-tolerated and effective in improving quadriceps strength and exercise capacity of COPD patients. Further, the following other (patho)physiological factors are thought to contribute to the variability to NMES training: hormonal status, thickness of subcutaneous fat tissue, supraspinal descending drive affecting the balance of inhibition and facilitation of the spinal circuits, changes in muscle excitability. I this talk, we will provide a framework by which to clarify NMES place in clinical practice, by discussing the optimal parameters for a NMES programme and presenting examples of criteria for predicting the response to NMES training that should be used in clinical setting to identify patients most likely to benefit.

Spatially Distributed Sequential Stimulation: Method to Reduce Muscle Fatigue During Transcutaneous Functional Electrical Stimulation

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Background: One of the limitations with the transcutaneous functional electrical stimulation is the rapid onset of muscle fatigue during repeated and extended contractions. Our team has developed a method called spatially distributed sequential stimulation (SDSS) to reduce muscle fatigue by distributing the center of electrical field over a wide area within a single stimulation site, using an array of surface electrodes. Objective: To extend the previous findings and to prove feasibility of the method by exploring the fatigue-reducing ability of SDSS for lower limb muscle groups in the able-bodied population, as well as in individuals with spinal cord injury (SCI). Methods: SDSS was delivered through four active electrodes applied to the knee extensors and flexors, plantarflexors, and dorsiflexors, sending a stimulation pulse to each electrode one after another with 90° phase shift between successive electrodes. Isometric ankle torque was measured during fatiguing stimulations using SDSS and conventional single active electrode stimulation lasting 2 minutes. Results: We demonstrated greater fatigue-reducing ability of SDSS system compared with the conventional protocol, as revealed by larger values of fatigue index and/or torque peak mean in all muscles except knee flexors of able-bodied individuals, and in all muscles tested in individuals with SCI. Conclusions: Our study has revealed improvements in fatigue tolerance during transcutaneous functional electrical stimulation using SDSS, a stimulation strategy that alternates activation of subcompartments of muscles. The SDSS protocol can provide greater stimulation times with less decrement in mechanical output compared with the conventional protocol.

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An Algorithm for NMES Therapy after Knee Surgery: A Novel Structured Approach

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BACKGROUND AND AIM: We present a two-phase algorithm for patient selection and treatment, which is intended to improve clinical decisions regarding: 1) the appropriateness of NMES therapy, 2) monitoring of patient progress, and 3) the timing and rationale for NMES therapy modifications or cessation in patients with knee surgery. METHODS: The algorithm consists of: treatment phase 1 (first 3 weeks after surgery), evaluation after a week of NMES use, and treatment phase 2 (>3wks after surgery). Ideally, patients are also given a home-based familiarization period consisting of a few days before surgery, which may facilitate better patient tolerance. Following knee surgery for Phase I, we recommend multiple daily bouts (2x/day) of at least 10-15 minutes (15-20 contractions) to maximize exposure when voluntary activation deficits are greatest using stimulation amplitudes set at the highest tolerable level. Relatively long phase durations (e.g. 300 μs) should be used, as wide pulses are more likely to target motor fibers (thus maximizing quadriceps force production), while shorter phase durations (< 100 μs) might preferentially target sensory fibers and contribute to uncomfortable burning sensations during NMES. Frequencies around 50pps are also recommended to maximize force production while limiting early muscle fatigue. We also recommend an on:off ratio of 10:30 seconds, again to maximize exposure while still providing reasonable rest periods between contractions. After the first week of Phase I, patient tolerance to NMES should be evaluated to ensure adequate dose. At a minimum, a full, sustained, tetanic contraction of the quadriceps (no fasciculation observed on visual inspection) should be present with visual or palpable evidence of superior patellar glide. If these criteria are not met, NMES therapy may not achieve therapeutic doses, and alternative rehabilitation strategies should be considered. Patients should be re-evaluated after 3 weeks for the presence of activation deficits to determine if a high-volume, high-intensity approach is still warranted. If activation deficits have largely resolved, a low-volume approach is recommended. Here, the goal is still to supply the quadriceps muscle with high-intensity (high-amplitude) NMES therapy, but with

longer rest intervals between treatment sessions to allow for adequate recovery (e.g., 1x daily or every other day). The only difference in NMES parameters between Phase 1 and Phase 2 is the treatment frequency of application. CONCLUSION: While NMES is most effective in populations where voluntary activation failure is present and most commonly include patients following knee injury or surgery, NMES treatment may also benefit patients with anterior knee pain, knee osteoarthritis or hip arthroplasty.

Low-frequency pulsed currents vs. Khz-frequency alternating currents

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Neuromuscular electrical stimulation (NMES) consists in the application of a series of intermittent stimuli to intramuscular nerve branches to trigger visible skeletal muscle contractions. NMES has received increasing attention in recent years because of its potential to serve as a strength training, a rehabilitation, a testing and a post-exercise recovery tool (Maffiuletti et al 2011). Traditional NMES consists of relatively short pulse durations (<400μs) delivered at low to moderate stimulation frequencies (15-40 Hz, low-frequency pulsed current - LFPC) and high stimulation intensities (Collins 2007). LFPC has been used for muscle strength training in healthy and clinical populations (e.g. orthopedic surgery, critically ill and elderly people; Herzig et al 2015). However, it has important limitations (excessive discomfort, limited spatial MU recruitment, high muscle fatigability) that impedes attaining high levels of evoked force. In 2002, Ward & Shkuratova described the pioneer works of Kots et al. (1971, 1977) who proposed a NMES type that was believed to solve some of the abovementioned limitations. Kots et al (1977) claimed that this kilohertz-frequency alternated current (KFAC, 2500 Hz, modulated at 50Hz, later named as Russian current) increased the maximal voluntary isometric contraction (MIVC) by up to 40%. The main reasoning for using KFAC was related to supra-threshold intensities with long-enough duration bursts, capable of producing multiple nerve fiber action potentials per burst that might elicit slightly greater force, smaller discomfort, but an undesirable increase in the rate of fatigue (Ward 2009). The differences in these two types of NMES should produce different physiological responses in terms of torque generation, skeletal muscle damage and discomfort levels. Adayel et al (2011) compared KFAC and LFPC effects on knee extensors torque output, rating of perceive exertion, skin temperature, hormonal responses and muscle damage. They showed similar effects in all parameters between the two NMES types. Silva's et al (2015) systematic review showed no difference on the current evidence between KFAC and LFPC effects on quadriceps-evoked torque and self-reported discomfort levels in healthy subjects. However, Vaz et al (2012) showed that LFPC was more efficient than KFAC to electrically elicited 10% MIVC due to the 15% smaller current amplitude and to the 50% lower perceived discomfort level. Based on the current literature the use of traditional NMES seems to be equal or superior to KFAC. Considering that LFPC stimulators are less expensive and more portable than KFAC stimulators, LFPC may be more advantageous in muscle training and clinical practice (e.g. Vaz et al 2013). However, new studies on the acute and chronic effects of NMES with changes on the existent stimulus parameters: large pulse width, higher frequencies, electrode positioning, and multiple current pathways that might show more encouraging results about LFPC.

O.7. EMG: signal processing

O.7.1 *Optimum threshold for slope sign changes and zero crossing features.*

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BACKGROUND AND AIM: For over two decades, Hudgins' set of time domain electromyography features has been extensively applied for classification of hand motions. The calculation of slope sign changes (SSC) and zero crossing (ZC) features uses a threshold to attenuate the effect of background noise. However, there is no consensus on the optimal value. In this study, we investigate for the first time the impact of threshold selection on classification accuracy, with specific attention to the effect over time. METHODS: Eight healthy subjects participated in the experiment (25 ± 1 years old). Surface EMG was recorded from five channels. Seven hand movements and a no motion class were collected over two separate days with two days in between. Each day, four repetitions were collected for each movement (3s

steady state contractions). The threshold was computed as a factor (R = 0:0.01:4) times the average root mean square of the no motion data. Hudgins' feature set was extracted from signal intervals of 200 ms in duration with 25ms overlap. For each day, classification error (CE) was quantified for each threshold value, including no threshold (CEr0). A subject-based best threshold with associated lowest error (CEbest) was also determined with a four-fold validation procedure. Subsequently, a cross day threshold validation was applied where, for example, CE of day 2 (CEdx) was computed based on the best threshold from day 1 (and vice versa). Finally, the effect of threshold on using training data from one day and test data of the other day was quantified using a two-fold validation across both days. For these purposes, all combinations of R (0:001:4) for SSC and ZC were investigated. RESULTS: On average CEbest (5.26 ± 2.42 %) was better than CEr0 (7.51 ± 2.41 %, P = 0.018), and CEdx (7.50 ± 2.50 %, P = 0.021). Optimising the threshold on day 1 and using it for day 2 (CEdx) provided similar performance (P = 1) as using R = 0 (CEr0). During the two-fold validation between days, the minimum of the average CE was 14.90 ± 3.8 % located at R = 0.06 and 2.18 for SSC and ZC respectively, although not significantly better than CEr0 (16.17 ± 4.05%). Interestingly, when using the threshold values optimized per subject from one day and applying to the other, the CE increased to 19.90 ± 4.6% and 22.86 ± 5.67% for day 1 and day 2 respectively. This is an indication that optimum threshold values do not generalize well. CONCLUSIONS: This investigation suggests that although an optimum threshold can be found, it is highly subject and data driven. This implies that eliminating the threshold for SSC and ZC is a good trade-off between performance and generalization.

O.7.2 ***Variability of Features Extracted from sEMG Signal***

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BACKGROUND AND AIM: The use of surface electromyography (sEMG) is promising in a wide range of applications such as muscle condition assessment during ergonomic and sport science studies, diagnosis of neuromuscular and musculoskeletal disorders, assistive device control, and rehabilitation. While it can provide a close look into underlying neuromuscular processes, sEMG is not currently widely used in applications, in part, due to its high inter-individual and test-retest

variability in sEMG measurements. Characterizing features extracted from sEMG, both in time- and frequency-domains, have demonstrated high variability between individuals and tests making it difficult to reliably interpret sEMG data. The variability in the measurements of sEMG mean frequency (MF), as one of the most popular frequency-domain features, is investigated in the present work. METHODS: Factors such as statistical estimation error, motor unit number and depth, firing statistics, and conduction velocity, will vary the power spectrum of sEMG and thus the MF measurement variability. It is also known that the sEMG from isometric/isotonic contractions can be considered as a self-stationary signal. However, if such a signal has been observed over a finite time duration, T, estimation error will arise. This is the source which determines the minimum possible MF measurement variability, and thus a baseline for MF variability. Once this baseline has been found, additional variation sources can be added and their effects can be observed. To gain full control of the sEMG being investigated an EMG simulation tool, is used so that the physiological, anatomical and instrumental parameters that might contribute to the variation of the sEMG can be configured. RESULTS: The results of the preliminary investigation show that, the baseline MF measurement variability decreases with increasing signal length T, as shown in Figure 1 for simulated sEMG with parameters set to resemble a bicep brachii during an isometric/isotonic contraction. A similar trend appeared when estimating the MF measurement variance for self-stationary band-limited white Gaussian signals. CONCLUSIONS: These results show that MF measurements must be performed with the knowledge of signal duration in mind. To make MF measurements from signals of different lengths comparable, the relationship between MF variance and T must be considered. The MF measurement variability due to other sources will be reported from theoretical and experimental work.

O.7.3 *Wavelet-based functional ANOVA to reveal statistically-significant contrasts between EMG waveforms recorded in different experimental conditions*

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BACKGROUND AND AIM: We often want to compare the shapes of EMG waveforms that are functions of time, but traditional statistical tests cannot reveal differences between curves without sacrificing temporal resolution or power. Waveform features identified visually may not be revealed by t-tests or ANOVA applied across time points due to the large number of comparisons. We developed wavelet-based functional ANOVA (wfANOVA) to solve this problem. In wfANOVA, ANOVA is performed in the wavelet domain because differences between curves tend to be represented by a few temporally localized wavelets. Differences are then transformed back to the time domain for visualization. In a previous study, we used standard statistical techniques to identify variation in EMG signals during automatic postural responses to perturbations as the peak acceleration and peak velocity of the support surface translation perturbation were varied (Welch and Ting, J Neurophysiol 2009). The aim of the present work was to compare the ability of wfANOVA and ANOVA performed in the time domain (tANOVA) to identify similar patterns of variation without requiring the experimenter to assume features or time bins a priori. METHODS: We applied wfANOVA and tANOVA to EMG recorded during translation perturbations of the support surface designed so that platform peak acceleration and peak velocity could be varied independently (acceleration: 3 levels; velocity: 4 levels). In wfANOVA, EMG waveforms were transformed to the wavelet domain and analyzed with three-factor fixed-effects ANOVA. Wavelet coefficients with significant initial F-tests ($P<0.05$) were evaluated for significant contrasts across velocity or acceleration levels with post-hoc Scheffé tests. Wavelet coefficients retained after post-hoc were then assembled into wavelet-domain contrast curves and transformed back to the time domain. In tANOVA, an identical analysis was performed in the time domain. RESULTS: In experimental EMG data, wfANOVA revealed the continuous shape and magnitude of significant differences over time consistent with previously described scaling relationships without a priori selection of time bins. However, tANOVA revealed only the largest differences at discontinuous time points, resulting in features with later onsets and shorter durations than those identified using wfANOVA ($P<0.02$). wfANOVA required significantly fewer (<1/4; $P<0.015$) significant F-tests than tANOVA, resulting in post hoc tests with increased power. CONCLUSIONS: This work demonstrates that wfANOVA may be useful for revealing differences in the shape and magnitude of neurophysiological signals (e.g., kinematic and kinetic data, EMG, M- and H-waves, firing rates) across multiple conditions with both high temporal resolution and high statistical power. Examples of wfANOVA applications to data including EMG and EEG from other laboratories are also presented.

O.7.4 *Nonnegative matrix factorization to assess spatiotemporal muscle activation*

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Introduction: The distribution of activity can change across a muscle. Such spatial heterogeneity of muscle activity has been assessed by comparing EMG amplitudes between channels within a grid of electrodes [1]. That procedure, however, involves averaging amplitudes over time and, hence, discards temporal information. As an alternative method a k-means clustering has been applied considering both temporal and spatial information [2]. However, this clustering approach requires a priori knowledge of the number of clusters present. Typically this number can only be estimated. If that estimate is incorrect, the clustering may yield an inadequate representation of muscle activity. The aim of the current study was to explore the utility of nonnegative matrix factorization (NMF) in the quantification of temporal and spatial variability of muscle activation. Methods: In eight subjects we measured surface EMG (49±8 electrodes covering the entire biceps brachii) during two contraction types: 1) pure elbow flexion (Fl) and 2) elbow flexion with a superimposed forearm supination (FlSu). The monopolar EMGs were spatially filtered with principal component analysis [3], rectified, smoothened, and normalized to maximum voluntary contraction. We used NMF [cf. 4] to decompose spatiotemporal EMG envelopes into a common signal (CS) and its gain distribution (GD). Furthermore, we quantified the common signal's correlation distribution (CD) and a value describing spatiotemporal heterogeneity by the overall variance accounted for (VAF, Figure 1). Results: VAF was significantly (43%) larger for FlSu than in Fl (89±3% vs. 51±9%). CD showed 28% higher mean, 57% lower standard deviation, and 70% lower mean gradient in FlSu. This hints at less heterogeneity of the spatial activation pattern than in Fl. In contrast, GD showed only a 13% larger mean gradient in FlSu suggesting more variability of the envelopes of closely spaced electrodes over the muscle for FISu than Fl. Conclusion: Our findings render NMF a powerful method for quantifying spatiotemporal muscle activation. NMF does not depend on a priori knowledge of spatial characteristics (e.g. number of spatial clusters), but exploits all temporal and spatial information. The VAF and spatial correlation were sensitive to the contraction type, while the spatial gain represented by GD was not. It can be concluded that the outcomes proposed were sensitive to contraction types and can be interpreted in a physiologically meaningful way. [1] Farina et al., J Electromyogr Kinesiol, 18: 16-25, 2008 [2] Staudenmann et al., J Electromyogr Kinesiol, 19: 882-895, 2009 [3] Staudenmann et al., IEEE Trans Biomed Eng, 53: 712-719, 2006 [4] Lee et al., Nature, 401: 788-791, 1999

O.7.5 ***Analysis of amplitude estimation of non-stationary myoelectric signals***

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BACKGROUND AND AIM: Muscle force is highly correlated with the amplitude of the surface electromyogram (sEMG) produced by the active muscle. This relation determines its importance as a feature of myoelectric signals and, hence, the wide spread use ranging from rehabilitation engineering to neuromechanical modeling to artistic performances. Correctly estimating this quantity and understanding its relation to neural drive and muscle force is therefore of paramount importance. The single constituents of the sEMG are called motor unit action potentials (MUAPs). Due to their biphasic nature, concurrent MUAPs are likely to interfere with each other. This phenomenon is called amplitude cancellation and its impact on the sEMG amplitude has been extensively investigated. In this study we first revisit its effect on the standard deviation and continue with an in-depth analysis of various amplitude estimators proposed in the myoelectric signal literature. METHODS: We simulate 10000 Poisson processes and convolve them with realistic MUAPs. We then estimate the standard deviation in case of interference and non-interference (by rectification before summation). The Campbell-Hardy theorem claims the standard deviation to be the same for both scenarios if the following assumptions are met: i) motor unit firing statistics are well described by Poisson processes and ii) a change in their firing rate occurs on a longer time scale (orders of magnitude) than voltage change of single units. We proceed with a comparison of several amplitude estimation techniques. For the comparison we set parameters such that the smoothness of the respective estimates is comparable. The estimation quality is measured in terms of time lag, root mean square (RMS) error and correlation coefficient between the estimate and the imposed neural drive. The tested estimators are RMS, variations of the Kalman filter and a Bayes-Chapman-Kolmogorov (BCK) filter (Sanger2007). RESULTS: As predicted by the Campbell-Hardy theorem we find no difference in estimated standard deviation when interference is compared with non-interference sEMG. When comparing different estimators we find that the BCK filter outperforms other methods. However, we note that the sensitivity with respect to sampling rate of this filter is substantial. Depending on the speed of change of the input signal a higher sampling frequency (~2kHz) might be required to perform better than the much simpler RMS. CONCLUSION: The evidence that the sEMG standard deviation is not affected by the MUAP shape is good news for the estimation of the neural drive. However, this finding stands in contrast with previous findings (Keenan et al. 2005) and, hence, further investigation will need to clarify these sharply contrasting results. The BCK filter proved to be the method of choice when estimating the neural drive, however, its sensitivity to sampling frequency might constrain its use to high-end myoelectric recording devices.

O.7.6 *Automated Detection of Fasciculations in Motor Neurone Disease Patients using B mode Ultrasound: A Comparison with Electromyography*.

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BACKGROUND AND AIM: Motor Neurone Disease (MND) is a progressive, neurodegenerative disease that causes muscle weakness and atrophy alongside involuntary muscle twitches such as fasciculations. The standard method for the detection of the presence of fasciculations is intramuscular electromyography (iEMG). iEMG detects the electrical activation within the muscle tissue that leads to these involuntary twitches. This can be used along with other tests such as nerve conduction, blood tests and MRI to form a diagnosis. However, iEMG is an invasive test, which can cause pain and discomfort for patients. This study investigates the performance of a number of ultrasound image based motion tracking techniques for fasciculation detection and how their performance is affected by different muscles and the orientation of the probe. METHODS: Ultrasound image sequences (35 sec duration, 80fps) and iEMG (48kHz) were collected from Medial Gastrocnemius (MG)

and Biceps Brachii (BB) in 13 MND patients. Longitudinal and transverse images were collected in each muscle, with two videos collected per muscle/probe orientation. Three different algorithms were applied; Kanade Lucas Tomasi motion tracker with mutual information (KLT), Horn-Schunck optical flow (HS) analysis and background subtraction using a mixture of Gaussians (GMM). Performance of each technique, across both muscles and probe orientations, was determined using receiver operator characteristics (ROC). Using the area under the ROC curve, levels of agreement between the iEMG signals and the computer vision were determined. RESULTS: In MG, longitudinal probe orientation gave results of 83.5% (GMM), 80.0% (HS) and 66.8% (KLT). In transverse probe orientation, agreement levels of 82.9% (GMM), 83.4% (HS) and 69.3% (KLT) were found. For longitudinal probe orientation, BB showed results of 83.5% (GMM), 76.2% (HS) and 69.3% (KLT). Transverse probe orientation gave agreement levels of 83.4% (GMM), 75.5% (HS) and 73.0% (KLT). CONCLUSIONS: Results showed good agreement for all muscles/probe orientations when using the GMM twitch detection method. HS performed well in the MG¬ muscle, but displayed a reduction in agreement in the biceps. The KLT had the worst performance throughout. Agreement results tended to be slightly higher in the MG in comparison to the BB, especially for HS, but little difference in agreement was seen between the two probe orientations. Variation between the iEMG and twitch detection signal may be due to large difference in pick-up area between ultrasound (approx.50mm2) in comparison, only the very tip of the needle can detect electrical activity. Therefore, twitches may be viewable in the ultrasound and not in the EMG signal. Overall, computational techniques show promise for automated, objective twitch identification. Further analysis will determine whether these techniques can provide a means to distinguish MND from healthy muscle based solely on fasciculation characteristics.

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O.8. Motor performance and Ergonomics

O.8.1 *The surgeon's workload; traditional laparoscopic (TLS) versus robot-assisted (RAS) surgery*

Bente Rona Jensen[1], Morten Dedenroth[1], Dorte Hartwell[1], Berit Mosgaard[1], Annemette Jørgensen[2], Torur Dalsgaard[1]

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Background & Aim: Musculoskeletal symptoms are common among surgeons performing minimally invasive surgery. Thus, 87 % (1) and 73% (2) of the surgeons who regularly perform traditional laparoscopic surgery (TLS) report work-related symptoms, mainly in neck/shoulder, upper-extremity, lower-back, hand and lower-extremity. TLS is characterized by less motion and more constrained and static postures than e.g. open surgery. Knowledge regarding the potential benefit of robot assisted surgery is lacking. The aim was to study musculoskeletal workload in surgeons during TLS compared to robot-assisted (RAS) surgery procedures. We hypothesized that RAS was less demanding than TLS. Methods: Twelve experienced surgeons (mean age 52 yrs., seniority 20.1 yrs.) performed hysterectomy as TLS and RAS. Each surgeon performed TLS and RAS on the same day (morning and afternoon). TLS was performed in a standing position with visual feed-back to the surgeon from 2D-monitors placed to the side of the surgeon. RAS was performed in a sitting position (Da Vinci SI, Intuitive Surgical System, USA) which allowed forearm and head support. The instruments were manipulated by the fingers and visual feed-back was given through a 3D-monitor on the console. Both types of surgeries were assisted by a colleague. Bipolar surface EMG was recorded bilaterally from neck extensor, upper trapezius and erector spinae (low-back) muscles. EMG measured during surgery was expressed relative to maximum EMG recorded during maximum contractions. Static (p0.1), median (p0.5) and peak (p0.9) muscle activation were calculated. Furthermore, perceived exertion was rated for fingers, wrist, lower arm/elbow, neck, shoulders, low-back and legs before and just after each surgery. Results: Total time for EMG analyses was 2-3 hours for each surgeon. Average neck muscle activity was higher during TLS than during RAS (p0.1: 4.7 vs. 3.0%EMGmax, p0.5: 7.4 vs. 5.3%EMGmax, p0.9: 11.6 vs. 8.2%EMGmax). Average static shoulder

muscle activity was higher for TLS than RAS (p0.1: 5.7 vs. 2.8%EMGmax). These differences were most likely due to available head and arm support during RAS. However, for the low-back higher levels of muscle activity was found during RAS on the dominant side, which emphasize that sitting does not ensure reduced loading of the low-back compared to the standing position. The general trend for the perceived exertion was lower values after RAS than TLS. Perceived exertion for dominant shoulder and legs was higher for TLS than RAS. Conclusion: The surgeons shoulder and neck workload was reduced markedly during RAS procedures compared to TLS procedures. However, prolonged static loading of neck and shoulder muscles still occur during the RAS procedures and individual advices regarding how to optimize sitting postures and working conditions during RAS procedures is therefore recommended. 1.Park, A. et al. J Am Coll Surg 2010;210:306-313 2.Sari, V. et al. Min Invasive Therapy 2010;19:105-109

O.8.2 *Characterizing changes in neuromuscular control in response to different locomotor tasks using electromyographic wavelet analysis*

Linard Filli[1], Martina Waser[1], Christopher Easthope[2], Tim Killeen[2], Christian Meyer[1], Lilla Loerincz[1], Armin Curt[2], Marc Bolliger[2], Bjoern Zoerner[1]

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BACKGROUND & AIM: The contribution of specific neural systems to human walking is not yet fully understood. Elucidating the sources of neural drive that coordinate walking is important for a fuller understanding of gait disturbance in specific neuropathologies and such may find utility in developing tailored neurorehabilitative therapies for patients. In this study, we characterized changes in sensorimotor movement control in response to altered walking conditions using detailed time-frequency analysis of electromyographic (EMG) signals. METHODS: Bilateral EMG recordings were made over the tibialis anterior (TA) and gastrocnemius medialis (GM) muscles in 28 healthy subjects (age: 50.2 ± 16.1 years; 17 men; 11 women) during normal treadmill walking at half-maximal speed, during dual task walking with a simultaneous cognitive load (Stroop task) and during semi-blind treadmill walking (obscured lower half of visual field). RESULTS: To detect basic changes in neuromuscular activity induced by different walking tasks, we first assessed total rectified EMG intensity of TA and GM for 10% bins of the gait cycle (GC). Total EMG intensity of TA was significantly modified by the different walking conditions ($p<0.0001$; 2-way ANOVA repeated measures). Post-hoc analysis revealed that TA activity was reduced in the dual task condition during the loading response (1-10%) of the GC (normal vs. Stroop: $p<0.01$). On the other hand, semi-blinded walking led to increased TA activity during the initial phases of the GC compared to normal walking (1-10% of GC: $p<0.001$; 11-20% of GC: $p<0.0001$). In contrast to TA, GM activity showed no overall changes with the factor "walking condition" on the total EMG activity pattern. Post-hoc analysis, however, did reveal significant modifications of GA activity within the mean activity period of the muscle (20-30% of GC; $p < 0.01$). Frequency-domain analysis of the EMG signal using 9 wavelet frequency bandwidths (center-frequencies: 6.9Hz, 19.29Hz; 37.71Hz; 62.09Hz; 92.36Hz; 128.48Hz; 170.39Hz; 218.08Hz; 271.5Hz) during different walking conditions showed that TA activity significantly increased its power within lower frequency bandwidths (spectrum 1: $p<0.0001$; spectrum 2: $p<0.0032$). GM activity showed only unilateral changes in EMG power in the high frequency spectra of the right leg (spectrum 8: $p<0.0009$; spectrum 9: $p<0.0001$). CONCLUSIONS: The preliminary data indicate that different walking conditions lead to altered neuromuscular control of TA muscular activity, with GM activity modified to a lesser degree. Wavelet frequency analysis demonstrated differential power of specific frequency spectra during different ambulatory conditions, which might suggest a change in the neural sources controlling specific walking tasks. Combined time-frequency analysis of the existing EMG data (including neurological patients) will be used to further interpret specific changes in neuromuscular control under different walking conditions.

O.8.3 *Temporal trunk muscle patterns are altered ipsilateral to back injury side despite perception of recovery*

D Adam Quirk[1], Cheryl Hubley-Kozey[1]

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BACKGROUND AND AIM: Altered neuromuscular patterns persist following recovery from low back injury (rLBI)[12]. Redistribution of multifidus muscle activation ipsilateral to the previously painful side includes increased activation of superficial multifidus fibers[1], possibly compensating for unilateral atrophy[3]. This redistribution could alter trunk muscle responses to frontal plane loading, yet current work has only evaluated

sagittal plane tasks. This study tested whether neuromuscular alterations are side dependent following recovery of a LBI during a dynamic controlled transfer task. METHODS: Surface electromyograms (EMG) were collected from 24 trunk muscle sites (12 abdominal and 12 back extensors) at 1000Hz from 63 rLBI participants[2] during a series of lifting tasks. Root mean square (RMS) EMG amplitudes were calculated and normalized to maximum voluntary isometric contractions. Raw EMG data were full-wave rectified, low-pass filtered (6 Hz), time normalized to 100% and amplitude normalized to average task amplitude; three trials were ensemble averaged for each muscle. A symmetric lifting task was used to determine RMS differences between multifidus sites indicative of a unilateral >20% or central <10% injury. Eight left rLBI (LrLBI), 8 right (RrLBI) and 8 central (CrLBI) participants were matched (age, sex, mass, height). A dynamic right-to-left transfer task predictably changed the moment acting on the trunk[2] (Figure). Temporal features were captured using principal component (PC) analysis, constructed from ensemble-average waveforms. Mixed model ANOVAs (group, side & muscle) on RMS amplitude and PC scores, were conducted for abdominals and back extensors separately. RESULTS: A group main effect ($p<0.001$) showed abdominal RMS amplitudes in LrLBI were higher than CrLBI, and CrLBI were higher than RrLBI. For back extensors a group*muscle*side interaction ($p=0.04$) captured that LrLBI had higher activation than 3/12 CrLBI and 4/12 RrLBI sites. PC1 captured a differential between RHT and LHT(Figure). For the back extensors there was a group*side interaction ($p<0.001$); RrLBI participants had a greater response to the lateral flexion moment than L&CrLBI, for left sites(Figure). LrLBI experienced a dip in activation (PC3) following lift off for left back extensor sites relative to C&RrLBI, group*side interaction ($p<0.001$)(Figure). CONCLUSIONS: Using multifidus asymmetries to indicate unilateral LBI, the results showed that LrLBI participants inhibit back extensor muscles ipsilateral to their LBI, evidenced by reduced responsiveness to loading, relative to RrLBI (PC1), and an observable dip in muscle activation (Figure). Both patterns reduced activation ipsilateral to the LBI. Yet, participants were recovered at testing suggesting motor learning. Future studies should investigate if these patterns are influenced by pain, or structural impairments. 1) D?Hooge et al, JEK 2013; 2) Hubley-Kozey et al, Work 2014; 3) Hides et al, Spine 1996

O.8.4 ***Computer mouse design and ergonomic mouse pads influence wrist angle, forearm extensor and upper trapezius muscle activity***

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BACKGROUND AND AIM: The computer mouse is used during 31 - 65% of commonly performed computer tasks and is the most widely used human interface device. Non neutral wrist position and wrist and finger extensor muscle activity are thought to contribute to the incidence of wrist and elbow pain associated with computer mouse use. Upper trapezius muscle activity is also associated with musculoskeletal disorders following computer use and can be influenced by the type of mouse used. Given that, ergonomic computer mouse configurations intend to minimise muscle activity and/or maintain neutral wrist angle. The aim of this study was to investigate the influence of 5 different mouse configurations on wrist extensor and upper trapezius muscle activity, and wrist position while performing two standardized mouse tasks. METHODS: Sixteen healthy participants performed two tasks (1) alternating single left mouse clicks between two digital targets and (2) a double left mouse click and drag of an object between 2 digital targets. Five different mouse configurations were used (a standard mouse, a standard mouse with a stationary wrist support, a stationary mouse with a gliding palm support, a vertical mouse and a touchpad). Extensor carpi ulnaris, extensor carpi radialis brevis, and extensor digitorum communis muscle activity was recorded using intramuscular electromyography (im-EMG). Upper trapezius muscle activity was recorded using surface electrodes(s-EMG). EMG data were filtered (band-pass, 4th order butterworth filter, at 20-500Hz for s-EMG, 20-1000Hz for im-EMG) then root mean square (RMS) EMG amplitude (time-constant 0.01 second) was calculated. Data were inspected for artefacts (e.g., high frequency peaks in the EMG signal that could not be accounted for by muscle activity), and 10 mouse clicks (from the middle of the task period) were used for analysis. EMG and wrist position data (±500ms for Task 1, ±1s for Task 2) were averaged around the selected mouse clicks. Muscle activity was normalised to maximal voluntary contractions. Wrist angle (flexion, extension, radial and ulnar deviation) was recorded with an electrogoniometer. RESULTS: Extensor carpi radialis brevis activity did not differ between mouse configurations or tasks ($p>0.71$). Extensor carpi ulnaris activity was greatest when using the palm support and touch pad configurations for both tasks ($p <.02$). upper trapezius activity was greater with

palm support compared to wrist configuration in the single click task ($p<0.01$). and configurations were associated less extension for both tasks (all $p<0.01$). radial deviation greatest when using vertical mouse $p<0.02$) double drag task. conclusions: no simultaneously maintained a neutral position minimized muscle activity. findings offer information that could inform selection of on case-by-case basis.

O.8.5 *Surface electromyographic inter-individual variability and pattern recognition in front crawl swimming*

Jonas Martens[1], Daniel Daly[1], Kevin Deschamps[1], Filip Staes[1], Ricardo Fernandes[2]

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BACKGROUND AND AIM: Amplitude analysis of electromyography (EMG) has been used to evaluate swimming technique but the variability of EMG recordings is a complex phenomenon rarely examined in this sport. The purposes of this study were to investigate inter-individual variability in muscle activation patterns during front crawl swimming and to explore if there were clusters of sub patterns present. METHODS: Bilateral muscle activity of rectus abdominis (RA) and deltoideus medialis (DM) was recorded using wireless surface EMG in 15 adult male competitive swimmers during three trials of 12.5 m front crawl at maximal speed without breathing. The median EMG trial of six upper limb cycles was used for the inter-individual variability assessment, quantified with the coefficient of variation, coefficient of quartile variation, variance ratio and mean deviation. Key features, i.e., sections of the EMG curve selected based on their potential to differentiate between muscle patterns and therefore to potentially classify the EMG patterns in clusters of swimmers, were selected based on qualitative and quantitative classification strategies to enter in a k-means cluster analysis. RESULTS: Inter-individual EMG variability in swimming was higher compared to what has been described for other cyclic movements, but when clustering swimmers, variability dropped in all measures with increased levels (clusters) with the exception of variance ratio for left DM (Table 1). Overall variability and variability in the clusters in RA was higher than in DM. In RA, clusters were differentiated by activity in the recovery phase and around the transition of pull to push phase. In DM, distinction was made by activity in the entry phase and during the exit and early in the recovery phase. CONCLUSIONS: Inter-individual variability in a group of highly skilled swimmers was higher compared to

other cyclic movements, which is in contrast with what has been reported in the previous 50 years of EMG research in swimming. In front crawl swimming there is not one general activation pattern for DM and RA, but several sub-patterns are present which are statistically different from each other during specific parts of the stroke cycle, mainly due to differences in amplitude. This leads to the conclusion that coaches should be very careful in using overall reference EMG information to enhance the technique of their swimmers. The present findings suggest that individual characteristics could be of more importance in determining the optimal muscle use pattern with the perspective of increasing performance on one hand or decreasing the risk of injuries on the other hand. The detection of these crucial individual characteristics could be a subject of future studies.

O.8.6 *Posture variation and maximal acceptable work pace during repetitive work*

Tessy Luger[1], Svend Erik Mathiassen[2], Tim Bosch[3], Marco Hoozemans[1], Marjolein Douwes[3], DirkJan Veeger[1], Michiel de Looze[1]

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Aim. It is generally agreed that work postures can lead to musculoskeletal disorders in the neck and shoulders. We investigated the extent to which more variation of upper arm postures in a repetitive task influences maximal acceptable work pace (MAWP), muscle activity, and perceived exertion. Methods. Thirteen healthy subjects (6F/7M; age 26 (SD 3) years) performed a repetitive pick-and-place task using their dominant hand in four one-hour conditions. In three conditions the average upper arm elevation was 30°, and the hand was moved (1) horizontally (H30), (2) diagonally with upper arm elevation between 20° and 40° (D20/40), (3) vertically with upper arm elevation between 10° and 50° (V10/50). In the fourth condition, the hand was moved horizontally at 50° average upper arm elevation angle (H50). The travelled distance of the hand was the same for all conditions. Using a psychophysical approach with imposed work paces changing every two minutes (7-13 cycles/min), we arrived at the MAWP of each participant after 50 min. Postures of the arm were recorded throughout, as well as dominant upper trapezius muscle activity. Participants reported their perceived exertion (Borg CR-10) just after each protocol. Results. Kinematic analyses showed that we successfully designed protocols (Figure) differing in posture variation but not in average upper arm elevation angle (H30,

D20/40, V10/50), and differing in average upper arm elevation angle but not in posture variation (H30, H50). MAWP was comparable in the conditions with differing posture variation (10.7 cycles/min), but lower in H50, although not significant (9.3 cycles/min). Subjects worked at MAWP with an upper trapezius activity level that did not significantly differ between experimental conditions (median 54% RVE). Dominant trapezius muscle activity at MAWP in H50 (78% RVE) was higher than in H30 (47% RVE), but not significant. Perceived exertion of the upper arm was higher in H50 (2.5) than H30 (1.5), but also not significant. Figure. Upper arm elevation average angle (left), average angle variation (SD; middle), and average upper trapezius activity (right) at MAWP. Boxplots show median values, 25th and 75th percentiles, and minimum and maximum values across subjects (n=10). Conclusion. Variation in upper arm elevation within the investigated limits did not affect MAWP although upper trapezius activity showed a tendency to increase with more variation. Increased working height tended to increase especially upper trapezius muscle activity and decrease MAWP. Thus, our results indicate that posture variation as applied in the current setting did not lead to significant differences in MAWP or muscle activity variables. More thorough workplace redesigns are apparently needed than those investigated by us to accomplish any major changes in psychophysical outcomes as measured by MAWP. Our results do show that engineers should pay attention to working height when advising companies on work pace.

O.9. EMG: novel applications

O.9.1 *Changes in the surface electromyographic signal during high intensity fatiguing dynamic exercise*

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BACKGROUND AND AIM: Techniques to quantify fatigue in surface electromyographic (sEMG) signals recorded during isometric contractions are relatively well established. However, identifying fatigue in sEMG during dynamic contractions is more challenging. This study aims to examine changes in features of

the sEMG signal recorded during fatiguing submaximal, dynamic exercise to exhaustion. METHODS: Five moderately active subjects, age 25.4±4.9 years, (1 female), participated in this study. Participants were instructed to cycle to exhaustion at a work rate of 161±17 W (approximately 70% VO2peak). Surface electromyography (EMG) was recorded from the rectus femoris, vastus medialis, vastus lateralis, semitendinosus and biceps femoris muscles of the dominant leg using wireless bipolar electrodes (Trigno Wireless System, Delsys, Boston, MA). The root mean square (RMS) amplitude and instantaneous median frequency (Fmed) of a 100ms section centered at the peak of each cycle was calculated for each muscle. The data were divided into bins each corresponding to 5% of the time to exhaustion, and a single average value of RMS amplitude and Fmed were calculated for each bin. These were then normalized with respect to the initial average value. RESULTS: The time to task failure was 4069±1535s. Fmed increased progressively during the trial in all muscles examined. The change in the EMG RMS amplitude and Fmed (averaged over the last 5% of time to exhaustion) for each muscle are presented in Table 1. CONCLUSION: The Fmed of the EMG signal increased progressively throughout the task. This is in contrast to the progressive reduction in Fmed typically observed during a fatiguing isometric contraction. This increase in Fmed may reflect changes in muscle temperature, swelling of muscle fibers, or altered excitability of the muscle fiber membrane in response to high intensity dynamic exercise.

O.9.2 *Feasibility of uterine electromyography outside pregnancy*

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BACKGROUND AND AIM: With an overall effectiveness below 30%, in vitro fertilization (IVF) is in urgent need for improvements, especially in view of the increasing trend towards postponing childbirth in developed societies. Abnormal contraction of the uterus may underlie impaired fertility and unsuccessful IVF. However, currently, there is no method for quantitative assessment of uterine activity and guidance of dedicated intervention. Analysis of the uterine electromyogram (EMG), referred to as electrohysterogram (EHG), has been extensively used in pregnancy for quantifying uterine contractions and could potentially be a valuable support during IVF treatments. In this paper, we preliminary evaluate, for the first time, the use of EHG analysis for characterizing contractions in women outside pregnancy. METHODS: The EHG signal was recorded longitudinally on 10 women with no fertility problems. The EHG was recorded by an 8x8 array of electrodes (2 mm diameter, 4 mm distance) for 4 minutes, during which 2-8 contractions could be expected to occur. On each woman, the EHG was recorded at 4 specific phases of the menstrual cycle, namely, during menstruation, before ovulation, and three and seven days afterwards. Due the hormonal changes it undergoes during the cycle, the uterine muscle is expected to show different behavior in these four phases. Comparison between the extracted feature in the different phases is here evaluated as an indirect validation of EHG analysis. We limited our focus to single channel parameters and estimated the signal energy of a bipolar derivation obtained by the combination of a couple of 2X2 adjacent electrodes selected from the grid. Based on previous studies on the EHG during pregnancy, the energy of the signal was first estimated in overlapping 8-s epochs [1]. In order to retain both frequency and amplitude information, the unnormalized first statistical moment (UFSM) was then selected as the global feature to be extracted from the estimated energy and compared among the recorded phases. A repeated one-way analysis of variance (ANOVA) was performed on this global feature in order to statistically evaluate the comparison. RESULTS: As shown in Fig.1, significantly higher values of UFSM ($p<0.05$) were found during menstruation relative to all the other three phases, when the evaluated feature shows a trend that progressively decreases (not significantly) along the menstrual cycle. CONCLUSIONS: The significant differences shown by the selected feature between the menstruation and the other evaluated phases of the cycle suggest the recorded signals to be representative of uterine activity and motivate further research on the use of the EHG outside pregnancy. Future investigations will explore additional features extracted from the EHG and aim at more direct and quantitative validation strategies. REFERENCES: [1] C. Rabotti et al. , Physiol Meas, vol. 29, no. 7, 2008, pp. 829-41.

O.9.3 *Nonlinear Analysis of Electromyography in Parkinson's Disease During Isometric Leg Extension*

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BACKGROUND AND AIM: Recent studies have employed nonlinear methods, including recurrence quantification analysis (RQA), to characterise dynamical changes of neuromuscular activity underlying motor control [4, 5]. RQA variables, percentage determinism (%DET) and recurrence rate (%REC), have revealed differences in electromyographic (EMG) signals at rest and during isometric contraction in patients with Parkinson's disease (PD) [3]. EMG in PD and healthy controls during unloaded isometric [1] and dynamic [2] contractions of the upper limb has similarly been investigated. Skewness and kurtosis have also been used to examine changes in EMG in PD [1]. The aim of this study was to compare EMG recorded in the upper leg in patients with PD and healthy age-matched controls during loaded isometric contraction. METHODS: Surface EMG was recorded from the extensor and flexor muscles of the upper leg in 15 healthy controls (65 ± 6 yrs.) and 13 PD patients (63 ± 6 yrs.) during isometric knee extension at 15% of maximum voluntary contraction. Each subject performed 4 trials, 25 s duration, against a resistive load at the ankle. A 7.5 s section of each trial was analysed in 1.5 s windows. From time-delayed phase space reconstruction of the EMG signals [7], recurrence plots were estimated to depict dynamic EMG behaviour. %REC and %DET were calculated from the recurrence plots to quantify the level of hidden nonlinear structure in the EMG. Skewness and kurtosis were also calculated to determine the degree of symmetry and "peakedness" about the mean of the probability distribution, respectively. RESULTS: %REC and %DET in the rectus femoris EMG were significantly increased in PD patients, for both left and right legs (%DET: $p < 0.01$; %REC: $p < 0.01$). Kurtosis was also significantly greater in parkinsonian EMG ($p = 0.046$), whereas skewness was not significantly different between groups ($p = 0.076$). CONCLUSIONS: The increased %REC & %DET in EMG of PD patients represents a greater level of structure in the underlying dynamics of the EMG signal [1, 3-5]. %DET indicates repeated hidden patterns over short periods of time. This may be due to increased synchronization of motoneurons, though may also be influenced by other parameters including muscle fibre conduction velocity [3, 4]. Increased kurtosis of PD EMG denotes a greater sparseness of the signal, suggesting periodic behaviour, also consistent with greater synchronization. These parameters which are more pronounced in PD EMG could potentially be employed as biomarkers to aid early diagnosis or monitoring of patient symptoms. REFERENCES: [1] A. I. Meigal et al., J Electromyogr Kinesiol, 19,

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O.9.4 *Chronic EMG activity reveals early changes in muscle activation in treadmill running SOD1 mice*

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Background and Aim: To improve early diagnosis of amyotrophic lateral sclerosis (ALS), a progressive neurodegenerative disease, we measured EMG activity in hindlimb muscles of SOD1G93A mice. Methods: In contrast to clinical diagnostic measures using EMG, which are performed on quiescent patients, we monitored activity during treadmill running in order to detect presymptomatic changes in motor patterning. Chronic electromyogram (EMG) electrodes were implanted into vastus lateralis (VL), biceps femoris posterior (BFP), lateral gastrocnemius (LG), and tibialis anterior (TA) in mice from postnatal day (P) 55-100, and results were assessed using linear mixed models. Results: Significant effects of SOD1G93A are mainly observed in three parameters: burst amplitude, intermuscular phase, and burst shape (skew). Burst amplitude in BFP is significantly larger in G93A mice, while amplitude in TA and LG increased as in interaction with treadmill incline (TA and LG), and age (LG) in G93A mice. In other words, effects of SOD1G93A on amplitude were significant only when mice ran on an incline, or as they aged. Phase and skew are related parameters that indicate changes in the relative timing of muscle activation during locomotion. In G93A mice, BFP and LG are significantly phase advanced and skew shifts earlier in the burst, while both parameters shift in VL in combination with treadmill incline. Conclusions: These novel results indicate locomotor EMG activity could be used as an early diagnostic tool, and suggest underlying mechanistic changes in the neural control of muscles during disease progression.

O.9.5 *The gluteus medius, gluteus minimus and tensor fascia latae are more active during gait in post-menopausal women with greater trochanteric pain syndrome*

Charlotte Ganderton[1], Tania Pizzari[1], Adam Semciw[2]

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BACKGROUND AND AIM: Greater trochanteric pain syndrome (GTPS) is a degenerative condition of the gluteus medius (GMed) and minimus (GMin) tendons and the trochanteric bursa that causes debilitating pain over the lateral aspect of the hip and most commonly affects post-menopausal women. Rehabilitation of this condition focusses on strengthening the lateral hip stabilisers (the GMed and GMin), however little is known about the function of these muscle in this population. The aim of this study was therefore to quantify and compare segmental muscle activation of the GMed, GMin and tensor fascia latae (TFL) during gait in post-menopausal women with and without GTPS. METHODS: Bipolar fine wire electrodes were inserted under ultrasound guidance into anterior, middle and posterior GMed and the anterior and posterior segments of GMin in 8 post-menopausal women with GTPS (mean age 58.9, SD 3.3) and 10 female controls (mean age 60.2, SD 2.6). A surface electrode was placed onto TFL and footswitches were positioned bilaterally. A series of 6 walking trials was completed at a self-selected speed in addition to maximum voluntary isometric contraction exercises. All electromyography (EMG) signals were received by a Delsys Trigno Wireless system, sampled at 2000Hz and were processed by high pass filtering, full wave rectification, and further low pass filtering to generate liner envelopes. For each muscle segment, the peak amplitude, average amplitude, and time to peak from each phase of the gait cycle (0-30%, 30%-toe off, total stance and swing) were obtained and compared between groups using independent t-tests and effect size (ES) calculations. RESULTS: Greater average muscle activity in all gluteal muscle segments in participants with GTPS was demonstrated and this was significant at some, but not all, phases of the gait cycle. Peak amplitude and temporal results were less consistent in the gluteal segments. TFL demonstrated significantly higher average (ES=0.84) and peak amplitude (ES=2.23) in the GTPS group only in the swing phase of gait. The EMG burst pattern of anterior GMin in participants with GTPS was reversed when compared to controls; with a larger burst of GTPS anterior GMin activity in early stance and a moderate to large (ES=0.76) difference in average amplitude in the first burst (Fig 1). CONCLUSION: The higher levels of gluteal and TFL muscle activation in response to unilateral loading in GTPS might demonstrate an inability to modulate corticospinal pathway excitability and appropriately grade muscle activity in response to task demands. Recognised in other chronic tendon complaints, this corticospinal driver may contribute to the

recalcitrant nature of this condition. The reversal of GMin burst activity; with a larger first burst and smaller second burst may impact the functioning of this segment as an anterior hip joint stabiliser in terminal extension. The findings of this study may assist with revising rehabilitation protocols for GTPS.

O.9.6 *Quadratus femoris is minimally active in common rehabilitation exercises*

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BACKGROUND AND AIM: Quadratus femoris (QF) is considered one of the most important muscles for hip joint stability. It is morphologically suited to draw the head of the femur into the acetabulum, facilitating hip stability. Dysfunction of this muscle has been associated with a range of hip and lower limb conditions including femoroacetabular impingement, patellofemoral pain syndrome and hamstring associated disorders. Despite its theoretical importance, most of what we know about the function of this muscle is based on cadaveric studies, radiographical imaging and biomechanical modelling. It is difficult then, to prescribe with confidence an exercise program for targeted QF rehabilitation. The aim of this study was therefore to evaluate the activity levels of QF across a range of commonly prescribed lower limb rehabilitation exercises. METHODS: Ten healthy young adults (mean age (range) = 23.8 (22-26) years; females=4) who were active in at least two hours of running related sports per week volunteered for this cross-sectional study. Fine-wire EMG electrodes were inserted into the QF (stance limb) under ultrasound guidance. Retro-reflective markers were secured to pelvic landmarks for the purpose of delineating between exercise phases and repetitions through three dimensional motion capture. Participants performed six repetitions of six exercises (clam, hip abduction, 'running man', single leg squat, single leg bridge, resisted abduction/ external rotation). This was repeated for three sets and the order of testing was randomly assigned. The average EMG activity for each exercise was normalized to percent of maximum voluntary isometric contraction (MVIC) and classified according to previously defined criteria; low (0-20% MVIC), moderate (21-40% MVIC), high (41-60% MVIC) and very high (>60% MVIC). Activity was compared between exercises using a non-parametric repeated measures Friedman's test (α=0.05) and post-hoc

comparisons performed with Wilcoxon signed rank tests ($\alpha=0.05$). To estimate the magnitude of difference in muscle activity between exercises, an effect size was calculated (ES = z-score / √ sample size), where 0.2, 0.5 and 0.8 were considered small, medium and large, respectively. RESULTS: Median activity of all exercises was rated as low, except for clam (moderate, 24% MVIC) (Fig 1). Mean activity was significantly different between exercises ($p=0.05$). Significant differences existed between the following pairs; clam > running man (ES=0.89), clam > abduction (ES=0.77), bridge > abduction (0.74). CONCLUSION: This is the first study to evaluate QF activity in common rehabilitation exercises. The minimal to moderate activity in these exercises is unlikely to provide sufficient stimulus for targeted QF hypertrophy, but could perhaps support use in early endurance or neuromuscular control training

O.10. Sensorimotor control and learning

O.10.1 *Locomotor Adaptation to Stable and Unstable Environments*

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BACKGROUND AND AIM: People use a combination of general and specific strategies to create stable walking. General stabilization strategies (e.g. wide steps) address uncertainty by reducing the nervous system's requirements to appropriately respond to destabilizing perturbations. However, because general strategies are present every step, they inherently limit gait speed and decrease energetic efficiency. In contrast, specific stabilization strategies (e.g. corrective steps) require greater levels of sensorimotor coordination but do not incur the same performance penalties as general strategies. Our purpose was to characterize how individuals adapted stabilization strategies based on environmental uncertainty and available sensorimotor resources. We hypothesized that people would decrease reliance on general strategies when walking in a stable environment, and, increase reliance on general strategies when walking in an unstable environment. METHODS: 8 incomplete spinal cord injury (iSCI) and 10 control subjects performed treadmill walking during three conditions in which external lateral forces were applied to the pelvis. The conditions were: Null: no forces applied Stabilization: a viscous force field resisted lateral center of mass velocity Destabilization: random impulse perturbations During each condition subjects performed 100 baseline steps, 200 steps in one of the force field conditions and then, all applied forces were abruptly removed and subjects performed 100 more steps to measure any after-effects. RESULTS: Both groups decreased step width and lateral center of mass velocity in the Stabilization field ($p<0.05$). When the Stabilization field was removed, the iSCI group demonstrated large and variable mediolateral movements. Both groups decreased step width ($p<0.05$) during the after-effects period. The average time for step width to return to steady state during the after-effects period was 13 steps, which did not differ between groups ($p>0.05$). Both groups decreased lateral center of mass velocity in the Destabilization field ($p<0.05$). The iSCI group took shorter steps ($p<0.05$) and had a larger lateral margin of stability ($p<0.05$) in the Destabilization field. When the Destabilization field was removed, there were no differences in step width, or lateral margin of stability for either group ($p>0.05$). CONCLUSIONS: Subjects reduced their reliance on general strategies when walking in the Stabilization field. This adaptation persisted when the Stabilization field was removed, resulting in a temporary decrease in lateral stability. In contrast, subjects increased their reliance on general strategies when walking in the Destabilizing field. Potentially, external stabilization could be used in gait training to prime the motor system for learning specific stabilization strategies by decreasing an individual's reliance on general strategies. Supported by the Department of Veterans Affairs, CDA2 #1 IK2 RX000717-01.

O.10.2 ***Hybrid Robotic System for Reaching Rehabilitation after Stroke***

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Aim: To validate the feedback error learning algorithm implementation to adjust the functional electrical stimulation (FES) intensity when it is combined with a passive upper limb exoskeleton to rehabilitate reaching movements in stroke. Method: One female chronic stroke patient with a hemorrhagic stroke (37 years old, right-handed, 13 months of evolution post-injury) participated in two experimental sessions. The subject was donned with a passive upper limb exoskeleton (to compensate the arm?s weight against gravity) and with two FES electrodes placed over the anterior deltoid and triceps muscles (to assist the shoulder flexion and elbow extension movements respectively). The experiment consisted in performing reaching movements with the affected arm following a reference presented on a screen in front of the patient. In session 1, patients performed 6 runs consisting of 8 movements each plus an additional run of three movements without FES assistance. In session 2, 8 runs plus an additional unassisted run were carried out. The reference trajectory was generated using the minimum jerk trajectory function. The arm position was estimated using the information of the resolvers embedded in the exoskeleton. We implemented two independent controllers (assuming that the movement of the forearm and upper arm were independent of each other). These controllers modulated the pulse width of the electrical stimuli, which in turn adjusted the delivered assistance. The implemented FEL controller was composed of a PID controller with an integral anti-windup strategy as feedback controller. The feedforward loop relied on a neural network (NN) learning the inverse dynamic of the system. Results: Fig 1 shows the summary of the results obtained. The two figures on the left depict the average RMS error for each run during day 1 (blue) and day 2 (red) for the shoulder (column 1) and elbow (column 2), respectively. The best-fitting linear regression line was calculated considering both the error of day 1 and day 2, which results in a slope of -0.491 (shoulder) and -0.715 (elbow). This negative slope is associated with the decreasing trend of the error as more task repetitions are performed (thus reflecting the learning of the controller). The figures on the right show the differences between completed movements with and without FES assistance. It can be observed the inability of the user to follow the reference without FES assistance (red line). Conclusion: The system is capable of learning the inverse dynamics of the controlled system and, using this information, it can reduce the error trajectory as the patient repeatedly rehearses the movement during the rehabilitation. The system assists in such way that it only provides the required assistance to allow the patient to complete successfully the task. Furthermore, its learning capability allows the system to compensate the variability of musculoskeletal responses to FES across time. Future work will test the effectiveness of the system as a rehabilitation tool. Figure 1. (Left): averaged RMS error for each run during day 1 -blue- and 2 -red-. The black line represents the

trend of the error. (Right): movements performed in session 2 with and without FES assistance compared to the reference trajectory.

O.10.3 *Size of kinematic error affects retention of locomotor adaptation in children with cerebral palsy*

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Rongnian Tang1,2,3, Janis Kim2, Deborah J. Gaebler-Spira2, Ming Wu2,3 1 Mechanical and Electrical Engineering College, Hainan University, Haikou, P.R. China 2 Sensory Motro Performance Program, Rehabilitation Institute of Chicago, Chicago, USA 3 Department of PM&R, Northwestern University Medical School, Chicago, USA Introduction: Gait impairment is the one of the most common abnormality in children with Cerebral Palsy (CP), and limited walking ability causes negative effect on their daily life [1]. Previous studies indicated error augmentation induced by force perturbation might accelerate motor learning during locomotor training [2]. However, it remains uncertain whether the size of error and the variability of error have an impact on the retention of locomotor adaptation. We hypothesized that the size of error but not the enhanced variability of error would have impact on the retention of locomotor adaptation in children with CP. Methods: Eleven children with CP aged 8-16 years old, were recruited to participate in this study. Three types of force perturbations (i.e., abrupt, gradual and noisy loads) were applied to the right leg above ankle starting from late stance to mid-swing in three test sessions while subject walked on a treadmill. Leg kinematics and EMG signals from 8 leg muscles were recorded using a customized 3D position sensor and surface electrodes, respectively, during treadmill walking [3]. Results: We observed that children with CP adapted to force perturbation and showed an aftereffect consisting of increased stride length after load release for the conditions with abrupt and gradual loads. Further, we observed a longer retention of aftereffect for the condition with gradual load than that with abrupt load. We observed no aftereffect for the condition with noisy load. Conclusion: Results from this study suggested that the size of error might have impact on the retention of locomotor adaptation of children with CP with longer retention for the condition with small size of error than that with large error. In addition, increased variability of error had a detrimental effect on locomotor adaptation. This finding suggests that applying a gradual perturbation load during locomotor training may facilitate retention of locomotor adaptation in children with CP. [1] Rosenbaum P., et al., Developmental Medicine and Child Neurology Supplement, 109: 8?14,2007 [2] Amy J. Bastian, et al., J Neurophysiology, 103: 2275-2284, 2010 [3] Wu M. et al., Experimental Brain Research, 216: 473-482, 2012

O.10.4 ***Motor learning with pain results in long-lasting changes in motor strategies***

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BACKGROUND AND AIM: Although sports and rehabilitation programs often involve training in the presence of pain, the effect of pain on motor learning and retention remains unclear. Studies in rats suggest that pain causes learning deficits lasting longer than the duration of nociceptive input, but human studies report conflicting results. The aim of this study was to assess how experimentally induced muscle pain affects motor performance and muscle activation strategies in humans when learning an arm-reaching task in a novel force field environment. METHODS: Eleven participants performed forward reaching movements with the dominant arm using a robotic handle. Participants could not see their moving arm; instead, a mirrored LCD screen provided real-time feedback of hand position. One hundred movements were performed in each of six conditions: Baseline 1, Baseline 2, Force Field 1, Washout 1, Force Field 2, Washout 2. During ?Force Field? trials, the robot applied a velocity-dependent force to the hand, perpendicular to movement direction. Muscle pain was induced in the anterior deltoid muscle of six people immediately before both Baseline 2 and Force Field 1 by injection of hypertonic saline (HYP), whereas isotonic saline (ISO) was used as a pain-free control for five people. Task performance was assessed by the mean orthogonal force applied against the walls of a force channel in force field trials, and by the mean orthogonal position error. EMG was recorded from biceps (BB) and triceps brachii (TRB), anterior (aDEL) and posterior deltoid (pDEL) with surface electrodes, and the EMG envelope was averaged across movement duration. RESULTS: Task performance was similar between groups across all conditions and epochs (no significant main effect or interactions with Group, all $p > 0.1$). However, several group differences were found in EMG amplitude (Group*Condition interactions, all muscles $p < 0.05$). Following the first injection

(Baseline 2), aDEL EMG was lower in the HYP than ISO groups ($p = 0.001$). After the second injection (Force Field 1, Washout 1), EMG was lower for all muscles in the HYP than ISO groups (all $p < 0.05$). EMG remained lower after pain had dissipated (Force Field 2, Washout 2, all $p < 0.001$), except for BB EMG ($p > 0.07$). CONCLUSIONS: Despite pain related to injection of HYP into aDEL, participants in both groups achieved a similar performance during perturbed arm reaching movements, suggesting that pain does not prevent the acquisition of a new motor task. However, the muscle activation strategy adopted by the HYP group to complete the task involved reduced activity of agonist and antagonist muscles, which might reflect an attempt to reduce the stress in the painful area. Remarkably, a similar strategy was used during re-exposure to the same perturbation in the absence of pain. Reduced EMG potentially provides short-term benefits (e.g. decreased muscle stress), but also long-term consequences (e.g. reduced joint stability).

O.10.5 *Neck pain: Do head movement qualities change during an intensive treatment period?*

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Background: Musculoskeletal pain is one of the most common reasons to seek contact with the health service world wide. It causes great pain and reduced function for the individual and great coasts for society. Neck pain is one of the most common musculoskeletal pain sites. Altered movement qualities such as range of motion (ROM), speed and smoothness is associated with neck pain. However, it is unknown how these dysfunctions changes with treatment and whether these functional properties change in parallel with the self-reported pain and neck function. Methods: 13 persons (11 females/ 2 male) with persistent neck pain aged 43.6 years (SD 9.0yrs) were included in a multi-disciplinary rehabilitation programme for 7-11 weeks. Patient reported data and movement qualities during voluntary head movements were collected at inclusion and end of the period. ROM, speed and smoothness were measured during movement in the horizontal and the vertical plane based on position data from six motion sensors attached to the head and trunc (Liberty, Polhemus Inc). The persons were instructed to first use their preferred pace, therafter a slow and maximum pace. Results: At inclusion, the NDI ranged from 18 to 66 %, and average pain last week from 1 to 8 (NRS 0 - 10). The group had a NDI score of 36.3% and average neck pain last week 4.6 (SD 2.4). ROM, average movement speed and smoothness increased through the rehabilitation period both for rotation and flexion. The increases were significant for the preferred and slow pace in both directions for ROM, speed and smoothness (exept slow pace flexion). The reduced smoothness is most likely linked to the increased speed. Conclusion: These preliminary results suggest that although no specific attention was directed towards movement qualities in the rehabilitation programme, the patients improved in these variables. They choosed to move at a faster self preferred speed after the treatment period. This will be explored further.

O.10.6 *Multichannel SEMG activity and force variability during isometric contractions at low level forces in diabetic individuals*

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BACKGROUND AND AIM: The aim of this study was to investigate if diabetic neuropathy progression resulted in changes on (i) lower leg muscular activity and (ii) force variability during low level isometric contractions. METHODS: Ten control subjects (49.4±9.6yrs) and 39 diabetic patients (59.4±5.0yrs; 13.7±10.1yrs of diabetes diagnosis; 209.7±88.2mg/dL blood glucose) participated. The participants were assessed for (i) vibratory perception (128Hz turning fork), (ii) tactile sensitivity (10g Semmes-Weinstein monofilament) and (iii) presence of typical neuropathy symptoms. These three groups of variables were used as linguistic inputs in a fuzzy system to classify the neuropathy degree (score 0-10). Multichannel Surface EMG (64 electrodes matrix: 15x4, OT Bioelettronica) was acquired during 10, 20 and 30% of maximum isometric voluntary contractions (MVC) of tibialis anterior (TA) and gastrocnemius medialis (GM). TA was evaluated during dorsiflexion and GM during plantar flexion, both performed with knee in full extension and ankle in neutral position. Contractions were performed for 10s and the central 5s (2.5-7.5s) were analyzed. Force levels were measured by means of strain gauges mounted on an ankle ergometer. The 2D maps of RMS were obtained from the SEMG recordings.

RMS values were normalized with respect to the mean RMS obtained over 0.5s epoch during MVC tests. After normalization, the mean RMS and maximum RMS values were obtained from each SEMG map. Standard deviation (SD) and sample entropy (SaEn) were calculated from force signals to assess mean force, as well as the amount and structure of variability. Correlation analyses were performed to investigate the association between RMS (mean, max) or force variables (SD and SaEn) and neuropathy degree ($p<0.05$). RESULTS: There was no correlation between any of the RMS variables and the neuropathy degree suggesting that there are no changes in the level of muscle activation during low level contractions due to the disease status. During 30%MVC plantar flexion, there was a trend for a higher force variability with the progression of neuropathy (SD: $p=0.053$, $r=0.285$) while force SaEn diminished with neuropathy degree ($p=0.013$, $r=-0.359$). During dorsiflexion at 10%MVC force, variability increased with neuropathy progression (SD: $p<0.01$, $r=0.389$) and SaEn tended to diminish ($p=0.082$, $r=-0.257$). We also found a tendency towards higher variability with neuropathy progression when subjects performed dorsiflexion at 20%MVC (SD: $p=0.083$, $r=0.256$). CONCLUSION: Although no differences were observed in the RMS, the observed changes in the amount and structure of the force variability suggest that the neuropathy progression affects motor control, especially for dorsiflexion, that is mainly controlled by TA muscle, and during lower level forces, indicating that a different muscle pattern of activation might be present.
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O.11. Novel measurement techniques

O.11.1 *High density multi-channel needle electromyography: towards electrical cross-sectional imaging of human skeletal muscle*

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Background and Aim: The distribution of muscle fibres is altered in various neuromuscular diseases. Electromyographers attempt to infer this 2-dimensional fibre distribution from the motor unit potential (MUP), a 1-dimensional voltage versus time signal recorded from a single recording surface at the tip of the needle [1]. This is highly subjective, and diagnostic accuracy is relatively poor [2]. Alternative techniques, eg scanning EMG can provide greater detail but are extremely time consuming to perform. We aimed to develop a clinically-applicable EMG system capable of rapidly determining muscle fibre localisation. Methods: We describe a novel electromyography system comprising a micro-fabricated parylene-C flexible electrode incorporating 64 recording surfaces each of 25µm diameter. These are arranged in two linear arrays, with an electrode spacing of 400µm but offset by 200µm to produce a zig-zag pattern. The electrode is 400µm wide and 20 µm thick allowing it to be bonded to a conventional 30G EMG needle for human recordings. To decompose the data into the constituent MUPs, we designed an iterative algorithm: the channels are first sorted based on their signal to noise ratio. The data from the channel with the highest SNR are clustered (using principal component analysis and Gaussian Mixture Model) and the MUP with highest amplitude is selected and subtracted from the rest of the channels. This process is repeated until no more MUPs are detected. The identified MUPs are then averaged and independent component analysis is used to decompose the MUP into fibre potentials. A Support Vector Machine classifier (trained on simulated data) is then employed to filter the ICA results and return the most likely number of fibres and their mixing coefficients. The mixing coefficients are then used to localize the fibres by fitting an approximated model of the fibre potential. Results: From a single needle insertion, we were able to characterise up to 8 motor unit cross-sections from normal human tibialis anterior and biceps brachii muscles from 30 second recording epochs. These motor unit cross sections showed median firing frequencies of 5.5 to 8.8s-1, and durations of 5.4 to 12.7ms. The length of the motor unit cross sections varied between 1.0 and 6.4mm. Our fibre localisation algorithm allowed the localization of individual muscle fibres within these motor units with a distance error of less than 200µm on simulated data. Conclusion: Our system allows the simultaneous recording of multiple motor unit electrical cross-sections from a single needle location. The ability to localise individual muscle fibres within these motor units promises a major

step forward in clinical EMG diagnosis. [1] Whittaker RG, Practical Neurology 2012;12:187?194. [2] Dardiotis E, et al. Acta Myol. 2011 Jun;30(1):37-41.

O.11.2 ***Spatiotemporal muscle activation of a sustained contraction until task failure assessed with nonnegative matrix factorization***

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Introduction: Changes in the spatial distribution of muscle activity have been observed during fatiguing contractions [1]. The procedure often involves averaging amplitudes over time and thus discarding temporal information. An alternative method is to apply k-means clustering to both temporal and spatial information [2]. However, this clustering approach requires a priori knowledge of the number of clusters present. To avoid this requirement we here explored the utility of nonnegative matrix factorization (NMF) in the quantification of spatiotemporal heterogeneity of muscle activation during a contraction sustained to task failure. Methods: Surface EMG signals (49±8 electrodes covering the entire biceps brachii) were recorded in 8 subjects during a sustained elbow flexion at 30% maximal voluntary contraction (MVC) force until task failure. The monopolar EMGs were spatially filtered with principal component analysis [3], rectified, smoothed, and normalized to obtain EMG envelopes over three 10 s time windows (Figure 1). The mean and variability of force and mean EMG envelopes were assessed. NMF [cf. 4] was used to generate a value that described spatiotemporal heterogeneity of the EMG envelopes by the amount of explained variance (VAF). VAF was also assessed for detrended EMG envelopes in order to determine the influence of the monotonic increase (linear fit in %MVC/s) within each time window on the NMF outcome. Results: Subjects sustained an elbow flexion force of 94±12 N for 5.6±2.4 min. There was a significant increase in force variability (2-5 N, $p<0.001$) and EMG amplitude (16-45%MVC, $p<0.001$). The VAF of the original EMG envelopes did not change during the fatiguing contraction (~54%, $p=0.197$), whereas VAF increased over the three time windows (35-48-59%, $p=0.002$) for the detrended EMGs. The increase in EMG activity within each time window showed an overall positive trend

0.33±0.65%MVC/s with no significant effect due to time ($p=0.32$). In contrast, the variability of the increase in EMG activity significantly increased across the three time windows (0.14-0.26-0.59% MVC/s, $p<0.001$). Conclusion: NMF can quantify spatiotemporal muscle activity and does not depend on a priori knowledge of spatial characteristics (e.g., number of spatial clusters). The VAF was sensitive to the monotonic increase in muscle activity, as indicated by an increase in homogeneity for the detrended EMG envelopes. The increase in force variability during the sustained contraction was accompanied by an increase in muscle activity [cf. 5] and appears also to involve a rise in the variability of the monotonic increase between channels over the muscle with fatigue. [1] Farina et al., J Electromyogr Kinesiol, 18: 16-25, 2008 [2] Staudenmann et al., J Neurophysiol, 11: 984-990, 2014 [3] Staudenmann et al., IEEE Trans Biomed Eng, 53: 712-719, 2006 [4] Lee et al., Nature, 401: 788-791, 1999 [5] Enoka RM, J Biomech, 45: 427-433, 2012

O.11.3 *Monitoring changes in motor unit behavior following short-term high intensity interval training with high-density surface electromyography motor unit tracking*

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BACKGROUND AND AIM: High intensity interval training (HIT) has been widely used to improve fitness and aerobic capacity. Although many studies have evaluated the short term metabolic and cardiopulmonary benefits of HIT, there are no studies investigating changes in neuromuscular function. We aimed to study the behavior of motor units (MU) after HIT. In particular, we evaluated the feasibility of using MU decomposition from high-density surface electromyography (EMG) recordings and tracking the decomposed MUs using cross-correlation of MU action potentials (MUAPs). METHODS: Six healthy men (29 ± 3 yr; 178 ± 7 cm; 80 ± 7 kg) performed six HIT training sessions over two weeks. Each session consisted of 8-12 x 60 s

intervals at 100% peak power output (352± 55 W), separated by 75 s of recovery. Pre and post intervention, participants were asked to perform maximal (MVC) as well as submaximal (10, 30, 50 and 70% of MVC) isometric knee extensions. EMG was recorded from the vastus lateralis (VL) and medialis (VM) muscles using grids of 64 electrodes. EMG data from the submaximal contractions were decomposed to obtain the firings of individual MUs using the convolution kernel compensation algorithm. Finally, and in order to track the different MUs, identified firings were used to trigger surface EMG signals by creating a MUAP profile for each MU which was then matched by cross correlation (CC). MUs that presented a CC > 80% were considered to be the same unit. Functional parameters such as peak torque (Nm), rate of force development (RFD), time-to-task failure as well as EMG amplitude (average rectified value; ARV) and individual MU characteristics (average and peak discharge rate and MU conduction velocity) were compared pre and post intervention by paired t-tests (α=0.05). RESULTS: Peak torque significantly increased after the intervention by 7% (217.8 ± 57.7 to 233.9 ± 49.4 Nm, p=0.02).This was accompanied by a significant increase in ARV at all submaximal contraction levels and at MVC, for both muscles (p<0.05).No changes in RFD and time-to task failure were observed (p>0.05). From VM and VL a total of 94 and 84 MUs were identified respectively. On average, 46.8% and 42.9% of the MUs identified by decomposition could be tracked pre to post intervention, for the VM and VL, respectively (average CC= 84.7± 0.7%). MU conduction velocity significantly increased for both muscles at all submaximal force levels, while the average and peak MU discharge rate significantly increased at 30, 50 and 70% MVC (p<0.01) for both muscles. CONCLUSIONS: Two weeks of HIT produced a significant increase in strength and changes in MU behavior. In particular, increased muscle activation as well as increased MU discharge rate were observed. Interestingly, these changes were greater among higher threshold MUs, which could be due to the higher loads used for HIT. The present study is the first to succesfully track MUs after a training intervention.

O.11.4 *Neuromuscular control adaptations in strength trained athletes: a high-density EMG study*

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BACKGROUND AND AIM:Whilst early neuromuscular changes elicited by strength training protocols in unaccustomed subjects have been extensively studied, little is known about the long-term effects in chronic strength trained athletes. The aim of the study was to test the hypothesis that chronic strength training results in specific changes in motor unit recruitment strategies. METHODS: Nine strength trained athletes (CST, age 23 ± 2 years, height 181 ± 9 cm, weight 86 ± 7 kg, mean ± SD) and eight moderately active controls (CO, age 23 ± 2 years, height 177 ± 3 cm, weight 70 ± 6 kg, mean ± SD) were enrolled in the study. Subjects were asked to follow a trapezoidal ramp trajectory by isometrically activating the elbow flexor muscles. Trajectories consisted of three different segments: 1) force-up phase from 0% to 70% MVC; 2) steady state phase at 70% MVC lasting 10 s; 3) force-down phase from 70% to 0% MVC. Rate of force increase/decrease was set at 5%MVC s-1, 10% MVC s-1 and 20% MVC s-1. Order of ramps was randomized and a convenient recovery time between attempts was allowed. High-density surface electromyography (HDsEMG, 128 electrodes) was recorded from Biceps Brachii muscle of the dominant arm. Global HDsEMG variables in both time and frequency domain (muscle fibre conduction velocity, MFCV, median frequency, MDF, and root mean square, RMS) were computed. Global MFCV, MDF and RMS were normalised for their maximum value at MVC. Area under the curve (AUC) from the MFCV, MDF and RMS values was calculated during each phase. RESULTS: Maximal isometric torque was significantly different (CST vs CO: 103 ± 17 vs. 62 ± 7 N*m; $p < 0.001$, mean ± SD), MFCV at MVC was higher for the CST cohort (4.82 ± 0.17 vs. 4.54 ± 0.28 ms-1, $p < 0.05$, mean ± SD). In Figure 1 data for 5%MVC s-1 ramp are reported. Both absolute and normalised MFCV (AUC values) for the ST cohort were higher during all the ramp contractions and ramp phases ($P < 0.001$). Normalised MDF (AUC) and RMS (AUC) were not significantly different during any ramp contraction ($P > 0.05$). CONCLUSIONS: Chronic strength training might elicit specific adaptations at the motor unit recruitment strategies. The ramp up-phases during the fastest and the slowest ramp contractions showed an increase in the range of motor unit recruitment for the CST subjects (i.e. higher upper limit of motor unit recruitment). However, the general control scheme is preserved.

O.11.5 ***Assessing somatosensory evoked potentials using high density surface electromyography grids***

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Aim. Somatosensory evoked potentials (SSEPs) have been recorded for the interest of evaluating spinal conduction during maturation[1], monitoring spinal cord function during spinal surgery for scoliosis[2], and identifying SSEP components in the upper limb[3]. Previous research involved invasive peripheral nerve recordings via needles, invasive oesophageal probes inserted through nostrils, and non-invasive spinal recording overlying spinous processes from L5 to C6^{4,5,6}. We aim to detect neuronal activity at spinous processes L4 and L5 with high-density surface electromyography (HD-sEMG) grids after electrostimulation of the N. Tibialis Posterior. Methods. Ten subjects (6F/4M) participated in the study. Subjects were lying in a prone position while being stimulated at the N. Tibialis just posteriorly of the Lateral Maleolus via two large square electrode pads (Dura Stick). A pseudorandomised protocol of 1,000 stimulations (0.2 µs duration; 3 Hz frequency) was applied on both the left and right side and repeated two times. Two HD-sEMG grids (8×8 electrodes with 4.0 mm inter-electrode distance) were attached laterally from spinous processes L4 and L5, bipolar EMG at the sternum (ECG response). A common ground electrode was placed on the Lateral Condylus of the recording site. All signals were sampled at a rate of 2,048 Hz along with the digitally converted pseudorandomised stimulations. We high-pass filtered signals offline (10 Hz, 2nd order Butterworth) and removed ECG artefacts using principal component analysis⁷. Epochs were temporally aligned and averaged to obtain SSEPs at each of the 128 recording sites. Results. The Figure displays the results of a typical subject, 128 temporally aligned SSEPs of both the left and right side. Signals are displayed from 6ms onwards, due to a delayed response at the spinal cord level. Regions particularly activated are both upper lateral sides, so mainly spinous process L4. The visible SSEPs are a summation of afferent neuron activity, not distinguishable into different afferent nerve fibres with the current equipment. Figure. Bilateral SSEPs recorded with HD-sEMG at vertebrae L4 and L5; arrows indicate positive (P) and negative (N) electrophysiological components (ms) of the nervous activity travelling wave. Conclusion. Our data show that HD-sEMG equipment may serve to reliably detect motor neuron activity at spinous processes L4 and L5. The signal-to-noise ratio appears sufficient but a higher sampling rate is needed to distinguish different

afferent neuron types contributing to the response signals. We consider HD-sEMG promising for future (clinical) research as a non-invasive method for detailed localisation of afferent nervous activity at the spinal cord level from peripheral electrical stimulation. References. 1 Cracco et al. 1979; 2 Macon and Poletti 1982; 3Rossini et al. 1981; 4 Desmedt and Cheron 1980; 5 Desmedt and Cheron 1981; 6 Desmedt and Cheron 1983; 7 Willigenburg et al. 2012.

O.11.6 *Design of New Multi-channel Electrodes for the Collection of Surface Electromyography Monopolar Signals for the Software Generation Signals for Linear Array and Laplacian Configurations for Digital Signal Processing*

Jeff Kilby[1], Krishnamachar Prasad[1], Grant Mawston[1]

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The aim of this research was to design and build a new multi-channel electrode, which is able to obtain more in quantity and refined data from muscle signals. The acquisition of surface electromyography signals from a selected muscle was to be executed using this multi-channel electrode. The first part of this research covered the design aspects that are required to be considered when developing a new multi-channel electrode. The new multi-channel electrode has eleven pins to collect monopolar signals, which are separately configured in a software that represent linear array and Laplacian configuration. The design specification of the new pre-amplifier ideally was to have a gain of 500 and a band-pass filter between 5 Hz and 1 kHz. The final design of the pre-amplifier circuit uses an INA 118 instrumentation amplifier which was built and tested to give values for gain of 501 with a band-pass filter of 6.8 Hz and 1.02 kHz. The new electrode with the pre-amplifiers was built and used for acquiring monopolar signals vastus lateralis muscle of the legs quadriceps from ten healthy participants. The participants performed a 50 % maximum voluntary isometric contraction until complete fatigue of the muscle. Using the five central monopolar signals, a linear array configuration was generated in the software to give either four single differential or three double differential signals. A three-channel Laplacian configuration was generated using all of the eleven monopolar signals. These new signals generated from both configurations were used for extracting features using signal processing techniques. The signal processing technique used was an overlapping window technique that extracts the features of mean frequency

(MNF) and median frequency (MDF) for each window of the Fourier transform power spectrum. Other features extracted for each window were the root mean square (RMS) values of the signal and the muscle fibre conduction velocity (MFCV). The configuration which gave more useful and refined results was the Laplacian rather than linear array. The results of the Laplacian configuration showed that the MNF, MDF and MFCV showed similar trend lines, where they remained at steady values between 20-30% and 70-80% of the signals analysed, after which they fell to 15-30% of this value. The RMS trend line showed a linear increase in value throughout the signal.

O.12. Motor Units II

O.12.1 *Comparison of Five Methods for Estimating Motor Unit Firing Rates from Firing Times*

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BACKGROUND: The central nervous system (CNS) regulates recruitment and firing times of motor units to modulate muscle tension. Understanding firing rate modulation provides insight into the CNS, in both health and disease. Estimation of the firing rate time series is typically performed by decomposing the electromyogram (EMG) signal into its constituent firing times, then lowpass filtering the constituent train of impulses defined by the firing times. Little prior work has quantitatively examined the performance of different estimation methods, particularly in the inevitable presence of decomposition errors. The study of electroneurogram (ENG) and electrocardiogram (ECG) firing rate presents a similar problem, and has applied novel simulation models and firing rate estimation techniques. METHODS: We adapted an ENG/ECG simulation model to generate realistic EMG firing times derived from known rates, and then assessed various firing rate estimation methods. Five different rate estimators were studied: the instantaneous rate, Hanning window filtering of the impulse train of firing times

(DeLuca et al., 1982), rectangular window filtering of the impulse train (Berger et al., 1986), the spline interpolation method of Mateo and Laguna (2000) and a (simpler) direct spline interpolation method. RESULTS: The ECG-inspired spline-based rate estimators worked exceptionally well when EMG decomposition errors were absent, but degraded unacceptably with decomposition error rates of 1% and higher. Typical expert EMG decomposition error rates are 3-5%. At realistic decomposition error rates, the instantaneous rate consistently exhibited higher errors than either of the Berger and DeLuca methods--so long as the optimal window duration was selected for these methods. When firing rate was modulated as a sinusoid, the Berger method (with optimal window durations selected) exhibited lower error than the DeLuca method, but only at the lowest modulation frequencies evaluated (0 and 0.25 Hz). However, the DeLuca method may have produced lower error had its window duration been permitted to extend beyond our maximum evaluated duration of 800 ms. When firing rate was modulated randomly over a 1 Hz bandwidth, the DeLuca method (with optimal window durations selected) exhibited lower error than the Berger method. CONCLUSION: Overall, each of the Berger and DeLuca methods performed well, so long as the optimal window duration was selected. Our results provide a mechanism for selecting the optimal window length for these methods, based on the characteristics of the modulation in firing rate for a particular application. Optimal window duration for the Berger and DeLuca methods decreased as modulation frequency increased, as average firing rate increased and as decomposition error rate decreased. References Berger, Akselrod, Gordon, Cohen. IEEE Trans Biomed Eng 33:900-904, 1986. DeLuca, LeFever, McCue, Xenakis. J Physiol 329:129-142, 1982.

O.12.2 ***The common synaptic input signal underlying the common drive***

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BACKGROUND AND AIM: The nervous system appears to regulate the strength of relatively steady muscular contractions by modulating the firing rates of all the active motor units in parallel. This process is often referred to as the "common drive." We attempted to estimate the common synaptic input to the motoneurons that produces this parallel modulation. METHODS: We used multiple electrodes and EMG decomposition to extract the firing patterns of up to 36 concurrently active motor units during steady contractions of human arm muscles. We estimated the synaptic input to each motoneuron using a simple model in which the motoneuron membrane voltage depends on the afterhyperpolarization and the synaptic input. This approach produced a scatter cloud of discrete points, with each point indicating the estimated synaptic input to one motoneuron at one of its firing times. An example is shown in the figure. RESULTS: In each contraction, the scatter cloud of points followed a common trajectory, showing that the synaptic input to each motoneuron consisted of a common signal plus synaptic noise. The common signal had most of its power below 10 Hz, and it produced motoneuron membrane fluctuations as large as 20% of the afterhyperpolarization amplitude. This common input signal was responsible for the parallel modulation of firing rates throughout the motoneuron pool. CONCLUSIONS: The synaptic input signal of each motoneuron is the sum of signals from multiple descending and peripheral sources. The fact that each motoneuron receives essentially the same net synaptic input signal implies that the various presynaptic signals are homogeneously distributed throughout the motoneuron pool. Because of this homogenous distribution, the motoneurons are modulated in parallel and the motoneuron pool as a whole acts as a single dimensional system, computing and transmitting a single regulatory control signal to the muscle.

O.12.3 ***Assessment of single motor unit activation in central and peripheral neuronal disorders***

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INTRODUCTION: Neuromuscular diseases represent a large group in the field of movement disorders. The malfunction of muscles can have its origin in the lower or upper motoneurons. An example for affected upper motoneurons is spasticity after stroke whereas in spinal muscular atrophy (SMA) lower motoneurons are affected. The symptoms of these neuromuscular diseases vary from muscle weakness to increased muscle tone and therefore the question arises whether there is an impact to muscular activation on the basis of different motoneurons. In this study the cerebral activation of single motor units of patients with spasticity and spinal muscle atrophy are compared. METHODS: The activation of single motor units is assessed noninvasively with high-spatial-resolution-electromyography (HSR-EMG). The HSR-EMG is the combination of a multi-electrode array and a two-dimensional Laplace-filter and enables a noninvasive recording of single motor unit activity. The abductor pollicis brevis muscle was measured at maximum voluntary contraction. Three groups took part in this study, the first one made up of ten patients with spasticity after stroke, the second of one nine patients with spinal muscle atrophy and the last group of eight healthy subjects. Several parameters, including general signal parameters like root mean square, entropy and number of peaks per second and peak parameters like firing rate and variation of peak amplitude, were calculated and compared for the analysis of the activation patterns. RESULTS: Root mean square had the lowest value for spastic group, the results for SMA group and healthy subjects were quite similar. Entropy was highest for healthy group and showed lower values for spastic group and SMA group. The healthy group had the highest variation of peak amplitudes; it was less for SMA group and lowest for spastic group. The number of peaks per second was highest for healthy group, less for SMA group and lowest in spastic group. The firing rate of isolated motor units was lowest and with little deviation in spastic group. In contrast the firing rate was similar for SMA group and healthy group whereas in SMA group the deviation of the firing rate was higher. CONCLUSION: The results show that, depending on whether upper motoneurons or lower motoneurons are affected, motor units are activated in specific activation patterns. The activation pattern in spinal muscular atrophy is similar to healthy muscles although, due to the loss of motor units, to a lesser extent. In a spastic muscle the number of activated motor units is also decreased. However, the firing frequencies are low and very constant. The combination of this activation pattern and symptoms like stretch reflex hyperexcitability points to an autonomous activation mechanism. The regulating effect of the brain is absent due to the affected upper motoneurons and the result is a self-excited activation of single motor units controlled by the spinal cord with an own natural frequency.

O.12.4 ***Modulation of motor units serving different VM fibers during knee extension***

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AIM: Fibers are angled by different amounts along the vastus medialis (VM) muscle; distal fibers are oriented more obliquely to the quadriceps tendon than the proximal fibers [1]. Consequently, the direction of the resultant force vector may be shaped according to the distribution of activity along VM. Based on previous evidence, suggesting the fibers of different motor units may reside within distinct VM regions [2], here we investigate whether knee extension demands a differential modulation of motor units serving different, proximo-distal VM fibers. METHODS: Ten healthy, male subjects (range: 24-32 years; 168-182 cm; 70-85 kg) were recruited. While seated comfortably on a dynamometer chair, with the knee held flexed at 80 deg, participants were asked to isometrically contract their knee extensor muscles. Visual feedback was provided to ensure that participants could successfully modulate their knee extension force according to a trapezoidal profile: from 0% to 20% of their maximal force in 5 s, at 20% for 10 s and then back to 0% in 5 s. Two arrays of eight electrodes were used to sample electromyograms (EMGs), each aligned parallel to VM proximal and distal fibers. EMGs were decomposed into trains of motor unit action potentials [3]. The cross-correlation function was then calculated for the firing pattern of: i) pairs of motor units identified from the same VM region; ii) pairs of motor units decomposed from EMGs detected proximally and distally. Kruskalwallis and Dunn-Sidak post-hoc tests were performed to compare how strongly modulations of firing rate in the two regions were similar during knee extension. RESULTS: Analysis revealed a significant difference in cross-correlation values between VM regions. The firing rate varied significantly more similarly for pairs of motor units identified from the same VM region, both proximal and distal, than for pairs of units in different muscle regions. CONCLUSION: Our results suggest that, at least during low level, isometric knee extension contractions, the firing rate of motor units identified from different VM regions may be modulated independently. It is therefore possible the nervous system tunes the VM force direction by shaping the distribution of activity within the muscle. [1] Smith, Nichols, Harle (2009) Do the Vastus Medialis Obliquus and Vastus Medialis Longus Really Exist? A Systematic Review. Clin Anat. 199: 183-199 [2] Gallina, Vieira (2015) Territory and fiber orientation of vastus medialis motor units: a surface electromyography investigation. Muscle Nerve. 52(6):1057-65 [3] Holobar, Zalula (2004) Correlation-based decomposition of surface electromyograms at low contraction forces. Med Biol Eng Comput. 42: 487-495.

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O.12.5 *Initial estimates of motoneuron after-hyperpolarization through the tonic discharge of motor unit populations*

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BACKGROUND AND AIM: Animal investigations provide a wealth of information regarding the biophysical properties of motoneurons. The translation of these findings to humans is limited, in part, by our inability to perform invasive recordings in humans. For example, recordings of motor unit action potentials (MUAPs) from muscle fibers provide limited information regarding the trajectory of membrane potentials in the soma of the corresponding spinal motoneuron. Motoneuron discharge can be faithfully assessed through identifying the activation of its associated muscle fibers. In turn, these discharge characteristics may afford valid estimates of membrane potential trajectories of spinal motoneurons, in particular the duration of the after-hyperpolarization (AHP). METHODS: The EMG activity underlying the tonic discharge of soleus motor units from the decerebrate cat is collected using a 64-channel electrode array and decomposed into corresponding MUAP spike trains. Interval death rate analyses are used to estimate the duration of the AHP for motor unit spike trains containing >1000 spikes. RESULTS: Our analyses focus on long trains of tonic discharge from 74 unique motor units from across 6 experiments. The validation and yield of these spike trains was improved through tracking the spike triggered average-derived MUAP waveforms across subsequent trials, resulting in an average of 1490 spikes per unit. These tonic motor units discharged at low rates (8.4±1.3 [SD] pps) with low variability (16.9±6.1 %CoV). By visually approximating the noise transition of the death rate function, the average duration of the AHP of soleus motoneurons is estimated as 134±18.3 ms. To assess the stability of the AHP, extremely large spike trains (>2000 spikes) could be separated in half, providing two continuous, nonoverlapping spike trains from the same unit. Using this approach, AHP estimates demonstrated good reliability across 16 motor units with an intraclass correlation coefficient of 0.84. The distribution of 27 motor units from a single soleus motor pool, yielded a range of AHP durations that was similar to the range of all 74 units recorded across animals. A strong negative

correlation is observed between the duration of the AHP and the mean discharge rate (r = -0.88; p<0.001) of a given motoneuron. CONCLUSIONS: Interval death rate analyses from the tonic discharge of soleus motor units in the cat provide reliable estimates of the AHP duration. These AHP duration estimates closely mirror the central tendencies of soleus motoneuron AHP durations from previous investigations, which acquired direct measurements through intracellular microelectrodes. The current data suggests the AHP may serve a prominent role in the regulation of the tonic discharge of soleus motor units. Developing parallel means to assess motoneurons in both animals and humans will aid our ability to understand spinal neuron changes in both health and disease.

O.12.6 *The Temporal Structure of Intermuscular Motor Unit Synchronization: Application of Wavelet Coherence*

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BACKGROUND AND AIM: Intermuscular motor unit synchronization (IMUS) is typically described using a Fourier-based coherence analysis between two EMG signals. Such analyses have demonstrated that IMUS between quadriceps muscles is task-dependent with enhanced synchronization during dynamic tasks. Within a dynamic task, the varying biomechanical conditions suggest an additional time-dependent property of IMUS. However, the lack of time resolution of Fourier-based coherence does not allow to investigate such temporal features. The extension of coherence to the wavelet transform combines good time and frequency resolution and thus allows to investigate the temporal structure of IMUS. The aim of this study was to test the application of a wavelet based coherence analysis to examine the temporal structure of IMUS between Vastus Lateralis (VL) and Medialis (VM) during gait. METHODS: Surface EMG signals from VL and VM were recorded from eight young adults during walking on a treadmill (40 strides) at their preferred speed. EMG signals were resolved into time-frequency space using 13 non-linearly scaled wavelets with center frequencies between 2-191 Hz. The wavelet cross- and power spectra were time-normalized to 100% of stride duration and averaged across strides. The wavelet coherence was then calculated as the squared wavelet cross spectrum normalized by the product of the individual wavelet power spectra. A reference coherence was defined as the coherence between the VL EMG and the VM EMG shifted by one stride. This reference coherence was subtracted from the wavelet coherence to remove any artificial coherence due to motion artifacts. The resultant wavelet coherence patterns for each subject were displayed for center frequencies between 32-191 Hz and for the time interval of 20% before and after heel strike when the Vastii muscles are most active. RESULTS: The wavelet coherence patterns showed both common and subject specific features. Except for subject #6, VL and VM EMGs were coherent intermittently for all subjects before and after heel strike. Significant coherence was generally present in three frequency bands: 45 Hz, 76 Hz, and 116 Hz. Particularly, subject #1 and #5 demonstrated high coherence in the 116 Hz and 45 Hz band, respectively. CONCLUSIONS: The wavelet coherence successfully resolved the temporal structure of IMUS between VL and VM during walking. Despite both muscles being active, coherence between VL and VM is not constant but rather occurs intermittently at specific time points before, during, and after heel strike. The presence of significant coherence between VL and VM EMGs in the frequency range between 45-76 Hz aligns with previous findings and demonstrates the validity of this approach. We speculate that the coherence in high frequency bands represents synchronization of individual motor units while coherence in low frequency bands indicates synchronized clusters of motor units in both muscles.

S.9. *Implementation of Impairment Based Neuro-Rehabilitation Devices and Technologies following Brain Injury*

The use of haptic robots to study neural mechanisms underlying the expression of sensorimotor impairments in stroke.

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BACKGROUND AND AIM: The implementation of electromechanical devices for the quantification, study and treatment of sensorimotor impairments (abnormal muscle synergies, spasticity, reduced reflex modulation, paralysis and proprioceptive deficits) resulting from brain injury is the main topic in this symposium. The specific requirements for the use of robotic devices to quantify these impairments, as well as study and ultimately treat them effectively, will be discussed by the various presenters. A case will be made that electromechanical devices not only allow the clinician to quantitatively control task practice and dosage, but more importantly, allow for the study and subsequent development of more targeted treatments of specific impairments, such as the expression of abnormal movement synergies. The use of robotics to study mechanisms underlying the expression of the flexion synergy will be discussed in this presentation. The flexion synergy consist of abnormal coupling between shoulder abduction and elbow/wrist and finger flexion in individuals with hemiparetic stroke. When increasing shoulder abduction, reaching distance and hand opening will become progressively more limited. METHODS: Eight able-bodied control subjects and 8 moderately to severely impaired individuals with chronic stroke with a single unilateral subcortical lesion participated in this preliminary study. All subjects performed ballistic reaching movements from a home target position. Three shoulder abduction loads were applied during reaching: 1) sliding on a haptic "table surface"; 2) reaching in free space with the limb fully supported by our haptic robot and 3) reaching in free space while lifting a load equal to 25% of the subject's maximum abduction force. A total of 120 trials were performed for each condition. Kinematic and HD-EEG signals (n=160) were recorded during the execution of this controlled motor task. RESULTS: Data will be presented that shows that as shoulder abduction loading is increasing, medicated by our robot, a concurrent increase in ipsilateral sensorimotor cortical activity is observed using high-density EEG. CONCLUSIONS: It is postulated that the proportional increase in ipsilateral cortical activity, as a function of shoulder abduction loading, results in activation of the ispilateral reticulospinal projections that have been shown to activate shoulder abductors and elbow/wrist and finger flexors hence resulting in a coactivation of muscles generating the flexion synergy. The need for a development of robot-medicated treatments that promote an increased use of the contralateral, lesioned, hemisphere, so as to reduce the expression of the flexion synergy, will be briefly discussed.

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Robotic assessment of the "good arm" following stroke

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Background and Aim: Impairment in the ipsilesional or ?good arm? following stroke is often discussed in the literature, but rarely treated in clinical practice. Many studies have investigated impairments of the ipsilesional arm in the chronic phase, but few examinations have been made in the subacute phase. In the literature, most measures of ipsilesional motor function have been made with observer based ordinal scales. These scales are typically not sensitive to more subtle, but important deficits in motor function. Robotic technology offers the ability to perform sensitive and highly reliable assessments of sensorimotor function. In the present study we used robotics in the subacute phase post-stroke to quantify motor function of the contra- and ipsilesional arms post-stroke. The aim of the study was to increase our understanding of the nature and prevalence of motor deficits in the ?good arm? following stroke. Methods: We examined 259 subjects with first time, unilateral stroke using a KINARM exoskeleton robot. Each subject completed a robotic assessment of visually guided reaching in both arms. Subjects also completed a variety of traditional clinical measures (Functional Independence Measure, Chedoke-McMaster Stroke Assessment, Purdue Pegboard) in order to make comparisons to robotic measures. Results: We found that impairments in the ipsilesional and contralesional arms were only moderately correlated for robotic measures of reaching (r values varied from 0.3 to 0.6 depending on parameter). Ipsilesional deficits occurred in 34% of subjects. Interestingly, the magnitude of impairment of the contralesional arm was similar for subjects with and without ipsilesional deficits. Conclusion: In summary, traditional thinking that impairment of the contralesional arm usually predicts ipsilesional impairment seems to be incorrect. Many subjects had quite severely impacted contralesional arm impairments with either no or negligible impairment of the ipsilesional arm. Robotic technology allows better characterization of visuomotor deficits than many traditional measures and may be helpful in personalizing rehabilitation strategies after stroke.

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Robotic Measurement and Intervention for Synergy-Related Reaching Dysfunction Following Stroke

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The onset and progression of upper extremity flexion synergy, also described as a loss of independent joint control, can be precisely measured beginning with the emergence of volitional movement in early recovery following stroke (see figure below illustrating the kinematic/kinetic measure of reaching workarea as a function of abduction loading). More specifically, the impact of flexion synergy on reaching function can be quantified with the robotic device, ACT3D. With this device, variable amounts of abduction support (also abduction resistance) are provided while the individual attempts to reach maximally in a horizontal plane at shoulder height creating a hand path envelope representing the total reaching range of motion. The resultant 2-dimentional area of the hand path envelope is calculated representing the "workarea" as a function of abduction loading. In this symposia talk, data will first be presented illustrating the ubiquitous expression of flexion synergy upon emergence of movement during early recovery even in individuals who transition to complete recovery of reaching function. Additionally, data will be presented illustrating the persistence of flexion synergy-related reaching dysfunction in individuals who transition to chronic severe impairment. An intervention strategy for targeting flexion synergy will then be discussed illustrating the capacity for robotics to serve as an effective exercise tool to ameliorate flexion synergy-related reaching dysfunction in severe chronic stroke. Initial studies implementing this approach indicate that progressing shoulder abduction loading as individuals improve in reaching range of motion is a key therapeutic attribute for restoring reaching function. Data from both early and chronic recovery suggests future investigation of the safety and effectiveness of targeting flexion synergy-related reaching dysfunction in early recovery in an effort to optimize the recovery trajectory.

Using Robotic Systems to Assess Proprioceptive Deficits in Individuals with Hemiparetic Stroke

Netta Gurari[1]

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Background and Aims: According to clinical assessments, nearly 70% of stroke survivors have compromised proprioception. Even so, our understanding about the reason for observed deficits based on currently available clinical proprioceptive assessments is limited since measurements: (1) lack sensitivity to identify the degree of a deficit (e.g., ratings are unimpaired, mildly impaired, severely impaired), (2) are subjective (e.g., a rater determines task performance based on visual inspection), (3) may not be reliable (e.g., ratings may differ depending on the rater and testing session), and (4) may be confounded by additional impairments. To address limitations of currently available clinical assessments, a number of research groups are employing robotic systems to standardize and automate the assessment of proprioceptive capabilities in individuals with stroke. Robotic systems allow for a number of advantages including the following. First, a single robotic device can create various types of virtual touch environments. For example, a user may feel at one moment as though he or she is moving the hand in free space, and a moment later that his or her hand is being moved by the robotic device. Second, sensors affixed to the robotic device can monitor the user's interaction, and the sensor data can be stored for off-line processing. In this work, I aim to demonstrate, using a robotic device, that proprioception within the paretic arm and non-paretic arm of individuals with chronic hemiparetic stroke may not be impaired even if these individuals have deficits matching positions across both arms. Methods: I investigated whether individuals with chronic hemiparesis who have deficits matching positions across both arms also have deficits matching positions within a single arm. Participants with chronic hemiparetic stroke having clinically determined mild elbow proprioceptive deficits (i.e., participants with stroke) and age-matched participants without neurological impairments (i.e., controls) partook in the experiments. A custom robotic system was used to quantify each participant's position matching capabilities during single arm and between arm position matching tasks. Participants wore a blindfold and noise-canceling headphones to ensure that they discriminated positions based on proprioceptive cues and not visual and auditory cues. Results: Results from the between arm position matching tasks demonstrate that, aligned with the clinical assessment findings, the participants with stroke performed significantly worse than the controls. However, results also reveal that the participants with stroke performed just as well as the controls during the single arm position matching tasks. Conclusions: Based on these findings, I propose that proprioception may be unimpaired both in the paretic arm and non-paretic arm of individuals with hemiparetic stroke who exhibit large matching errors during bimanual position matching tasks.

Training modalities in robot-mediated upper limb rehabilitation in stroke

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Upper-limb rehabilitation robotics can be beneficial tools for robot-assisted therapy. These technologies provide motivational and interactive therapy for the patient and can perform quantitative measurements of post-stroke impairments and degree of recovery for therapists and clinicians. A major question is in which way technology can provide the largest benefit, especially regarding application in clinical practice. The types of devices that are available for upper-limb rehabilitation can be classified as weight-support devices, robotic endpoint manipulators, and exoskeletons. Each of these have specific advantages and disadvantages. We have classified eight training modalities that are commonly used by these devices, yet currently not enough evidence exists to determine their exact impact on the rehabilitation outcome. In an attempt to better determine what are the most effective components of upper-limb rehabilitation, we have compared the outcomes of most clinical studies that use robotic rehabilitation to studies that focus on constrained induced movement therapy (CIMT), electrical stimulation therapy (EST), or mirror therapy (MT). We compared the results of the Fugl-Meyer Assessment (FMA) of Motor Recovery after Stroke, but found little differences. When comparing involvement of proximal (shoulder, elbow) or distal components (wrist, hand) in the therapy, again little differences can be found. Combining both proximal and distal therapy does seem to hint (without statistical evidence) at a higher effect on the FMA outcomes, which would be logical as the FMA contains specific proximal and distal components. Interestingly, in chronic studies there does seem to be a clear regression to a mean improvement of about 4.0 on the FMA. That is, the outcome of a randomized clinical trial (RCT) study will regress to 4.0 if more subjects are included. Results with fewer subjects are more likely to diverge, with the variance of study means inversely correlated with the number of subjects. The few studies that report above-expected results are now of most interest, with one study using EST showing most promise. The most disturbing results perhaps is that correlating study outcomes to the year of publication shows little effects of all research efforts in the last two decades. For the current therapies, active physical and mental involvement of the individual after stroke and the number of repetitions appear to be the most important components to achieve improvements on the FMA in RCTs, but the exact type of therapy, devices or training modalities seems to have little to no influence. However, preliminary evidence exists that more individualized and impairment-directed therapies could have a stronger influence, as the other presenters in this workshop might demonstrate.

4D EEG: Assessing the role of the sensorimotor cortex in reflex modulation during motor control.

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The motor cortex is involved in initiating the volitional motions of the muscular system. Through the direct connection between primary motor neurons and á-motor neurons, the muscles are being activated. In addition, it is hypothesized that the motor cortex is involved in the modulation of the reflex gains at the spinal cord level, thereby adapting the impedance of the limbs. The impedance of the limbs is the result of the segment inertia, the muscle stiffness and viscosity and the proprioceptive reflexes, i.e. the position and velocity feedback through the muscle spindles, and the force feedback through the Golgi tendon organ. It has been frequently shown that the impedance is being modulated, e.g. by muscle co-contraction increasing the visco-elasticity, and by the reflex modulation. However, since the neuromuscular control system is a closed-loop system, one has to impose an external signal to identify the properties of the elements inside. We are using robot manipulators with multisine force perturbations with specific frequencies to perturb the neuromuscular system, and measure the position, force and muscular EMG. Neuromuscular parameters like muscle visco-elasticity and position, velocity and force feedback can be calculated from the Frequency Response Function. Variations of parameters over time can be assessed using a Linear Time Varying (LPV) system identification paradigm in the time domain. In the experiment the subjects were requested to move their hand back- and forward. During the movement continuous force perturbations were applied. In the LPV algorithm, position was used as scheduling function, and a time-varying state space model was estimated on the data set. After fitting a neuromuscular model to the state space model, with mono-articular shoulder and elbow muscles and also bi-articular muscles, it showed that the intrinsic muscle viscosity and reflex gains varied regularly with the change of position. The VAF in lateral-medial direction was 92% and in forward/backward direction 73%, affected by the volitional motion. Feedforward (volitional) muscle control for a complex system as the shoulder and elbow might be relatively easy compared to the reflex gain control in order to provide the desired impedance. Such a highly multivariable and coupled system is unequalled in robotic control. It is likely that larger parts of the cortex, and presumably the motor cortex, is occupied with this task. The total reflex gain is a combination of tonic drive to the á-motor neuron, the presynaptic inhibition and the ã-motor neuron activating the intrafusal muscle fibers. It is hypothesized that the motor cortex is involved in the presynaptic inhibition and ã-motor neuron activation. Goal of the 4D EEG project is to track the propagation of neural signals through the brain, with a spatial accuracy of 2 mm (using EEG source localization) and a temporal accuracy of msec. In the 4D EEG project the EEG responses to the multisine force perturbations are being recorded. About 85% of the EEG signal power is due to non-linear contributions, showing up in higher harmonics of the EEG signal. Using MultiSpectral Phase Coherence (MSPC) the time-delay can be accurately assessed. The challenge is to fit a non-linear dynamic model to the data, which would be for the first time result in a quantitative model of the cortical activity. The current study showed that the gain settings are continuously modulated, presumably in a feedforward manner simultaneously with the muscle activation. The role of the motor cortex in the modulation can be recorded using EEG source localization.

S.10. ***Neural mechanisms underlying falls and impaired balance: an introspective from animal to patient***

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Are Hypermetric Stretch Reflexes Significant Contributors to Falls in Stroke Survivors?

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BACKGROUND AND AIM Half of the 6.5 million stroke survivors living with disability in the US fall each year. Despite this statistic, remarkably little information is known about the sensory mechanisms that contribute to falls in this population. The objective of this study was to evaluate the stretch reflex response, known to be abnormal following stroke, during laboratory induced "falls." The importance of the stretch reflex in the ability to resist perturbation throughout the body is well documented. Further, we have previously shown that muscle spindle afferents, which drive stretch reflex responses, can provide information about the direction, amplitude, and velocity of a perturbation during a whole-body balance disturbances. Still, these previous studies have predominately been evaluated during postural challenges where a step was not needed and a fall did not occur. Thus, the role of stretch reflex pathways during postural challenges that induce a fall is unknown, particularly in stroke survivors. Given the heightened stretch reflex response that often accompanies stroke in the form of spasticity, we hypothesized that stroke survivors would have larger stretch responses when they fell. METHODS We evaluated 16 unilateral stroke survivors and exposed them to backward perturbations requiring a forward step to maintain balance. Subjects were fitted with a harness such that injury could not occur if a loss of balance occurred. A "fall" was recorded if the subject became unambiguously supported by the harness. We evaluated kinematics (e.g. trunk flexion) as well as muscle activity in the paretic and non-paretic rectus femoris, semitendinosus, and gastrocnemius muscles. The time window of 50-100ms was considered the stretch reflex response. RESULTS Sixteen trials resulted in a fall and 9 subjects were classified as Fallers. We found larger stretch reflex (50-100ms) responses in the paretic rectus femoris muscle during fall trials and in subjects classified as Fallers. This activity was sensitive to perturbation size indicating it is the likely result of stretch sensitive pathways. Importantly, there were no significant differences seen in trunk flexion at the time of the stretch. This indicates that the heightened stretch response is not related to the subject experiencing a larger perturbation during the fall but rather due to an intrinsically heightened response. CONCLUSIONS Given previous reports showing that large hip flexion during a balance disturbance increases the likelihood of a fall, our results suggest that abnormal stretch reflex responses may contribute to larger hip flexion putting stroke survivors at risk of falling. Still further study is needed to fully determine the functional consequences of this hypermetric stretch reflex response. Finally, future work should evaluate if clinical measures of spasticity may be an appropriate predictor of falls.

Strategies to maintain static and dynamic lateral stability during locomotion in the cat

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BACKGROUND AND AIM: During walking, cats as humans are less statically stable in the frontal plane than in the sagittal one due to geometry of the base of support (Winter 1995; Misiaszek 2006). Given similarities in postural responses of walking cats and humans to lateral perturbations (Misiaszek 2006; Hof et al. 2010), cats appear to be a convenient animal model to study neural mechanisms and biomechanical strategies of lateral balance control during locomotion. METHODS: In a series of studies, we investigated the static and dynamic stability of cats when lateral balance was challenged by (1) constraining step width to 5 cm during overground walking, (2) changing the speed difference between the two treadmill belts during split-belt treadmill walking, (3) removing cutaneous input from the fore- and hindpaws of one side of the body using anesthetic injections, and (4) osseointegrated transtibial passive prosthesis during overground walking. Static stability was determined as the shortest distance between the vertical projection of the center of mass of the body (CoM) and the boundary of the support area in the lateral direction, whereas the margin of dynamic stability was defined as the difference between the center of pressure (CoP) and the extrapolated center of mass (xCoP, Hof et al. 2007) or as the difference between CoP and the boundary of the support area (Farrell et al. 2014, 2015). CoM position was computed using 3D recordings of 28 markers on major

body segments and a full-body cat model with known inertial body segment parameters (Hoy, Zernicke 1985). CoP was derived from paw position and ground reaction forces measured by an instrumented split-belt treadmill. RESULTS: Despite very different mechanical or sensory challenges to lateral balance, the adopted strategies to maintain lateral balance were similar. Cats increased step width except when it was constrained, increased the area of support and relative time spent in 3-legged support, decreased the duration of the double support phase by fore- and hindlimbs on the affected body side (prosthetic, anesthetized or moving faster on the split-belt treadmill), and shifted body weight and CoM towards the contralateral side except during anesthesia of paws when the body shifted in the opposite direction. As a result of these changes in locomotor mechanics, margins of static and dynamic stability in the direction of the affected body side increased. For example, dynamic stability margins during double support by fore- and hindlimb of the affected side (prosthetic gait or walking with anesthetized paws) were typically greater than 2 cm and exceeded those on the contralateral side by 2 times. Increases in margins of dynamic stability have also been found during prosthetic walking in human amputees (Hof et al. 2007). CONCLUSIONS: The obtained results provide important new insight into possible strategies for improving lateral stability during walking in challenging conditions.

New rehabilitation tools and technologies to improve balance and mobility

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The control of posture and upright balance requires complex multisensory integration and sensorimotor coordination. Information from multiple sensory channels is processed, and appropriate muscles are activated for appropriate action with, and adaptation to environmental demands. Sensory and motor systems compromised with aging or neurological diseases such as stroke likely impede this process. Extensive human and animal studies have shown, however, that improvements in sensorimotor functions can result from experience-dependent neuroplasticity achieved through salient, repetitive, intensive and motivating practice. New technologies, based on virtual reality (VR) and robotics, have the capacity of simulating environments, providing a new and safe way to not only increase practice time but also to create the varied environments and controlled constraints needed to maximize learning (Darekar et al, 2015). An advanced balance and locomotor system that combines VR with a self-paced treadmill mounted on a motion platform has been developed to allow patients to be exposed to more complex physical environments (both indoors and outdoors) including environmental hazards without physical danger (Fung et al, 2006). VR systems can be combined with the manipulation of physical environments and sensory feedback to create a mixed reality system for multisensory integration and sensorimotor enhancement. Sensory manipulation with augmented cues from the visual, auditory and proprioceptive systems can be used to enhance motor functions for the control of balance. Haptic touch has emerged as a novel and efficient technique to improve postural control and dynamic stability. Improvement of balance and mobility functions with a mixed reality system incorporating VR, surface perturbations and haptic manipulation is evidenced by kinematic and kinetic changes in postural adaptations and reactions. Furthermore, the enhancement of sensorimotor integration is revealed by cortical activation changes measured with near-infrared spectroscopy (Sangani et al, 2015). This symposium presentation will focus on evidence-based tools and technologies that can be used to evaluate and enhance posture and balance control in post-stroke and older adults. References: Darekar A, McFadyen B, Lamontagne A, Fung J (2015) Efficacy of virtual reality based intervention on balance and mobility disorders post-stroke: a scoping review. J NeuroEng Rehabil 12:46. Fung J, Richards CL, Malouin F, McFadyen BJ, Lamontagne A (2006) A treadmill and motion coupled virtual reality system for gait training post-stroke. Cyberpsychology and Behavior 9(2):157-162. Sangani S, Lamontagne A, Fung J (2015) Cortical mechanisms underlying sensorimotor enhancement promoted by walking with haptic inputs in a virtual environment. Progress in Brain Research 218: 313-30.

Balance reactions following perturbations to touch are more pronounced when standing on an unstable surface

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BACKGROUND AND AIM: Lightly touching a stable reference reduces sway during standing. Recently, we demonstrated that rapid displacements of a touch reference

leads to fast reactions in leg muscles during standing with eyes closed, suggestive of a balance reaction. However, these presumptive balance reactions were only seen in half of the participants, and were only observed following the first exposure to the perturbation. We suggest that fingertip cutaneous cues can evoke balance corrections, but that their expression is context dependent. In the present study, the challenge of the task was increased by asking the participants to stand on foam with their eyes closed. Standing on foam creates mechanical instability, but also is argued to impair feedback from the feet and ankles. We hypothesized that participants would increase their reliance on the touch cues to stabilize balance and that this would be reflected by increased expression of balance reactions with displacement of the touch surface. METHODS: 20 participants were asked to stand on foam placed atop a force plate. Electromyographic activity was recorded from the right tibialis anterior (TA), soleus (SOL), anterior deltoid, posterior deltoid and sternocleidomastoid, along with electrogoniometer records from the right elbow, hip and ankle. Participants stood naturally in 4 conditions: a) eyes open, b) eyes open while touching, c) eyes closed, and d) eyes closed while touching (ECT). Conditions a-c were used as a deception. During ECT participants stood quietly while lightly touching (< 1 N) a touch plate for 1 min before touch plate displacements (12.5 mm, 124 mm/s) were unexpectedly introduced. Displacements were separated by a period of 6-15 s. Participants received a block of 10 displacements in a single direction (forward or backward). Half received forward perturbations. RESULTS: All participants responded to the touch plate displacement with a balance reaction at the ankle in at least two trials. 6/10 participants responded with TA activation following the first exposure to forward touch displacement and importantly, with a median response rate of 8.5 per participant across all 10 trials. 8/10 participants responded with SOL activation following the first exposure to backward touch displacement, with an overall median response rate of 6 per participant across all 10 trials. 14/20 participants responded in trials 9 and/or 10. CONCLUSIONS: These results confirm that cutaneous inputs from the fingertip can induce a balance corrective response, even in the absence of an overt balance disturbance. Importantly, the contribution of light touch to balance control is augmented in conditions when other sensory sources are impaired or unreliable, even though participants became aware that the touch cue itself was unreliable. This suggests that cutaneous input from the hands is an important sensory cue in balance control when the hands are engaged in balance tasks.

Basic insights in tripping responses can assist in designing appropriate fall prevention programs.

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To understand the neural mechanisms of falls it is essential to consider the circumstances leading to a fall. Many falls occur during walking and are due to unsuccessful trip recovery (Robinovitch et al., 2013; van Dieën & Pijnappels, 2008). Hence the need to study tripping responses generated under these circumstances. From animal studies it appears that stumbling reactions are organized at a low level in the nervous system. The studies on humans give a similar picture. Responses after stumbling occur with a latency which is below those seen in voluntary motor actions, suggesting they are involuntary reactions. These responses are smaller and slightly later in elderly as compared to young adults. However, these responses do not determine the strategy used to overcome the obstacle (short or long step strategy). In addition it was shown that the crossing behavior and movements could be adjusted while ongoing (hence they are not ballistic movements; see Potocanac et al., 2016). Finally, following the tripping responses there is a substantial period before touching the ground in case of an unsuccessful recovery attempt. The latter prompted us to experiment with training methods to teach elderly to fall safely, based on martial arts techniques. It was demonstrated that these techniques reduce the fall impact. Furthermore, a fall prevention training program was able to reduce falls and to improve obstacle avoidance skills. It is concluded that basic insights in tripping responses can assist in designing appropriate fall prevention programs.
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Altered sensorimotor transformations for balance in Parkinson's disease

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BACKGROUND AND AIM: Automatic postural responses to balance perturbations are often abnormal in Parkinson's disease (PD), which may increase fall risk. However, pathological changes underlying abnormal postural responses are poorly understood, limiting our ability to develop improved therapies. We have developed a mechanistic model of the sensorimotor feedback transformation used to activate muscles during postural responses: the Sensorimotor Response Model (SRM). Previous work in animals and in young healthy individuals demonstrated that postural responses are created through multisensory estimates of the motion of the center of mass (CoM) that activate muscles in an optimal tradeoff between postural error and neural effort to stabilize the body. Here, we used the SRM to test whether this sensorimotor transformation is altered in PD. METHODS: We compared postural responses to backward support-surface perturbations in two female patients: one with moderate PD and falls history (age, 75 y; Hoehn & Yahr stage 3), and one with mild PD and no falls history (54 y; Hoehn & Yahr 1.5), with those from healthy older (70 y, no falls history) and healthy young (19 y) female participants. We quantified average electromyographic (EMG) responses in agonist medial gastrocnemius (MGAS) and antagonist tibialis anterior (TA) with SRM parameters, including feedback gains on CoM jerk (kj), acceleration (ka), velocity (kv), and displacement (kd). RESULTS: Altered SRM parameters accounted for abnormal agonist-antagonist co-contraction in PD. While healthy participants maintained balance primarily via activation of agonist MGAS, PD patients maintained balance primarily via agonist-antagonist co-contraction, with increased SRM parameter magnitudes in antagonist TA ($P<0.001$) but not in agonist MGAS ($P<0.25$). Altered SRM parameters also accounted for shortened EMG initial bursts in PD, which were most pronounced in the individual with moderate PD. PD EMG responses exhibited elevated SRM paramter kj ($P<0.05$, ANOVA) and a trend towards elevated ka ($P<0.10$), suggesting that contributions of higher-order derivatives of CoM motion to muscle responses

were elevated in these individuals compared to controls. Overall, delayed sensorimotor feedback of CoM motion was sufficient to reproduce recorded muscle activity with high precision in all participants (variance accounted for = 0.87±0.09). CONCLUSIONS: These results provide initial evidence that sensorimotor transformations during balance control are altered in PD, resulting in EMG responses with abnormal magnitude and timing. Larger prospective studies are required to establish temporal relationships between altered postural responses, disease onset, and the appearance of falls. Refinements of the SRM may provide insight into how PD affects balance and enable clinicians or therapists to better direct individuals to interventions to mitigate fall risk.

S.11. *EMG Signal Analysis in Clinical Applications*

The use of EMG in neuromuscular diagnosis: an overview

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INTRODUCTION: EMG is the measurement of electric muscle activity: - during voluntary activation (interference pattern) - after electric pulses over a peripheral nerve evoking a compound muscle action potential (CMAP) - similarly, as motor evoked potential (MEP) after transcranial magnetic brain stimulation (TMS). In clinical practice, both needle- and surface-EMG are used for different applications. NEEDLE EMG: Thanks especially to the pioneering work of Buchthal [1] and Stålberg [2], needle-EMG is well standardized in clinical diagnostics observing voluntary activation. Crucial in needle EMG is the quantification of motor unit action potentials (MUAPs) or single muscle fiber potentials (SFAPs), estimating both the activity and the properties of single motor units, the basic functional building blocks of a muscle and even of single muscle fibers. CONVENTIONAL SURFACE EMG: Single channel surface EMG is the standard for compound muscle activity after nerve or cortex stimulation. It supports the diagnosis of peripheral nerve conduction and central nerve conduction both in terms of a possible loss of axons and decreased conduction velocities. It is also connected to standardized clinical protocols [3]. HIGH-DENSITY

SURFACE EMG: New possibilities came up with multi-channel surface EMG, especially versions with small inter-electrode distances up to 10 mm, often denoted as high-density surface EMG (HD-sEMG). It goes back to the work of Gydikov and colleagues [4]. With one-dimensional array electrodes, motor unit action potentials could be followed along the muscle fibers. Later, two-dimensional grids were introduced, first by Masuda and colleagues [5]. It allowed the description of an EMG signal as a spatio-temporal phenomenon instead of a single point observation, making sense from both anatomical and physiological perspective. HD-sEMG methods were developed to also characterize single motor units, to measure action potential propagation along the muscle fibers and to focus observations by spatial filtering. A systematic review in 2006 evaluated the clinical applications of HD-sEMG [6]. At that time and still, most studies are in a stage of bringing mainly important pathophysiological insights. It concerns muscle fatigue, motor neuron diseases, neuropathies, myopathies, spontaneous muscle activity like in ALS and MU firing characteristics. An overview of challenges towards routine clinical applications of advanced surface EMG techniques will be given. REFERENCES: [1] Buchthal F, Neurol Clin. 1985; 3:573-598. [2] Stålberg E, Muscle Nerve. 1991;14:293-303. [3] Johnsen B, Fuglsang-Frederiksen A, Neurophysiol Clin. 2000;30:339-351. [4] Gydikov A, Kosarov D, Electromyogr Clin Neurophysiol. 1972;12:283-305. [5] Masuda T, Miyano H, Sadoyama T, Electroencephalogr Clin Neurophysiol. 1983;55:594-600. [6] Drost G, Stegeman DF, van Engelen BG, Zwarts MJ, JEK. 2006;16:586-602.

A novel method for analysis of pathological tremor in electroencephalograms

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BACKGROUND AND AIM: The role of cerebral cortex in the generation of essential (ET) and Parkinsonian (PD) tremor is not yet fully understood. In the past, it has been investigated non-invasively using coherence analysis between cortical activity, recorded with EEG or MEG, and muscle activity as assessed from EMG. While robust,

coherence only indirectly measures corticomuscular coupling, does not support tracking of tremor over a short time scale and requires cleaning of EEG artefacts. We propose a method that circumvents these limitations. METHODS: 5 ET (age 67±6 years, Fahn-Tolosa-Marin scale score of 39±10) and 5 PD patients (age 71±11 years, UPDRSIII scale score of 9±4) participated in the study that was approved by local ethics committee. Patients performed two repetitions of a 30 s long postural task. Surface EMG was recorded from the right wrist flexors and extensors by two arrays of 5 by 12 electrodes (LISiN-OT Bioelettronica, Italy). The signals were band-pass filtered (10-750 Hz) and sampled at 2048 Hz by 12-bit A/D converter (OT Bioelettronica, Italy). EEG was recorded with 32 passive Au or active Ag/AgCl electrodes, placed on the extended 10/20 system cap (g.Tec, Austria), amplified, band-pass (0.5-60 Hz) and notch filtered (50 Hz) and sampled at 256 Hz with 24 bit resolution (g.Tech, Austria). A common clock signal was used to synchronize the EEG and EMG recordings. EEG signals were manually inspected to ensure the absence of head tremor or tremor-related movement artefacts. We identified 6±3 (ET) and 9±5 (PD) motor units (MU) from each muscle by CKC method [1]. Discharge patterns of all MUs were assessed with >90 % accuracy, as verified by Pulse-to-Noise Ratio [1]. Their cumulative spike train (CST) was used to construct a Linear Minimum Mean Square Error (LMMSE) estimator of the tremor component in EEG. Finally, the coherence between the CST and the extracted EEG tremor component was compared to the coherence between the CST and Laplacian-filtered EEG at C1 position. RESULTS: The CST-C1 coherence was 0.02±0.03 (range 0.001 - 0.12) in ET and 0.01±0.02 (0.001 - 0.09) in PD patients and increased significantly (Wilcoxon signed rank test, $p<0.0001$) to 0.13±0.09 (0.005 - 0.42) in ET and to 0.1±0.09 (0.014 - 0.45) in PD patients when computed between the CST and the LMMSE tremor estimate. The relative power of the first tremor harmonic in extracted tremor components with significant corticomuscular coherence was stronger in PD than ET patients (Kruskal-Wallis test, $p < 0.05$). CONCLUSIONS: The presented technique extracts tremor-related component from EEG and supports detailed tremor analysis and discrimination of PD and ET patients. This study was supported by Commission of the European Union, within Framework 7 (projects NeuroTREMOR and FP7-PEOPLE-2013-IOF-627384) and by Slovenian Research Agency (projects L5-5550 and J2-7357). [1] Holobar A. et al. 2014, J Neural Eng. 11(1):016008.

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High Density Surface EMG Examination of Motor Unit Firing Behavior in Amyotrophic Lateral Sclerosis

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BACKGROUND AND AIM: Electromyogram (EMG) examination has been used for diagnosing and tracking amyotrophic lateral sclerosis (ALS). Compared with routine examinations, such as detection of fibrillation and fasciculation potentials, quantitative motor unit action potential analysis and motor unit number estimation, motor unit firing behavior alterations in ALS have not been widely studied. The objective of this study was to examine motor unit firing behavior of ALS patients using high density surface EMG decomposition. METHODS: Surface EMG signals were recorded from the first dorsal interosseous (FDI) muscle of 10 ALS subjects (age 53.1±12.5 years) and 10 matched neurologically intact subjects (age 51.2±15.3 years) using a flexible 64-channel surface electrode array (8 by 8 electrodes, inter-electrode distance of 4 mm). Each subject was asked to perform a series of 10 s long isometric contraction at different force levels ranging from 10% to 100% of maximum voluntary contraction (MVC) at 10% increment. Sufficient rest time between trials was provided to avoid mental and muscle fatigue. The surface EMG signals were sampled at 2 kHz per channel with a band-pass filter of 5-500 Hz (TMS International BV, Netherlands), and decomposed offline using the Convolution Kernel Compensation (CKC) technique [1]. The motor unit firing behavior was examined for both ALS and matched control subjects. RESULTS: The MVC force of the tested FDI muscles ranged from 1.5 to 32 N for the ALS subjects, and from 19 to 46 N for the matched control subjects. A total number of 675 motor units from the ALS subjects and 1038 motor units from the matched control subjects were extracted. The number of extracted motor units from a single trial, regardless of force level, was 7±4 for the ALS group and 12±5 for the control group. A linear regression model (y=Ax%2BB) was fitted between the mean motor unit firing rate and the contraction force for each subject. For the ALS subjects with mild to moderate weakness, ?A? and ?B? variables were in the same range as the matched control subjects. However, the variables were quite scattered for the 4 ALS subjects with severe weakness (MVC < 5 N). The ALS subjects with very weak muscles tended to have higher motor units firing rates than the

matched control subjects at the same absolute forces. CONCLUSIONS: Our results showed that ALS patients had a similar pattern of motor unit behavior to the matched control subjects, except for those with severe weakness. [1] Holobar A, Zazula D. Multichannel blind source separation using convolution kernel compensation. IEEE Trans. Signal Process 55(9):4487-4496, 2007.

A novel device for assessing pelvic floor muscle function in women

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BACKGROUND AND AIM: Current tools only assess single aspects of pelvic floor muscle (PFM) function, and most are limited to static testing. This study tested the reliability of a novel device for assessing the PFMs during functional activities. METHODS: A self-retaining vaginal device was developed. Two Freescale Semiconductor MPX2300DT pressure transducers were mounted on the device: 1. level with the PFMs (PFP) and 2. superiorly for intra-abdominal pressure (IAP). Two pairs of electrodes were mounted adjacent to the PFMs (PFM_L and PFM_R). The electrodes were interfaced with miniTrignoTM electrodes and the pressure sensors were interfaced with TrignoTM load cell adaptors. Eight pelvic floor physiotherapists, mean age 42 years, were recruited. They performed three repetitions each of PFM maximum voluntary contractions (MVCs) and maximum effort coughs, in supine and standing, on two occasions one week apart. EMG and pressure data were recorded simultaneously at 2000 Hz using a Delsys TrignoTM wireless EMG system. EMG data were rectified and smoothed using the root mean square: 200 ms sliding window, 199 ms overlap. Peak values were extracted. First the independence of the channels was determined. Cross-correlation functions were performed to determine the time lag between the pressure channels. Repeated measures analyses of variance (ANOVAs) were computed to compare the pressure channels and the PFM sides. The mean absolute difference between the sides was calculated and normalized to the higher side (nMAD). Second the between trial reliability was determined. Repeated measures ANOVAs were computed for each channel and task. The coefficient of variation (CV) was computed for each channel, by task and day. Third the test-retest reliability was determined. Spearman?s Rho was calculated between days for each channel and task. Repeated measures ANOVAs were computed for each channel and task. The between days nMAD was also calculated. RESULTS: There were no time lags between the pressure signals (p>0.05). The amplitudes were different between the pressure channels for all tasks (p≤0.01) except the supine cough (p=0.66). During the MVCs PFP was higher than IAP, during the standing cough IAP was higher. The PFM_R was higher than the PFM_L (p≤0.003). See Table for the nMADs. There were no between trial differences in the peak amplitudes (p>0.2). See Table for the CVs and the results for the between day Spearman?s correlations and nMADs. The test-retest ANOVAs displayed significant between day differences in the pressure data (p<0.02), but not in the EMG. CONCLUSIONS: The signals recorded by the two pressure sensors were clearly independent, as were the two sides of the PFMs. Between trials, the pressure and EMG amplitudes were not different. Between days the EMG signals were not different, the pressure recordings did change, in a way that suggests learning or functional adaptation. The signals seemed to be less variable in standing than in supine.

Alterations in motor unit firing rate and action potential properties during isometric fatigue in stroke survivors

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BACKGROUND AND AIM: The limited number of studies that have investigated fatigue in chronic stroke survivors during voluntary contractions to the endurance limit have reported relatively higher central fatigue and lower peripheral fatigue on the affected side when compared to the less-affected side and healthy controls (Riley and Bilodeau, 2002; Knorr et al., 2011). Although these changes have been investigated using global indices of motor unit (MU) activation, alterations at the level of the single motor unit have not yet been examined. METHODS: Surface EMG activity was recorded during isometric abduction of the first dorsal interosseous muscle in twelve chronic stroke survivors, before, during and directly after a sustained fatiguing contraction at 30% maximum voluntary contraction (MVC) held until the endurance limit. A series of 10 second duration contractions were performed pre- and post-fatigue, four at 20% MVC and three at 40% MVC. Individual

motor unit spike trains were extracted from the surface EMG signal using the decomposition algorithm outlined in Nawab et al., (2010). The MU action potential waveform was characterised by using the identified MU firing times to spike trigger average the surface EMG signal. Motor units were accepted for further analysis based on the reliability tests outlined in Hu et al., (2013). RESULTS: Motor units on the affected side displayed a greater decline in firing rate during the sustained, fatiguing isometric contraction than on the less-affected side in chronic stroke survivors. Motor unit mean firing rates on both sides exhibited a tendency to be lower directly post-fatigue when compared with pre-fatigue. This was accompanied by evidence of a derecruitment of motor units as fatigue progressed on both the affected and less-affected sides. A significant increase in action potential duration was observed on both sides. However, the magnitude of the change was lower on the affected side. CONCLUSIONS: These results collectively indicate that a higher level of central fatigue is present on the affected side during isometric, fatiguing contractions in stroke survivors. In addition, this study demonstrates that manifestations of peripheral fatigue at the motor unit level, i.e. changes in MU action potential duration, are greater on the less-affected side following voluntary fatiguing protocols. [1] Riley, N. A., & Bilodeau, M. (2002). Changes in upper limb joint torque patterns and EMG signals with fatigue following a stroke. Disability & Rehabilitation, 24(18), 961-969. [2] Knorr, S., Ivanova, T. D., Doherty, T. J., Campbell, J. A., & Garland, S. J. (2011). The origins of neuromuscular fatigue post-stroke. Experimental brain research, 214(2), 303-315. [3] Nawab, S. H., Chang, S. S., & De Luca, C. J. (2010). High-yield decomposition of surface EMG signals. Clinical Neurophysiology, 121(10), 1602-1615. [4] Hu, X., Rymer, W. Z., & Suresh, N. L. (2013). Motor unit pool organization examined via spike-trigge

Contribution of deep and superficial motor units to the surface EMG of the masseter muscle.

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INTRODUCTION: The masseter muscle is, relatively, the strongest muscle in our body. It is also one of the most complex organized muscles. Localized motor unit territories and task specific motor unit activity enables the masseter to control different muscle portions independently. In this study we aimed at determining the amplitude profiles of masseter motor units in the depth of the muscle and at the skin surface. AIM: Determine the contribution of superficial and deeply located motor units of the masseter to activity measured using surface EMG (sEMG). METHODS: In a cohort of 10 healthy subjects we obtained high-density sEMG (256 channels, inter-electrode distance of 3 mm) of the right masseter during low levels of contractions. Simultaneously, motor unit activity from intramuscular fine wire electrodes is obtained and a monopolar needle is retracted via a stepper motor to obtain the motor unit territory in the depth of the muscle (scanning EMG). Via decomposition of the intramuscular EMG (iEMG) and spike triggered averaging the motor unit potential at the surface is determined. Next, sEMG signals are decomposed into the contribution of individual motor units. The contribution of the deep and superficial motor units to the sEMG is determined. RESULTS: Scanning EMG resulted in a total of 161 MU territories. Small and large MUs were found throughout the muscle depth. MU electrical size from the surface was strongly related to the electrical size determined by macro EMG after correction for depth of the MU. Unfortunately, no units that were decomposed from the surface EMG were detected by the scanning needle. Hence, no direct relation between the surface decomposed signals and MU depth could be obtained. Preliminary results show that a large part of the deeper units are within the noise level of the sEMG and hence can not be obtained for analysis without intramuscular electrodes. CONCLUSIONS: Large and small MUs can be found throughout the depth of the muscle. Our preliminary results show that masseter contains many small MUs that are only in part detectable by the surface electrodes. Hence, as may be expected, superficial and large MUs may be detectable at the surface and their firing patterns can be obtained using sophisticated decomposition techniques. This may bring insight in the possible role of neural alteration due to pain in this muscle. Additional experiments might give more insight in the limitation of the sEMG to see small and deeper MUs.

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S.12. *Spastic muscle and its treatment using botulinum toxin: new viewpoints with major implications*

Experimental and Modeling Assessments Specific to Treatment Aims Indicate New Viewpoints and an Understanding of Mechanisms of Effects of Botulinum Toxin Type A

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BACKGROUND AND AIM: Botulinum toxin type A (BTX-A) is widely used in treating spasticity. Partial muscle paralysis helps blocking the hyper-excitable stretch reflexes and reduces active force production. BTX-A is considered to improve function by acting against an agonist-antagonist force imbalance, increasing joint range of motion and decreasing passive resistance. However, a comprehensive understanding of its effects requires more critical and specific testing. Particularly, it should be assessed if BTX-A actually increases muscle length range of force exertion (Lrange) and decreases muscle passive forces. Moreover, an understanding of mechanism of BTX-A effects is lacking. The goal was to address these issues experimentally and using finite element modeling. METHODS & RESULTS: Experiments: Muscles of intact rat anterior crural compartment were tested 5 days post injection [1-3]. 0.1U BTX-A in 20μl of saline (BTX-A group) or only 20μl of saline (control group) was injected into mid-tibialis anterior (TA) belly. (i) The TA was lengthened (BTX-A, n=8, body mass 312.5±14.6g; control, n=8, body mass 318.5±12.5g). (ii) The extensor digitorum longus (EDL) was lengthened and, (iii) its relative position was changed (BTX-A, n=8, body mass 315.0±6.3g; control, n=8, body mass 300.0±6.9g). In (i) and (ii) muscles other than the one lengthened and in (iii) all muscles were kept at constant length. Findings: (1) BTX-A spreads to all compartmental muscles (peak force decrease range 47.3-85.6%). (2) Force decrease is not constant, but length dependent (TA force drop increases from 46.6% to 55.9% with shortening), (3) Lrange does not increase, but can decrease (for the EDL by up to 26.1%), (4) passive forces (for all muscles, minimally three-fold) and extracellular matrix (ECM) collagen content increase, (5) intermuscular interaction gets compromised (EDL proximo-distal force differences vanishes). Model: The middle half of Linked Fiber-Matrix Mesh model was inactivated

to represent BTX-A induced partial muscle paralysis. A key effect is restricted sarcomere shortening due to muscle fiber-ECM mechanical interactions [4-5]. This is central to effects of BTX-A on muscle mechanics increasing force production capacity of activated sarcomeres, decreasing Lrange, and explains (2) and (3). If modeled ECM stiffness is increased as indicated by (4), these effects get more pronounced and become permanent, post-treatment (ceased muscle paralysis). CONCLUSIONS: Our experiments reveal remarkable new effects of BTX-A worthwhile further clinical testing. Simulations suggest that ECM adaptations can affect muscles exposed adversely during spasticity management and post-treatment leading to a stiffer muscle, with elevated tone and reduced Lrange. [1] Yucesoy et al., J Biomech Eng, 2012 [2] Ates & Yucesoy, Muscle Nerve, 2014 [3] Yucesoy et al., Muscle Nerve, 2015 [4] Turkoglu et al., J Biomech, 2014 [5] Yucesoy, Exerc Sport Sci R, 2010 TUBITAK grant: 113S293

Structural and Functional Consequences of Neurotoxin injection in a Rat Model System

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INTRODUCTION: Over the past several decades, there has been a dramatic increase in the clinical indications for neurotoxin (NT) injection that range from cosmetic to therapeutic. While the basic mechanism of action of NTs are known, the long and short-term effects on skeletal muscle are poorly understood. We have developed a rat model1 that allows us to study these effects and thus to address clinically relevant problems of neurotoxin use. METHODS: We studied muscle properties associated with injection of Botulinum toxin (onabotulinumtoxinA, Allergan, Inc.) the most commonly injected NT. We determined the effect of varying injectate dose and volume in 9 groups of animal subjects (6u/100µL, n=10), 6u/20µL (n=5), 6u/4µL (n=6), 3u/100µL (n=6), 3u/20µL (n=7), 3u/4µL (n=7), 1u/100µL (n=6), 1u/20µL (n=6), and 1u/4µL (n=10)2. We also studied the effect of NT injection alone (NT, n=8), NT injection followed immediately by 10 isometric contractions (ISO; n=9), and NT followed immediately by 10 muscle passive stretch/release cycles (PS; n=10)3. Finally, we have mapped the expression of from 4 groups (n= 4/group) at 1, 4, 12, and 52 weeks after NT injection.4 RESULTS: Regarding dose and volume, we found a

significant effect of dose (P<0.05) but no effect of volume (P>0.2) and no interaction between dose and volume (P>0.2). Regarding tissue manipulation the ISO and PS groups demonstrated significantly lower torques compared to the NT group which received no physical manipulation (p<0.05) indicating greater efficacy. Even more surprising was that the ISO and PS groups both demonstrated a significantly smaller contralateral effect compared to the NT group that received no manipulation (p<0.05) indicating a decreased systemic effect. Finally, dramatic transcriptional changes occurred at 1 week with a paradoxical increase in expression of slow and immature isoforms, activation of genes in competing pathways of repair and atrophy, impaired mitochondrial biogenesis, and increased metal ion imbalance. Adaptations of the basal lamina and fibrillar extracellular matrix (ECM) occurred by 4 weeks. The muscle transcriptome returned to its unperturbed state 12 weeks after injection. DISCUSSION: These studies confirm dramatic effects of NT on muscle and may provide guidelines to minimize systemic side effects while still producing therapeutic results. For example, since NT dose dominates its functional effects, this implies free transport throughout the rat tibialis anterior muscle. Whether this applies to human injections remains to be determined. Implications for understanding normal muscle structure-function relationships will also be discussed in the symposium.
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The effect of botulinum toxin injections on gastrocnemius muscle volume in children with spastic cerebral palsy

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[1]Guy's & St Thomas' Foundation Trust

BACKGROUND AND AIM: We investigated the effect of botulinum toxin A (BTX) on gastrocnemius volume in children with cerebral palsy (CP) 4 months after injection. We expected significant reductions in muscle volume and that change in muscle volume would be related to the dose per unit muscle volume (DUMV). METHODS: 15 ambulant children with CP (2.91-8.87 years; 3F; 4 unilateral) had BTX injections to their gastrocnemii. Doses were consistent with the European Consensus Statement. 3D ultrasound scans of the gastrocnemii were made before, and four months after,

injection. We measured change in gastrocnemii volume over this period. Muscle volumes were normalised to body mass. The dependence of change in muscle volume on DUMV and on muscle volume prior to injection was evaluated using regression analysis. RESULTS: At 4 months post-injection, there was a reduction in gastrocnemius volume (mean 15.9%, $p < 0.018$). We found no significant relationship between DUMV and change in muscle volume ($p=0.852$). However, we found a dependence of change in muscle volume on original volume ($p=0.000$, $r2 = 0.612$) with larger muscles losing as much as 40% of their volume while there was little change in the size of the smaller muscles. CONCLUSIONS: Only small doses of toxin are required to induce significant atrophy in targeted larger muscles. In smaller muscles, a combination of increased diffusion of the toxin away from the target muscle and increased non-myofibrillar content may limit the therapeutic effect of the toxin.

Muscle material properties in children with hemiplegic cerebral palsy

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BACKGROUND AND AIM: Individuals with cerebral palsy (CP) tend to have altered passive muscle properties, however, quantification of material properties such as stiffness, has been limited to invasive methods such as biopsies or non-invasive measurements of muscle and joint stiffness such as torque-angle measurements, compression elastography, and tendon indentation. This talk will discuss shear wave (SW) ultrasound elastography to measure SW speed, which is related to stiffness, in vivo in individual muscles. The goal of this study was to evaluate SW speed of the medial gastrocnemius (MG) and tibialis anterior (TA) in children with hemiplegic CP over a range of ankle positions and torques. METHODS: Eight individuals (mean (SD) age: 9.4(3.7) yrs; height: 1.31(0.17) m; body mass: 33.3(12.8) kg; Gross Motor Function Classification System (GMFCS) Levels: three subjects at I; five subjects at II) participated in the study. Subjects were seated in a device (IntelliStretch rehabilitation robot) with their knee in full extension and foot strapped to a rotating footplate. SW elastography ultrasound measurements (Aixplorer, SuperSonic

Imagine) of the MG and TA muscles, as well as joint angle and torque measurements, were made with the ankle set at different angles (0° dorsiflexion (DF), maximum (DF), maximum plantarflexion (PF), and two other intermediary angles) while the muscle was passive. RESULTS: Our main findings show that SW speed in the MG and TA of the more-affected limb was 14% and 20% higher than the less-affected limb at 0° DF, respectively. At the limits of ankle range of motion, the SW speed in the TA in maximum plantarflexion was significantly higher in the less-affected limb, by 11% (p=0.006). Moreover, SW speed increased in MG and TA with increasing ankle angle, torque, and fascicle strain (linear and quadratic fit, respectively). CONCLUSION: We demonstrate that SWs travel faster in the MG and TA of the more-affected than the less-affected side of individuals with hemiplegic CP, suggesting that the affected muscles have altered material properties, specifically greater stiffness. Possible factors include increased collagen content in the extracellular matrix and other connective tissue, stiffer fibers, and titin. Our result of increased SW speed with longer muscle lengths further suggests that increased passive tension is largely responsible for the changes in SW speed rather than muscle activity or hypertonicity. Greater SW velocity was also correlated with reduced ankle range of motion, indicating that increased stiffness of the MG was limiting DF range of motion for some individuals. Use of SW elastography may provide an additional means to quantify muscle material properties in a patient-specific, non-invasive, real-time manner. Being able to characterize altered muscle material properties is important for understanding the causes of abnormal muscle function, aiding diagnosis, and guiding treatment planning.

Persistent muscle weakness and contractile material loss in a clinically relevant botulinum toxin type-a (btx-a) injection protocol

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BACKGROUND AND AIM: Botulinum toxin type-A (BTX-A) is a common therapeutic treatment modality to relax spastic muscles by preventing acetylcholine release at the motor nerve endings. Although considered safe and FDA approved, our previous studies showed persistent muscle weakness and contractile material loss following BTX-A intervention using an aggressive injection protocol that did not reflect clinical

BTX-A treatment practice. Therefore, the aim of this follow up study was to evaluate possible changes in muscle strength and contractile material in a clinically relevant BTX-A injection protocol. All experiments were performed using the quadriceps femoris musculature of New Zealand white (NZW) rabbits. METHODS: Twenty-three (n=23) NZW rabbits were divided into four groups as follow: Control saline injections (n=5); Single BTX-A injection (1-BTX-A; n=6); Two BTX-A injections (2-BTX-A; n=6), and Three BTX-A injections (3-BTX-A; n=6). BTX-A experimental group animals received an injection (3.5U/kg) unilaterally into the quadriceps femoris. Repeat injections were separated by a three months interval. Animals were evaluated six months following the last BTX-A injections. The primary outcome measured were knee extensor strength and the percentage of contractile material in the BTX-A injected muscles compared to the muscles in the Control group rabbits. Muscle strength was assessed by measuring the maximal isometric knee extensor strength obtained via femoral nerve stimulation. The percentage of contractile material was determined histologically as the area fraction of contractile material relative to the total muscle cross-sectional area. A one-way ANOVA was performed at $\alpha=0.05$. RESULTS: Six months following a single BTX-A injection, muscle strength (not shown) and contractile material (Fig. 1) were significantly reduced to 45% and 59%. Respectively, when compared to Control group rabbits. Interestingly, there was no additional loss in strength and contractile material in muscles receiving 2 or 3 repeat injections compared to rabbits receiving a single injection. CONCLUSIONS: The results of this study suggest that muscle strength and contractile material do not fully recover within six months of a clinically relevant BTX-A injection protocol, suggesting that BTX-A has long lasting adverse effects which may further compromise muscle function. Furthermore, it appears that multiple injections have an increased treatment effect without additional adverse effects, thereby allowing for prolonged reduction of spasticity without penalty to muscle structure and function. Fig 1 Histological cross-sectional image showing the percentage of muscle contractile material (H&E - red staining) and non-contractile material (white color - primarily fat and connective tissue). The amount of contractile material for Control group rabbits was 96±3.0% (top left). Following a single BTX-A injection, there was a significant reduction of contractile material for 1-BTX-A g

Intraoperative Testing of Individual Spastic Knee Flexor Muscles' Capacity to Affect Impeded Knee Joint Function in Cerebral Palsy Patients

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BACKGROUND AND AIM: Diagnostic tests and the treatment plan in spastic cerebral palsy (CP) including botulinum toxin type A administration or surgery are based on gross joint motion limitation, despite being applied to individual muscles. However, the relationship between individual muscle mechanical characteristics and the joint function is not known. Recently, we developed an intra-operative method to measure the forces of knee flexor muscles with respect to knee angle [1]. This method allows determining individual muscle's capacity to affect joint mechanics. The aim of this study was to assess (i) if mechanics of spastic semitendinosus (ST), semimembranosus (SM), and gracilis (GRA) muscles activated alone are representative of the impeded knee joint function and (ii) how simultaneous activity of an antagonistic muscle affects those mechanics. The following hypotheses seeking for reflections of muscle contracture at the joint were tested: (i) the muscle's joint range of force exertion is narrow, and (ii) high muscle forces are available in flexed knee positions. METHODS: During remedial surgery, forces of exclusively activated ST (n=7, 12 limbs), SM (n=8, 13 limbs), and GRA (n=7, 10 limbs) muscles of spastic CP patients were measured as a function of knee angle from flexion (120°) to full extension (0°). GRA muscle was tested also with added vastus medialis (VM) activation (n=6, 10 limbs). RESULTS: For most limbs, spastic muscle force-knee angle curves show only an ascending portion and for the remaining limbs the curves have also a descending portion for ST, SM, and GRA muscles [e.g., 2]. Lack of curves showing a descending portion alone indicate no narrow joint range of force exertion. Capacity of producing knee flexion forces (mean (SD): at KA=120° ST: 11.4% (21.4%), SM: 4.2% (3.4%), and GRA: 59.4% (33.3%); at KA=90° ST: 33.2% (27.5%), SM: 10.7% (9.7%), and GRA: 75.1% (28.6%)) show significant differences between muscles. However, for none of them, force production capacity in flexion was supreme to cause the apparent joint movement limitation. Yet, simultaneous activation of the VM, caused seven of the ten limbs to show availability of high GRA forces in flexed knee positions (with minimally 84.8% of peak force at 120°). A clear narrow operational joint range of force exertion was observed for four limbs [3]. CONCLUSIONS: Both hypotheses were rejected if muscles are stimulated exclusively. Therefore, individual mechanics of spastic ST, SM, and GRA muscles do not represent

impeded knee joint function. However, antagonistic co-activity does cause substantial changes in force production capacity of spastic GRA muscle. Therefore, we concluded that inter-antagonistic mechanical interaction is an important factor determining spastic muscle's contribution to impeded joint function. [1] Yucesoy C.A. et al. J Biomech, 2010 [2] Ates F. et al. Clin Biomech, 2013 [3] Ates F. et al. Clin Biomech, 2014 TUBITAK grant 113S293 is acknowledged.

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DAY 3, FRIDAY JULY 8

S.13. *Prosthetics to Orthotics: Transferable Expertise*

The state-of-the-art EMG control in dynamic orthoses

Derek Kamper[1]

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Orthoses have similar task objectives as prostheses, yet pose unique challenges due to the presence of the impaired limb. To simulate discussion during our workshop (?Prosthetics to orthotics: transferrable expertise??), I will describe current techniques employing electromyography (EMG) to control external devices, with an emphasis on applicability to orthoses. While assistive technology has become increasingly sophisticated, user control of these devices remains challenging. The human body employs billions of neurons to provide the exquisite sensoriomotor control of the limbs. Replication of this system is neither currently possible nor foreseeable. Instead, other means of signaling user intent must be found. One intuitive method involves use of a subset of the residual neuromuscular system. Electrical activity can be monitored in the central nervous system, such as with electrode arrays implanted in the cortex, or recorded in the periphery at the neuromuscular junction. The latter method, relying on EMG, has advantages in that it is less invasive and the nerves normally associated with the desired functional task can be more easily targeted. Studies employing directed reinnervation of a designated muscle with residual nerves which formerly ran to muscles which have been lost due to amputation, have noted the facility with which users can use the system[1]. Lightweight, flexible surface electrodes provide a comfortable interface for deciphering user intent. These electrodes can be embedded into the assistive device itself. As a mapping is generated between EMG activity and desired task, exact positioning of the electrodes on the limb may not be crucial. Repeatable modulation of EMG patterns specific to a task is more important than the absolute activation pattern. Untargeted electrode replacement may perform as well as targeting specific muscles[2]. Signals may, in fact, be acquired from the contralateral limb to control a device on the ipsilateral

limb. EMG bandwidth can be increased by utilization of electrode arrays. For greater precision, electrodes can be placed within the body, such as by inserting into the muscle or surrounding the nerve. The implantable myoelectric sensors (IMES)[3] and the longitudinally implanted intrafascicular electrodes (LIFE)[4] have been developed to provide user control of hand prostheses. These electrodes could also be employed to control orthoses, although a number of the populations which could potentially benefit from orthoses have altered neuromuscular systems which could hinder recording and deciphering EMG signals. Such individuals may, however, derive therapeutic benefit from the use of EMG-controlled devices through the training of creating specific activation patterns. 1) Kuiken TA, et al., Prosthet Orthot Int 2004; 28: 245-253 2) Farrell TR and Weir R, IEEE Trans Biomed Eng 2008; 55: 2198-2211. 3) Weir RF, et al., IEEE Trans Biomed Eng 2009; 56: 159-171. 4) Micera S, et al., IEEE Rev Biomed Eng 2010;

Unassisted FES is all you need to regain hand function

Thierry Keller[1]

[1]Tecnalia Research and Innovation

Orthoses have similar task objectives as prostheses, yet pose unique challenges due to the presence of the impaired limb. This is specifically the case for active orthoses. Functional electrical stimulation driven orthoses, called transcutanous neuroprostheses act with and on the impaired limb and use both remaining residual voluntary functions and elicited muscle activations. As such the impaired limb serves as actuator and is at the same time actuated. Specific challenges of FES driven limbs are: i) mechanical/wearability properties of the orthotic structure; ii) properties of the electrode interface; iii) specificities of the stimulated neural/musculoskeletal structure; iv) neuroprosthesis control challenges; and the multi-dimensionality challenge. This is particularly the case for neuroprostheses enabling hand function. The main novelty in transcutaneous neuroprostheses research in recent years was the investigation, modeling, analysis, development and application of transcutaneous FES arrays that allow a dynamic distribution of electrical fields over the limb surface. They allow an improved control over eliciting action potentials in superficial nerve branches and lead to improved limb functions. This session contribution will discuss the above mentioned challenges and show how far the field currently is from having an unassisted transcutaneous neuroprosthesis to regain hand function.

Direct mechanical control outperforms EMG control

Dick Plettenburg[1]

[1]**Delft University of Technology**

BACKGROUND AND AIM: Orthoses have similar task objectives as prostheses, yet pose unique challenges due to the presence of the impaired limb. To stimulate discussion during our workshop "Prosthetics to orthotics: transferrable expertise?", I will defend the hypothesis that direct mechanical control outperforms EMG control. METHODS: The sound human arm has an excellent controllability due to a highly sophisticated network of sensors and information paths [proprioception] providing extensive feedback. In the use of prostheses most of these feedback paths are missing. This is often true for orthoses as well. For the optimal subconscious control of a prosthesis or orthoses the patient feedback present must be employed as completely as possible. This requires the use of the principles of extended physiological proprioception. RESULTS: From the control options presently available, myoelectrical control must be considered as an open loop system. It lacks by principle the feedback indispensable for the subconscious control level desired. The harnessing of body movements has the inherent ability to fully employ the principles of extended physiological proprioception. However, the present harnessing techniques fail to do so and are generally of a dreadful engineering quality. The challenge for the prosthetic/orthotic profession is to make subconscious control of prostheses and orthoses available. Therefore, research should focus on the [improvement of] control options that comply with the rules of extended physiological proprioception. By principle, myoelectrical control cannot meet these rules. Hence, any further research into myoelectrical control does not contribute to the answer this challenge. CONCLUSIONS: Improvement of harnessing techniques in combination with improvements in efficiency of prosthetic/orthotic mechanisms does answer the challenge. In addition, they have the added benefit of being lower in mass, more reliable, faster, and smaller when compared to electro-mechanical

solutions. Therefore, mechanical solutions are the better choice in prostheses and orthoses.

Surface EMG control in neurorehabilitation: experiences from EMG-driven modelling and robotic for upper and lower limb post-stroke rehabilitation

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Background: The recovery of motor function following stroke remains a challenge in neurorehabilitation. Often, the remaining impairments are associated with poor autonomy in daily life. Innovative approaches are therefore needed, employing advances in neuroengineering into clinically viable devices. Purpose: The FP7-EU project MYOSENS aims at translating technological advances in surface electromyography (sEMG) into new classes of robotic devices for rehabilitation. These devices close the sensory-motor loop on the basis of the predicted motor intention derived from residual sEMG recorded from post-stroke patients. The prediction and control may be based either exclusively on signal features or on musculoskeletal mechanical variables estimated by musculoskeletal models from the raw EMG. Methods: Musculoskeletal modelling formulations driven by sEMG were developed to bridge the neural and mechanical aspects of motor functions in vivo in the intact human. These models allow predicting the musculoskeletal response to any recordable neuromuscular behaviours (healthy or pathological). In this context, two robots (Shoulder: RehArm®, FERROBOTICS GmbH; Hand: Amadeo®, Tyromotion GmbH) were used to test the clinical effect of using sEMG closed-loop control to practice voluntary movements as rehabilitation treatment. Two feasibility studies (N=20 each) were conducted in patients with every impairment of upper limb motor function after stroke. Fugl-Meyer upper extremity (F-M UE), FIM®, Nine Hole Peg test (NHPT) and Reaching Performance Scale (RPS) were assessed before and after a therapy of 15 sessions over 3 weeks. Results: All patients enrolled completed the experiments without side effects. The shoulder treatment induced significant improvement at F-M UE, RPS and FIM. Patients with severe impairment (F-M UE < 40/66) were able to complete a comparable number of repetitions of shoulder motion as mild patients when using sEMG for control, but not when using force control. The hand treatment induced significant improvements at F-M UE, FIM, RPS

and BBT. In this case, all the patients could control the robotic devices by sEMG, but not by torque. Moreover, threshold scores of specific outcome measures could predict the ability of the individual patients to control exclusively using sEMG (RPS≥3, F-M UE≥10 points) or also with torque (BBT≥3). Conclusion: EMG can be used for controlling rehabilitative robotic devices with methods clinically feasible. The proposed EMG-based experimental treatments resulted in a significant improvement of robust clinical outcomes, indicating that EMG control is feasible for a greater proportion of patients with respect to torque control. Grants: The EU FP7 project "Myoelectric interfaces for motor control - MYOSENS" (286208).

The case for impedance control in wearable robotics

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Powered orthoses--often termed exoskeletons--have similar design and control constraints to prostheses, with the unique and important challenge of interacting with existing limb anatomy. Furthermore, exoskeleton wearers have varying abilities to voluntarily control their limbs, depending on the specific pathological application of the exoskeleton. In this talk, part of the symposium on translating prosthetic research to orthotic applications, I will defend the hypothesis that impedance control implemented in exoskeletons will provide superior performance. The rationale for this hypothesis is that impedance control enables the mathematical framework to offset the biomechanical changes that occur following neuropathologies, as well as provides a mechanism to define the impact of the additional (and often unpredictable) effort provided by the wearer. Examples will be highlighted from the prosthetics and orthotics literature, as well as the author's previous work. A common result of neuromotor impairment is a reduction in the ability to voluntarily control joint mechanical impedance. Clinically, this is known as spasticity, hypertonia, and contracture that causes changes in the velocity and position dependent joint mechanics (i.e. damping and stiffness, respectively). These changes induce unwanted joint resistance that the patient must overcome during movement. Due to accompanying weakness or hemiparesis, overcoming the additional resistance can be extremely challenging. Thus, impedance control is a promising control methodology as it enables the ability to counteract the impedance changes that occur as a result of neuromotor injury. Classical position and torque control focus on controlling these variables directly while following a pre-determined path, driving the error in these quantities to zero. Conversely, impedance control focuses on controlling the relationship between position and torque, rather than either of these variables directly. Impedance control is often parameterized in similar terms of stiffness, damping and inertia, and changes in these parameters affect the enforced dynamics between position and torque. Using the impedance control framework, the pathologically altered joint mechanics can be appropriately compensated with the impedance parameters specified in the control system. Additionally, impedance control is advantageous because it couples and bounds the position and torque, preventing potentially unwanted or unsafe changes due to the joint effort of the wearer. Classical torque control does not restrict or depend on position, and position control does not restrict torque. However, when the existing anatomy is present and providing additional torques in parallel with the exoskeleton, traditional torque and position control cannot define the impact of the additional effort provided by the wearer. This may cause unwanted changes in torque or position that can destabilize the wearer, compromising balance and safety.

Structured panel discussion on prosthetics to orthotics: transferrable expertise

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Orthoses have similar task objectives as prostheses, yet pose unique challenges due to the presence of the impaired limb. To stimulate discussion during our workshop ("Prosthetics to orthotics: transferrable expertise?"), we will invite audience participation to discuss the presented hypotheses. Below you see a list of propositions that are stated such that they evoke discussion. We will summarize the main arguments and invite the room to a structured discussion. - Derek Kamper: State of EMG control in dynamic orthoses. - Thierry Keller: Unassisted FES is all you need to regain hand function. - Dick Plettenburg: Direct mechanical control outperforms EMG control. - Elliott Rouse: Force/impedance control outperforms EMG control in orthoses. - Dario Farina: EMG control gives the most functional gain.

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S.14. Clinical applications of muscle synergies

Function and dysfunction in brain connectivity coordinating muscle synergies in humans

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BACKGROUND AND AIM: The human brain is believed to simplify the control of the large number of muscles in the body by flexibly combining muscle coordination patterns, termed muscle synergies. However, the neural connectivity allowing the human brain to access and coordinate muscle synergies to accomplish functional tasks remains unknown. Moreover, dysfunction in the brain connectivity that coordinates muscle synergies may be an important component in disorders of neuromuscular control. METHODS: We define and demonstrate the capabilities of a multimodal approach to investigate brain connectivity of muscle synergies. First, using electromyography (EMG), we describe and quantify synergistic interaction among a group of muscles. Second, using functional magnetic resonance imaging (fMRI), we identify cortical and subcortical regions-of-interest (ROI) associated with activation of specific muscle synergies. Third, using transcranial magnetic stimulation (TMS), we show that different fMRI-identified ROI act as "muscle synergy access points" which activate different muscle synergies. Fourth, using resting-state fMRI (rs-fMRI), we make whole-brain maps of the functional connectivity (interaction strength during rest) of different muscle synergy access points. Finally, we associate inter-individual differences in functional connectivity of muscle synergy access points with inter-individual differences in muscle control and disease status for patients with chronic pain. RESULTS: Results for muscle synergies involving pelvic floor muscles are presented. EMG recordings verify that pelvic floor muscles are synergistic with gluteal, toe, and deltoid muscles but not finger muscles. fMRI data uncover motor cortical ROI that activate during voluntary activation of pelvic floor muscles and also activate during voluntary activation of pelvic floor muscle synergists. fMRI data also uncover motor cortical ROI specific to activation of the pelvic floor synergists. TMS experiments show that motor cortical ROI are muscle synergy access points, each activating different muscle synergies. rs-fMRI maps of functional connectivity

demonstrate that motor cortical access points to different muscle synergies have significantly different functional connectivity with distinct and distant brain regions. Finally, we show that inter-individual differences in the functional connectivity of motor cortical muscle synergy access points are associated with inter-individual differences in muscle synergy strength at the EMG level in healthy individuals, and are associated with symptom intensity and muscle synergy strength in individuals with chronic pelvic pain. CONCLUSIONS: These results suggest that proper function in human brain connectivity plays a critical role in coordinating different muscle synergies, and dysfunction in this connectivity may play an important role in chronic pain disorders.

Does modularity in post-stroke motor coordination differ in dynamic and static tasks?

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Background and Aim: Previous studies of human reaching and locomotion in stroke survivors (Cheung et al., 2009, 2012; Clark et al., 2010) suggest that the structure of muscle synergies (a coordinated pattern of activities of a group of muscles) is conserved, but the activation profile of the synergies is altered post-stroke. In contrast, our previous studies of isometric force generation (Roh et al., 2013, 2015) demonstrated that stroke induces alterations in the structure of upper limb muscle synergies. These results suggest that the underlying mechanisms of post-stroke motor performance in dynamic (reaching or locomotion) and static (isometric force control) conditions may differ from the perspective of modularity in motor coordination. To address this question, we examined the modular organization of muscle activation patterns across the time course of isometric force development, while our previous work solely focused on the averaged, stable force match phase. Methods: EMG was recorded from eight major muscles of the affected arm of eight chronic stroke survivors with severe impairment (Fugl-Meyer < 25) and both arms of six age-matched control participants, during a 3-dimensional isometric force matching task. A non-negative matrix factorization algorithm identified muscle synergies in two time windows: force ramping phase, and stable force match. Correlation coefficients between any potential pair of end-point force components were also computed for the same time windows. Results: The same set of synergies was expressed during both phases of force generation, in both stroke and control subjects. In stroke, but not in the control, the structure of two proximal synergy patterns was altered. The atypical co-activation of the three heads of the deltoid was conserved throughout force development in the stroke group. In addition, the activation profiles of two elbow and shoulder synergies were synchronized so that the corresponding synergy pattern appeared as a merged one in stroke survivors. In both groups, all computed force correlations were significantly higher ($p<0.05$) during the force ramping phase compared to stable force generation. In stroke, a higher force directional error was observed during the force ramp phase ($p<0.05$). Conclusions: Stroke-specific muscle synergies are conserved throughout the entire duration of isometric force development. During stable isometric force generation in both control and post-stroke groups, the CNS is able to appropriately modulate the activation profile of muscle synergies to maintain the targeted force, which, in turn, decreases the corresponding force couplings and directional error. Overall, these findings indicate that stroke may induce alterations in the structure of muscle synergies in a task-specific way, while the merging of muscle synergies is common to the temporal EMG profiles of both dynamic and static motor tasks following stroke.

Neuromotor modules as markers of diseased states and progress of motor recovery

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BACKGROUND AND AIM It has been suggested that the combination of discrete motor modules is a viable framework for mechanistically understanding how the immense variety of movement patterns are generated by the CNS. In most formulations, a motor module consists of a set of time-invariant activation weights across many muscles (widely called a "muscle synergy"), and a time-varying coefficient that scales the muscle weights across time. Experiments performed using techniques ranging from multi-channel EMG recordings to optogenetics have provided evidences that support the neural origin of motor modules. If motor modules are indeed neurophysiological entities employed by the CNS for control, characterizing their deviations in diseased conditions should not only offer insights into the underlying pathology responsible for the dysfunctional movement, but also suggest how an effective intervention may be rationally designed. At the very least, distinctive patterns of abnormal motor modules may be robust signatures of particular diseased states, and thus be potentially used as markers for diagnosing a condition, or for evaluating the progress of recovery. Here, we argue, with two examples, that abnormal patterns of either the muscle weights or temporal activations of the motor modules may serve as markers of diseased states. METHODS EMG signals and kinematics were recorded from upper-limb of adult stroke survivors (for example 1) and lower-limb of children with delayed-onset locomotion (for example 2), respectively, before and after rehabilitation. Motor modules were extracted from the signals using the non-negative matrix factorization algorithm. RESULTS The first example concerns upper-limb modules observed in stroke survivors. We have previously shown that severe post-stroke motor impairment is associated with merging of the modules' muscle weights, while the chronicity of stroke is reflected as fractionation of the muscle weights. Our preliminary results from chronic survivors undergoing rehabilitative training indicate that enhanced post-rehab motor recovery is associated with the activation of a specific module in the affected arm after rehab, one that can be regarded as a marker of post-training recovery. The second example concerns lower-limb modules observed in infants with delayed-onset locomotion, a condition with variable causes that affects up to 5-15% of newborns. We found in our pilot data that in these children, the temporal activation burst of one module was consistently time-shifted to the right relative to the burst of another module. Children responsive to physiotherapy displayed a post-rehab temporal activation pattern similar to that observed in age-matched, normally developed children. CONCLUSIONS The above two examples illustrate the potential of using either the muscle weights or temporal activations of specific modules for early detection and/or evaluation of recovery progress for different movement disorders.

Synergistic changes in muscle coordination post-stroke in a locomotor learning task

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BACKGROUND AND AIM: Promising studies have shown that patients post-stroke can re-learn to step symmetrically after walking on a split-belt treadmill, which moves their legs at different speeds (Reisman et al. 2013). While this is encouraging, little is known about the underlying changes in muscle activity. The latter is important to understand the actual plasticity of neural mechanisms in these patients. METHODS: We investigated changes in muscle coordination of 16 chronic post-stroke subjects and 16 sex- and age-matched controls during split-belt walking. All patients were in their chronic stage (>6 months after stroke) and had diverse motor impairments as quantified by their Fugl-Meyer scores ranging from 21 to 33. Patients experienced a typical adaptation paradigm consisting of a baseline, adaptation, and post-adaptation conditions. In the baseline and post-adaptation conditions both legs moved at the same speed, whereas in the adaptation condition legs moved at different speeds (i.e., the paretic leg moved twice as slow as the non-paretic one). We measured electromyographic activity in 15 muscles on each leg and evaluated changes in activity between the adapted vs. both the baseline and the post-adaptation conditions using Skillings-Mack test. Bonferroni correction was used to account for multiple comparisons. In addition, a measure of independence in muscle activity was obtained using principal component factorization analysis. This was done to determine if abnormal muscle synergies post-stroke were disrupted when experiencing the split-belt condition (Fig. 1A). RESULTS: We found consistent changes in muscle coordination bilaterally and not only in the sound limb. Interestingly, we observed partial spatial and temporal symmetricity in these changes. In other words, increased activity on one side was mostly matched by decreased activity on the other side (spatial symmetricity) and changes in muscle activity for each leg occurred during the same phase of the ipsi-lateral gait cycle (temporal symmetricity). Similar adaptation of muscle activity was observed in age-matched controls. Importantly, our analysis of muscle independence indicated that paretic muscles increased its independent activity during the adaptation condition compared to baseline (Fig. 1B). This suggests that patients can modulate paretic muscles independently when learning a new walking pattern on the split-belt treadmill. CONCLUSIONS: Our results indicate that walking in a novel condition, such as split-belt walking, induces changes in the paretic limb beyond the expected compensatory changes in the non-paretic limb. Moreover, our proxy for muscle control independence suggests that co-activation of paretic muscles can be reduced during split-belt walking. Taken together, these are promising findings indicating that chronic post-stroke patients may still have the flexibility to change their muscle coordination to improve their walking despite of their cortical lesions.

Do muscle synergies change after treatments in cerebral palsy?

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BACKGROUND AND AIM: Cerebral palsy (CP) is a neuromuscular disorder that occurs at or near the time of birth that affects mobility and muscle control. Each individual with CP has a specific injury to the brain, which manifests as a unique set of movement impairments. Current treatments include physical therapy, pharmacological interventions such as botulinum toxin injections (BTA), and surgical options such as selective dorsal rhizotomy (SDR) and single-event multilevel orthopaedic surgery (SEMLS). Improving movement requires that treatments be tailored to each individual. However, properly tailoring treatments remains a persistent challenge and new methods are needed to quantitatively characterize muscle control for use in treatment planning. The goal of this study was to evaluate whether muscle control as measured by synergies changes after treatment and if synergies are associated with treatment outcomes in CP. METHODS: We retrospectively analyzed 174 cases of children with CP that received gait analysis before and after treatment. This study included 62 cases of BTA, 65 cases of SEMLS, and 47 cases of SDR. Electromyography data was processed using nonnegative matrix factorization which identifies a specified number of weighted muscle groupings, or synergies. Synergy complexity was taken as the total variance account for by one synergy (tVAF). Changes in gait were evaluated with the Gait Deviation Index (GDI) and dimensionless walking speed. T-tests were performed to examine whether each treatment resulted in changes in tVAF, GDI, or walking speed. Linear mixed effects models were computed to determine whether initial measures of synergies were correlated with post treatment changes in GDI or walking speed. RESULTS: There were no significant changes between pre and post gait analyses in tVAF, walking speed, or GDI for the BTA or SDR groups ($p>0.05$). The SEMLS group

showed significant changes in tVAF, walking speed, and GDI ($p<0.05$) after treatment. In the SEMLS group, walking speed decreased while tVAF and GDI were more similar to unimpaired gait after treatment (Figure 1). The linear mixed effects models indicated a correlation between pre-tVAF and post-walking speed in the SEMLS and SDR groups, as well as a correlation between pre-tVAF and post GDI in the SEMLS group ($p<0.05$). CONCLUSIONS: There were significant changes in tVAF after SEMLS which had large changes in outcomes. When there were small changes in outcome measures muscle synergy complexity did not change. Pre-treatment measures of muscle synergies were also associated with changes in gait for SEMLS and SDR suggesting that synergies may be a useful measure of motor control. Figure 1: Before vs after SEMLS treatment values of tVAF (top), dimensionless walking speed (middle), and GDI (bottom). Paired t-tests were used to compare each variable before and after treatment with significance set at $p<0.05$. tVAF and GDI improved while dimensionless walking speed did not.

Long-term training modifies the modular structure and organization of walking balance control

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Background and Aim: How long-term training affects the neural control of motor behaviors is not well understood, but may reveal previously unknown mechanisms of motor coordination and learning that could guide future rehabilitation efforts. Therefore, our goal was to determine how the structure and organization of muscle coordination patterns for walking and balance are affected by long-term training. We hypothesized that long-term training leading to skilled motor performance increases the recruitment of common muscle patterns across different motor behaviors. In lieu of searching for behavior-specific or optimal muscle patterns, generalizing the same muscle patterns across behaviors may enable rapid, reliable, and efficient identification of motor solutions. Methods: To test this hypothesis we recruited 13 professional ballet dancers (experts) and 10 untrained novices. We used muscle synergy analysis to quantify and compare the structure and organization of their muscle coordination patterns during overground walking and a challenging beam-walking task designed to assess walking balance proficiency. Results: Consistent with

our expectation that experts would have better walking balance proficiency, experts walked farther than novices on the narrow beam. During beam walking experts recruited more muscle synergies than novices, suggesting a larger motor repertoire. In contrast, the number of muscle synergies recruited during overground walking did not differ between experts and novices, but their composition did, suggesting that extended practice on one behavior (ballet) can alter the control of another (walking). Muscle synergies in experts had less muscle coactivity and were more consistent than in novices during beam and overground walking, reflecting greater efficiency in muscle output. Moreover, the pool of muscle synergies shared between beam and overground walking was larger in experts compared with novices, suggesting greater generalization of muscle synergy function across multiple behaviors. These differences in motor output between experts and novices could not be explained by differences in kinematics. Thus, they likely reflect differences in the neural control of movement following years of training rather than biomechanical constraints imposed by the activity or musculoskeletal structure and function. Conclusions: The recruitment of common muscle synergies between beam and overground walking by experts suggests that to learn challenging new behaviors we may take advantage of existing muscle synergies used for related behaviors and sculpt them to meet the demands of a new behavior rather than create de novo behavior specific muscle synergies. Therefore, successful rehabilitation outcomes may require therapies that train patients to utilize common muscle synergies across different motor behaviors rather than behavior specific motor solutions.

O.13. Muscle Physiology

O.13.1 *Passive stiffness of lumbar multifidus and erector spinae muscle fibres is decreased in ENT1 deficient mice*

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BACKGROUND AND AIM: Mice lacking equilibrative nucleoside transporter 1 (ENT1) develop progressive ectopic mineralization of the fibrous connective tissues of the

spine [1], which is believed to result in a stiffer spine as the disease progresses caudally with age. Experimentally induced intervertebral disc (IVD) degeneration creates a less stiff spine, and in rabbits, has been shown to increase the passive mechanical stiffness of the adjacent multifidus muscle (muscle fibres and bundles of fibres) [2]. The purpose of this study was to determine how the passive mechanical stiffness of muscle fibres and bundles changes in the paraspinal muscles of an ENT1 deficient mouse. It was hypothesized that both fibres and bundles of these muscles would be less stiff in ENT1 knockout (KO) compared to wild-type (WT) mice, demonstrating an inverse compensatory relationship of the stiffness of muscle with the stiffness of the structure to which it attaches (the spine). METHODS: Lumbar multifidus (M) and erector spinae (ES), and tibialis anterior (TA) muscles of male, littermate paired, 8 month old, ENT1 KO and WT mice (n=8 each) were harvested; 3 fibres and 3 bundles from each muscle were tested. Sarcomere length and force were recorded as each sample was rapidly stretched every 2 minutes by increments of ~0.25 μm [2]. The force at the end of every 2 minutes was normalized to the cross sectional area of the sample to give a measurement of stress which was plotted against sarcomere length. A quadratic curve was fitted to the data points and passive elastic modulus was determined by finding the tangent slope at a sarcomere length of 3.2 μm. T-tests were used to compare modulus between KO and WT for each muscle, in both fibres and bundles. RESULTS: Fibre passive elastic modulus was lower in KO compared to WT in the M and ES muscles, while TA showed no difference (Figure 1A) (p=0.0262, 0.0016, 0.3436 respectively). M, ES, and TA bundles were not significantly different between KO and WT (Figure 1B) (p=0.1223, 0.1641, 0.1410 respectively). CONCLUSIONS: Muscle fibre passive elastic modulus (stiffness) was lower in the ENT1 KO, as expected, while bundles were not. Bundles were expected to show a similar if not greater difference than fibres, as this was seen with IVD degeneration [2]. It was suggested that this was mostly due to an increase in fibrosis of the connective tissue matrix [2]. This would suggest that in the mineralized spine of the ENT1 KO, the muscle connective tissue is not impacted, but some other mechanism is responsible for causing greater stiffness of the individual muscle fibres.
REFERENCES: [1] Warraich S et al. (2013) J Bone Miner Res 28 (5); p. 1135-49. [2] Brown S et al. (2011) Spine 36 (21); p. 1728-36.

O.13.2 *High-resolution in vivo measurement of changes in architecture of the human medial gastrocnemius muscle during passive lengthening*

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BACKGROUND AND AIM: The capacity of muscles to generate force is partially determined by the arrangement of its fibres, i.e. by the muscle's architecture. Most muscles have complex three-dimensional (3D) architectures which are difficult to reconstruct with conventional methods based on 2D ultrasound images. For this study we obtained high-resolution 3D measurements of the architecture of the human medial gastrocnemius muscle at three different lengths using diffusion tensor imaging (DTI), an MRI technique that can be used to reconstruct muscle structure in 3D in vivo. METHODS: DTI scans and anatomical MRI scans were obtained from eight healthy subjects at three ankle joint angles: (1) the angle at which fascicles first start to lengthen (the slack angle, which was measured with ultrasound); (2) full ankle dorsiflexion; and (3) an angle between (1) and (2). The knee was flexed ~18°. For each joint position in each subject, DTI tractography was used to reconstruct 10,000 fibre tracts in the medial gastrocnemius. Second order 3D polynomial functions were fitted to the tracts. The curves were then linearly extrapolated until they terminated on both the deep and the superficial aponeuroses, which were reconstructed from the anatomical MRI scans. Tracts that were extrapolated by more than 30% of their initial length were excluded from the analysis. The remaining tracts were assumed to represent the course of muscle fascicles. At least 2,800 and on average 4,200 fascicles were reconstructed per muscle. The 3D pennation, length and curvature of the fascicles were calculated. RESULTS: At their shortest in vivo length fascicles were, on average, 38 mm long (subject means ranged from 31-50 mm) and had a pennation of 29° (range 24-34°) and a curvature of 8 m-1 (range 5-13 m-1). At full dorsiflexion with the muscle-tendon unit at its longest in vivo length, the mean fascicle length increased to, on average, 56 mm (range 38-69 mm) and pennation and curvature decreased to 20° (18-26°) and 5 m-1 (4-7 m-1), respectively. At the intermediate ankle angle intermediate values of length, pennation and curvature were seen. Using estimates of the total muscle-tendon length based on cadaver measurements, these measurements show that, on average, 55% of the total lengthening above the slack length occurs in fascicles. There was variation between subjects, with fascicles contributing as little as 41% or as much as 74% to the total change in muscle-tendon length. A preliminary analysis did not identify major regional variations in fascicle

lengths or changes in length during passive lengthening. CONCLUSIONS: These data represent the first high-resolution, 3D measurements of changes in architecture of the whole human medial gastrocnemius muscle during passive lengthening. The novel techniques used in this study can also be used to measure architecture of other muscles and changes in architecture during active contractions and in muscles affected by disease.

O.13.3 ***Inhomogeneity of emg-and ultrasound-detected onset of voluntary muscle activation explains their inconsistent relationship***

Angela Dieterich[1], Alberto Botter[2], Taian Vieira[2], Anneli Peolsson[3], Frank Petzke[1], Paul Davey[4], Deborah Falla[1]

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BACKGROUND AND AIM: Ultrasound (US) measures of muscle activation are becoming increasingly utilised in musculoskeletal research particularly to characterise the behaviour of deep muscle activation. However, contradictory conclusions have been observed when evaluating the behaviour of muscles with either US or electromyography (EMG), for instance, changes in the behaviour of the transversus abdominis muscle in people with low back pain. The aim of the study was to examine the influences of (a) regional heterogeneity of EMG and US onset and (b) contraction speed on the difference between EMG- and US-measured activation onsets. METHODS: 28-channel high-density surface EMG with an electrode transparent to US and M-mode US were used to measure the onset of voluntary biceps brachii activation. Isometric elbow flexion was performed in 20%, 30%, 50% and 70% MVIC on a Biodex by 10 healthy young men. The first EMG onset, EMG onset at the US transducer and M-mode US-measured muscle motion onset were determined using computed and visual detection. Onset differences and correlations with EMG between-channels onset variation and rate of torque development were statistically evaluated. RESULTS: EMG onset at the US transducer was detected AFTER motion onset in 44% of trials based on computed detection of the onset and 79% based on visual detection of the onset. Multi-channel EMG indicated substantial onset heterogeneity; between-channel standard deviation was 73 ms and 28 ms (median) for the computed and visual analysis of onset detection, respectively. M-mode US

indicated additional onset differences between superficial and deep regions of the biceps brachii. Differences between EMG- and US-measured onsets increased with higher onset heterogeneity (computed: rho= 0.242, P< 0.01, visual detection: rho= -0.392, P< 0.001). Onset heterogeneity was markedly influenced by contraction speed (computed: rho= -0.471, P< 0.001, visual detection: rho= -0.652, P< 0.001). CONCLUSIONS: Inconsistency exists between EMG onset and muscle motion onset detected with US. Muscle activation elicits muscle motion that is transmitted through the muscle, which may be detected before EMG onset in other regions of the muscle. US-measured onset of myomechanical activation provides a viable, non-invasive assessment of muscle activity, however not a simple substitute for EMG. Caution should be taken when comparing results from EMG and US studies which evaluate the behavior of muscles.

O.13.4 *Feasibility of quantitative uterine motion analysis by ultrasound speckle tracking outside pregnancy*

Federica Sammali[1], Nienke Kuijsters[2], Chiara Rabotti[1], Benedictus Schoot[3], Massimo Mischi[1]

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Background and aim: Boosted by the modern trend in postponing conception, the number of women facing infertility problems is considerably increasing. Many couples are therefore referred for in vitro fertilization procedures. Despite representing the most advanced option, in vitro fertilization still counts for a low success rate of about 30%. There is evidence that uterine movement may play an important rule influencing fertilization outcomes. Until now, no objective means of measuring uterine movement is available. Therefore, in this work we present the first method for quantitative analysis of the uterine motion and strain. Methods: Given its widespread availability and cost effectiveness, ultrasound imaging is employed for the analysis. In particular, a speckle-tracking algorithm has been implemented that is based on block matching by normalized cross correlation. Weiner deconvolution is used to regularize the image resolution (speckle size) prior to speckle tracking (see Figure 1), and correlation filtering is adopted to improve the method reliability. The value of the cross correlation peak was evaluated to optimize block size and image

oversampling ratio. The search area was based on the maximum observed velocity. The method feasibility was tested in vitro as well as for its ability to distinguish between active and non-active phase of a natural menstrual cycle in six women. An ultrasound scanner Accuvix 20 (Samsung-Medison) equipped with a transvaginal EC4-9IS probe was employed for the acquisition. Two pairs of sites were manually defined on the uterine muscle and automatically tracked for four minutes (see Figure 1). Sites close to the fundus were chosen due to the higher activity of this region. Standard deviation (SD) and mean frequency of the strain and distance between these sites were the features extracted and evaluated for classification. Results: The extracted motion features permitted successful separation between active and non-active phase of the natural menstrual cycle. In particular, SD of the measured distance between the tracked sites showed a significant difference between the two phases ($p<0.05$ by paired, double-tailed, Student t-test). Conclusions: Quantitative uterine motion analysis is feasible. Additional motion/strain features can be considered in the future for the analysis. Moreover, 3D imaging will be employed to avoid block decorrelation due to out-of-plane motion. More in general, extensive validation is necessary to show the clinical value of the proposed method.

O.13.5 *Three Different Cell Types Produce Collagen During Skeletal Muscle Fibrosis*

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INTRODUCTION: The extracellular matrix (ECM) of tissues and organs provides structural support and unique niches for resident cells. However, identities of the cells responsible for creating specific ECM niches have not been determined. The identity of these cells becomes important in disease when ECM changes result in muscle fibrosis and subsequent increased stiffness and dysfunction. Here we describe a novel approach to isolate and identifying cells that maintain the ECM niches in both healthy and fibrotic muscle. METHODS: A model of muscle fibrosis (nesprin-desmin double knockout [DKO] mouse [1]) was crossed with a mouse line expressing GFP under the control of the collagen-α1 (I) promoter [2]. Fluorescence activated cell sorting (FACS) was used to isolate GFP%2B cells from adult muscle. Antibodies were used against CD31, CD45, α-7 integrin, and Sca-1 to subdivide the mononuclear cell population. GFP%2B cells in wild-type (WT) (n=16) and DKO (n=14) mice were identified as either muscle progenitors ("SMP"= CD31-, CD45-, Sca-1-, α-7 integrin%2B) or fibro/adipogenic progenitors ("FAP" = CD31-, CD45-, Sca-1%2B, α-7 integrin-). Remaining cells were considered to be fibroblasts (FB). To characterize each cell population, RNA was isolated and RNA sequencing performed on Illumina Hi-seq 2500. RESULTS: The GFP%2B cell population in both genotypes was composed of 50% FAP, 20% of SMP and 30% of FB cells. A significant increase in GFP%2B cells/muscle mass was found in DKO mice (1,506±58 GFP%2B cells/mg muscle) compared to WT mice (657±81 GFP%2B cells/mg muscle; $p<0.001$). While the number of GFP%2B cells increased in DKO mice, the proportion of FAPs, SMPs, and FBs did not change, demonstrating that all three populations participated in the fibrotic response. RNAseq revealed differential expression of ECM genes among the three cell types. Differential gene expression of SMPs, FAPs and FBs in WT and DKO animals demonstrated distinct roles for each cell type in ECM production. FBs showed elevated expression of fibrillar ECM proteins. FAP cells had elevated expression of basal laminal ECM proteins. Finally, SMP cells had elevated expression of a few genes important for the satellite cell niche. DISCUSSION: These data demonstrate a 130% increase in collagen I producing cells compared with WT in fibrotic model. Furthermore, our data demonstrate a significant increase in all three collagen producing cell populations, while the GFP%2B cell composition generally remained the same between WT and DKO. These findings suggest that ECM production is a coordinated effort among different cell types to achieve a fully functional composite of ECM proteins. Furthermore, during fibrosis the tissue responds by increasing the production of all cell types, and thus the amount of each ECM niche. REFERENCES: 1. Chapman et al. Hum. Mol. Gen., 23:5879-5892, 2014. 2. Yata et al. Hepatology, vol. 37:67-76. 2003.

O.13.6 *Functional Relevance of Epimuscular Interactions at Forearm: In vivo Assessments with Ultrasound Elastography*

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BACKGROUND AND AIM: Lateral transmission of forces through epimysia (epimuscular myofascial force transmission; EMFT) is known for in situ animal muscles to substantially affect passive as well as active force production [1]. Recently, epimuscular interactions were reported for resting human muscles in vivo [2]. However, the existence of EMFT and its functional relevance in active human muscles are not yet clear. Shear wave elastography (SWE) is an ultrasound-based technique to evaluate muscular stiffness. The elastic modulus value obtained with this method is strongly linearly related to muscle force [3]. Therefore, SWE would provide a unique opportunity to delineate EMFT non-invasively. The aim of this study was to assess the functional relevance of in vivo epimuscular interactions on forearm in active condition by using SWE. Following hypotheses were tested: (i) Activation of an elbow flexor, brachioradialis (BR) changes the forces at wrist joint and elastic modulus of a wrist flexor muscle, flexor carpi radialis (FCR). (ii) Voluntary activation of wrist flexor muscles affects elastic modulus of an elbow flexor, BR. METHODS: 6 healthy males (27.9 ± 3.4 years old) participated. After securing the elbow and wrist joints, (i) BR was submaximally stimulated by surface electrodes with a constant current (50Hz, 10-15mA) for 3 sec and (ii) wrist flexors were voluntarily contracted at 25% and 50% of maximum voluntary isometric contraction (MVC). EMG and elastic modulus values of BR and FCR as well as the wrist torque were recorded for both conditions at 80, 60, 40, 20, 0 (=full extension) degrees of elbow angles. Root Mean Square (RMS) of EMG data was calculated. RESULTS: (i) Stimulation of BR caused an increase in wrist flexion torque by 22.8N ± 5.1N (24.0% ± 4.3% of wrist MVC) on average. Elastic modulus of not only activated BR (60.4% ± 14.6%) but also distant FCR (54.2% ± 6.0%) muscle increased significantly regardless of elbow angle. (ii) During voluntary wrist flexion, elastic modulus of a wrist flexor, FCR significantly increased by 67.9% ± 7.0% and 78.2% ± 5.4% (Figure 1A) whereas the EMG RMS values increased by 17.8% ± 13.8% and 32.6% ± 17.8%, at 25% and 50% of MVC respectively. Elastic modulus of BR increased by 48.7% ± 21.3% and 74.0% ± 7.9% as well (Figure 1B) while the increase in the EMG RMS values increased only by 2.0% ± 1.1% and 6.5% ± 4.3% at 25% and 50% of MVC respectively. CONCLUSIONS: Both of our hypotheses were supported. FCR muscle showing substantial increase of stiffness during BR stimulation clearly reflects force transmission from the latter to the former. It is also concluded that considerable amount of EMFT exists in forearm during voluntary contractions as well. Wrist flexion deformity is one of the major problems in neuromuscular diseases, and our study suggests considering elbow flexors in the treatment plan. [1] Huijing P.A. J Biomech, 1999. [2] Yaman A. et al. J Biomech Eng, 2013. [3] Hug F. et al. ESSR, 2015.

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O.14. Movement Disorders

O.14.1 *A startling acoustic stimulus influences initial and late phases of postural responses differently in people after stroke*

Jolanda Roelofs[1], Milou Coppens[1], Nicole Donkers[1], Jorik Nonnekes[1], Vivian Weerdesteyn[1], Alexander Geurts[1]

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BACKGROUND AND AIM: Rapid postural responses are essential to recover from balance perturbations and prevent falling[1]. Although postural responses are delayed after stroke[2], a startling acoustic stimulus (SAS) can accelerate the initial phase of planned postural responses (StartReact), presumably by direct activation of the reticospinal tract[3]. We aimed to investigate whether in people after stroke initial and late phases of postural responses are similarly facilitated by a SAS. METHODS: Twelve people with chronic stroke and 12 healthy controls of similar age were included. Participants received 16 support-surface translations (2.0 m/s^2) in the forward direction and were instructed to respond with a single backward step. Four trials contained a SAS (120 dB) simultaneously with the start of the translation. Using surface EMG, we determined onsets of tibialis anterior (TA) and rectus femoris (RF) bilaterally to study differences in the initial response phase between SAS and non-SAS trials, between groups and between the paretic and non-paretic leg. To study the late response phase, we determined biceps femoris (BF) onsets of the stepping leg and step onsets (using 3D motion analysis). We conducted a repeated measures ANOVA for all analyses. RESULTS: No differences in TA and RF onsets were found between the non-paretic leg and controls for non-SAS trials (TA:140±14 vs. 143±10 ms; RF: 149±9 vs. 149±15 ms) and SAS trials (TA: 118±25 vs. 127±20 ms; RF: 130±16 vs. 129±19 ms). The SAS accelerated TA and RF onsets compared to non-SAS trials ($p<0.01$) in both groups. In people after stroke, TA onsets were similar between legs. In contrast, RF onsets of the paretic leg (non-SAS: 165±13 ms; SAS: 147±36 ms) were delayed compared to the non-paretic leg ($p=0.043$). With regard to both legs, a uniform SAS effect was found for TA and RF onsets ($p<0.05$). In the late response phase no SAS effect was present for BF or step onsets. However, we found a trend towards a group*SAS interaction (BF: $p=0.068$; step: $p=0.057$). In people after stroke,

BF and step onsets did not differ between SAS and non-SAS trials (BF: 189±40 vs. 184±26 ms; step: 315±40 vs. 313±29 ms), whereas in controls the onsets were facilitated by the SAS (BF: 174±34 vs. 192±27 ms; step: 291±32 vs. 305±28 ms). CONCLUSIONS: The SAS accelerated reaction times of initial postural responses irrespective of group, whereas it did not facilitate late postural responses in people after stroke. These results confirm intact reticulospinal motor control of proximal and distal leg muscles mediating the initial postural responses. In the late phase, however, reticulospinal control appears less potent after stroke. The reticulospinal tract might thus be less able to compensate for defective corticospinal control of stepping responses. REFERENCES: [1]Maki & McIlroy. Age Ageing, 2006;35(Suppl 2):ii12-ii18 [2]Weerdesteyn et al. J Rehabil Res Dev, 2008;45(8):1195-1214 [3]Nonnekes et al. J Neurosci, 2014;34(1):275-81

O.14.2 ***Evaluations of wrist spasticity post stroke***

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BACKGROUND AND AIM: Spastic hypertonia is a major source of disability in stroke. The increased mechanical resistance to passive movement can be due to hyperactive reflexes and/or to nonreflex changes in muscles and connective tissues. All these changes may contribute to the increased resistance in passive movement of spastic limbs, and whether each of these components (tonic and phasic stretch reflex, elastic stiffness, and viscosity) is enhanced in spastic limbs or not is not clear. The goal of this study was to evaluate both reflex and nonreflex changes in stroke survivors' wrist through in vivo experiments under passive (relaxed) condition. METHODS: Eleven stroke survivors (mean (SD) age: 58.2(8.0) yrs; sex: 4F/7M; impaired side: 7R/4L; stroke duration: 9.6(7.5) yr; height (HT): 1.74(0.07) m; body mass (BM): 94.3(22.4) kg; Modified Ashworth Scale: 2.1(0.9); Deep Tendon Reflex: 1.8(1.0)) and 11 age-, HT-, BM-, and sex-matched controls (age: 51.9(9.5) yr; sex: 4 F/7M; dominant arm: 11R; HT: 1.71(0.1) m; BM: 77.6(16.8) Kg) participated in the study. With forearm fixed to a bench, the subjects' hand was attached to a rotating arm of a portable wrist robot. First, the Flexor Carpi Radialis (FCR) tendon was tapped with an instrumented tendon

tapper to measure a tapping force at 0° flexion, with FCR and Extensor Carpi Radialis (ECR) EMG measured. Then, the wrist was extended at 4 different constant speeds (5, 90, 180 and 270°/s) passively by the robot. With no FCR and ECR activities at 5°/s, the corresponding wrist torque was used to calculate wrist elastic stiffness. At the higher speeds, the first 50 msec data were used to calculate viscosity and inertia, and the difference between the total toque and nonreflex torque components was used to calculate the reflex-mediated components. RESULTS: Stroke survivors showed significantly higher tendon reflex gain (4.8(3.8) mm) than the controls (2.2(1.4) mm; p=0.044) and longer relaxation time (from the impulse response peak to 50% decay; 115.7(67.3) msec vs. 72.5(43.4) msec; p=0.044). Stroke survivors showed higher stiffness (2.9(1.6) Nm/rad vs. 0.6(0.2) Nm/rad; p<0.01), and higher viscosity (0.09(0.05) Nm/rad/s vs. 0.03(0.01) Nm/rad/s; p<0.01). The control group showed no reflex response. Slope of the patients' reflex torque with respect to the flexion angle (2.0(1.6) Nm/rad) was significantly higher than zero (p<0.01). Stroke survivors' maximum reflex torque at the 90°/s extension (1.5(1.3) Nm) was significantly smaller than that at 180°/s (1.9(1.6) Nm; p=0.021) and at 270°/s (2.3(1.7) Nm; p<0.01). CONCLUSIONS: A unique and practical method was developed to determine changes of the various reflex and nonreflex components at the wrist of stroke survivors. It provides us several quantitative measures that can be used to evaluate reflex and nonreflex changes post stroke accurately, provide insights into underlying pathological mechanisms, and potentially guide rehabilitation treatment.

O.14.3 ***Coordination of deep hip muscle activity is altered in symptomatic femoroacetabular impingement***

Laura Diamond[1], Wolbert Van den Hoorn[2], Kim Bennell[1], Tim Wrigley[1], Rana Hinman[1], John O'Donnell[3], Paul Hodges[2]

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BACKGROUND AND AIM: The prevalence of symptomatic femoroacetabular impingement (FAI) appears to be increasing, yet the associated physical impairments remain poorly defined. FAI is a morphological hip condition common in young active adults that can cause joint pain and stiffness, muscle weakness, impaired function, and eventually hip osteoarthritis. Evidence of abnormal hip biomechanics during

walking in symptomatic FAI is limited. Hip muscle activity during gait has not been investigated but may provide further insight into the physical impairments of this patient population. This study aimed to analyse muscle synergies (i.e. patterns of activity of groups of muscles activated in synchrony) during gait to compare coordination of deep hip muscles between individuals with and without symptomatic FAI. METHODS: Fifteen individuals (11 males) with symptomatic FAI (clinical examination and imaging) and 14 age- and sex-comparable controls without morphological FAI on magnetic resonance imaging underwent testing. Intramuscular fine-wire and surface electrodes recorded electromyographic activity of selected deep and superficial hip muscles. A non-negative matrix factorization algorithm extracted three synergies which were compared between groups. The FAI group synergy vector was used to reconstruct individual electromyography patterns. Patterns were also reconstructed with the control group synergy vector. The total variance accounted for (VAF) and the VAF of each individual muscle were calculated from the reconstructions and compared between groups using independent t-tests and Mann-Whitney U tests where required ($P<0.05$). RESULTS: Groups were comparable for age, BMI, sex, dominant leg tested and spatiotemporal gait variables. VAF by three synergies was less for the control (94.8 (1.4)%) than FAI (96.0 (1.0)%) group ($P=0.03$). VAF of obturator internus (OI) was significantly higher in the FAI group ($P=0.02$). VAF of the reconstructed individual electromyography patterns were significantly higher for the FAI group ($P<0.01$), regardless of the group vector used for reconstruction. VAF of quadratus femoris (QF) was reduced to a significantly greater extent in controls ($P=0.04$). CONCLUSIONS: Coordination of deep hip muscles in the synergy related to hip joint control during early swing differed between individuals with and without symptomatic FAI. The control group demonstrated higher inter-subject variability with respect to this synergy than the relatively homogeneous pattern of those with FAI. This was most apparent for activation of OI and QF, which are important hip external rotator muscles. Although the implications of these findings for symptoms and function are not yet clear, they could plausibly be related to enhanced protection for the hip, but with possible long-term consequences. Future studies should examine patients prospectively and post-operatively to establish whether treatments targeted at these features would be beneficial.

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O.14.4 *Trunk neuromuscular patterns in recovered low back injury individuals differs between those who do and do not reinjure at one-year follow up*

Cheryl Hubley-Kozey[1], D Adam Quirk[1], Daniel Trudel[2]

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BACKGROUND AND AIM: Delayed offset of trunk muscles[1], and poor proprioception are risks for low back injury (LBI)[2]. Since neuromuscular patterns are altered in those recovered from a LBI[3], we hypothesized that those with impaired feedback control would be more likely to reinjure following a LBI. Our objective was to establish if neuromuscular patterns during a dynamic leg loading task in those recovered from a LBI would differ between those who reinjure at one-year follow up. METHODS: Sixty-three recovered LBI participants (4-12 weeks post injury with minimal pain and disability) were recruited. Lying supine, participants performed 3 trials of a leg loading task, timed to a 4 second count, while instructed to minimize pelvic motion (Figure). Surface electromyograms (EMG) were collected from 24 trunk muscle sites (12 abdominal and 12 back extensors) at 1000Hz. EMG were full-wave rectified, low-pass filtered (6 Hz), time normalized to 100% and amplitude normalized to maximum voluntary isometric contractions[3]. EMG ensemble-average waveforms were calculated for each muscle site and participant. Temporal features were captured using principal component (PC) analysis models constructed separately for abdominal and back. Participants were separated as reinjury (RE) or no-reinjury (NoRE) based on 1 year follow-up (self-identified LBI limiting activity for>3 days). Mixed model ANCOVA (group, muscle, covariates: age, sex & mass) were conducted on PC scores. Tukey HSD post-hoc analyses were performed. RESULTS: Reinjury data were collected in 51 participants (24 RE). For the abdominals, five PCs captured 95% of the total variance; PC1, 4 & 5 captured group main differences ($p<0.001$), see figure. PC1 found RE had overall higher activation amplitudes than NoRE. PC4 captured that RE had higher activation following left leg lift relative to activation at the beginning of left leg lower. PC5 captured that RE had higher activation near the end of left leg lower relative to end of left leg lift. No group differences were found for back PCs ($p>0.05$). CONCLUSIONS: Higher activation (PC1) in RE, could reflect reduced abdominal strength or an attempt to increase trunk stiffness. Temporal differences while modest showed differential responses to changing external moments between groups. Higher activation and delayed offset (left leg lift) suggests

an exaggerated response to the changing sagittal plane moment in the RE group (PC4). Higher and prolonged activation during late left leg lower (PC5) may compensate for the reduced activation at the beginning of left leg lower. These data suggest those that reinjure may have impaired feedback requiring exaggerated responses to periods of the task with increased external moments (Figure), a finding consistent with risk of first time LBI[1 2]. Hence abdominal neuromuscular patterns may be useful to predict reinjury. 1) Cholewicki et al, JOSPT 2002; 2) Claeys et al, JEK 2015; 3) Moreside et al, Arch Phys Med Rehab 2014

O.14.5 *Extrinsic finger muscle stiffness contributes substantially to increased passive stiffness of the wrist and finger joints in chronic hemiparetic stroke individuals: A Pilot Study*

Benjamin Binder-Markey[1], Julius Dewald[1], Wendy Murray[1]

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BACKGROUND AND AIM: Both the neural impairments and increased passive stiffness of the joints in the hand [1,2] associated with chronic hemiparetic stroke make hand opening exceedingly difficult. To aid in the development of rehabilitation interventions, we aim to determine which musculoskeletal structures contribute to increased stiffness about the wrist and fingers post-stroke, something no previous study has evaluated. METHODS: Passive torques about the wrist and four MCP joints were quantified in the paretic limb of 2 males (55 & 66 yrs, 6 & 16 yrs post-stroke) with moderate to severe hand impairments associated with chronic stroke (CMSA-Hand: 3 and 2, and FMA-UE: 24 and 14). Torques were quantified throughout each joint's range of motion using a custom device, the PIP & DIP joints were splinted. EMGs were monitored to ensure the muscles were passive. Torque data for each subject were fit to an exponential analytical model, designed to theoretically separate the torques contributed by the extrinsic finger muscles from other, lumped, single-joint structures.[3] Passive stiffness, the derivative of the analytical model, was then compared to comparable data from the non-dominant limb of 2 healthy males (25 & 28 yrs). RESULTS: Passive stiffnesses quantified in two chronic stroke subjects was greater than that of two healthy subjects. (MCP: μ_{stroke} = 1.63Ncm/° vs $\mu_{healthy}$ = 0.37Ncm/°; Wrist: μ_{stroke} = 2.79Ncm/° vs $\mu_{healthy}$ = 0.67Ncm/°). Passive stiffness of the extrinsic finger muscles were higher in the two stroke subjects (Fig. 1a). No

difference was observed for the lumped, single-joint structures about the MCP joints (ligaments, capsule, & intrinsic hand muscles; Fig. 1c). Passive stiffness of the single-joint structures about the wrist (ligaments, thumb and wrist muscles) were larger in the stroke subjects (Fig. 1b). CONCLUSION: Within our pilot study the stiffness of the extrinsic finger muscles contributed substantially to increased total passive joint stiffness observed at wrist and finger joints in chronic stroke. In contrast, the combined passive stiffness of the intrinsic hand muscles and MCP joint structures post-stroke was comparable to young, healthy males. Understanding how different musculoskeletal structures contribute to increase passive stiffness in the hand and wrist will influence the development of appropriate rehabilitation interventions and devices. ACKNOWLEDGEMENT: NIH-NIBIB T32EB009406; NIH 1R01HD084009-01A1 Dewald/ Murray (PIs); Feinberg School of Medicine Dean's Dual Degree Scholar Award; and NUPTHMS 1. Kamper, DG, et al. Arch Phys Med Rehabil. 2006;87(9):1262-1269. 2. Kamper, DG, et al. Muscle Nerve. 2003;28(3):309-318. 3. Knutson, JS, et al. J Biomech. 2000;33(12):1675-1681.

O.14.6 ***Humeral rotational capabilities of stroke survivors and pattern recognition of intent during shoulder tasks***

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BACKGROUND AND AIM: Abnormal movement synergies exist in the stroke surviving population, but humeral internal (IR) and external (ER) rotation has not been explored to the same extent as other components of the synergies. It is unknown how independently humeral rotation can be controlled from other shoulder motions. There are two aims of this study; firstly to quantify the internal and external humeral rotation capabilities and their role in the common synergy patterns seen after stroke; secondly to investigate if user intent can be decoded from muscle activation patterns during single and dual shoulder-tasks. It is hypothesized that individuals with stroke will have an impaired ability to operate outside of this pattern, especially at higher amounts of effort. Longer term, these results may be important to develop control for a powered orthosis to help stroke survivors broaden their functional capability. METHODS: Using an isometric upper-extremity device instrumented with a 6-degree

of freedom (DOF) load cell, maximal torque generation capabilities of 21 stroke survivors and 4 healthy control subjects were recorded in four DOF's (shoulder abduction/adduction, flexion/extension, IR/ER, and elbow flexion/extension). During these maximal voluntary contraction single-DOF tasks, electromyographic (EMG) signals were recorded from eight ipsilateral upper extremity muscles. User intent was decoded from the EMG using linear-discriminant analysis (LDA). RESULTS: The survivors of stroke in this study have the torque generating capability to move their arm in external and internal rotation. But, as seen in Figure 1a, ER often occurred concurrently with shoulder abduction and IR often occurred concurrently with shoulder adduction. An examination of the LDA classification accuracy between tasks showed difficulties in discriminating between these "within synergy" movements with classification accuracies dropping from ~95% to ~80% (Fig 1b). An LDA of the control subject EMG also had difficulty discriminating between these same movements. CONCLUSIONS: Stroke survivors have the torque generation ability to rotate their humerus, however rotational control in this task is coupled with shoulder abduction/adduction in both populations. The pattern recognition system has the capability to decode most shoulder movements with high accuracy; however there is some confusion between within synergy movements. Therefore, further testing is now being conducted using a dual-task methodology to decouple these DOF's and better target the specific movement impairments in individuals with stroke. These experiments will characterize the humeral rotation isometric torque generation capabilities of hemiparetic shoulders and examine synergy induced changes during different levels of shoulder abduction and adduction effort.

S.15. ***Multichannel EMG: decomposition and other applications***

Convolutive source deflation significantly improves convergence of blind motor unit identification from surface electromyograms

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BACKGROUND AND AIM: Several algorithms have been proposed for decomposition of high-density surface electromyograms (hdEMG) [1,2]. Many of them model

hdEMG as convolutive multiple-in-multiple-out (MIMO) system with motor unit (MU) discharges as inputs, MU action potentials (MUAP) as impulse responses and EMG signals as outputs. Sequential MU identification is then applied by identifying one MU filter per single decomposition run and applying it to hdEMG signals. This MIMO model is very powerful as it implicitly resolves MUAP superimpositions and accounts for arbitrary MUAP changes in different EMG channels. However, it is also redundant as it uses ~30 delayed replicas of the same MU discharge pattern to describe convolutions with MUAPs. As a result, decomposition techniques reconstruct several delayed versions of the same MU discharge pattern, what makes them computationally suboptimal. METHODS: Subtraction of identified MUAP trains from the hdEMG signals has been proposed [2] to deal with this problem, but this approach is sensitive to accumulation of errors. Source deflation with Gram-Schmidt orthogonalization (GSO) of MU filters is also possible, but this orthogonalization only protects against convergence to exactly the same replica of MU discharge pattern. In this study we propose an extension of GSO scheme to convolutive MIMO model. Array of 5 by 12 electrodes (LISiN, Italy) was used to record hdEMG during different contraction levels (from 10% to 70% of MVC in steps of 10% of MVC) of tibialis anterior muscle in 6 healthy subjects. Monopolar signals were bandpass filtered (20-750 Hz), amplified and sampled at 2048 Hz with 12 bit resolution (OT Bioelettronica, Italy). Recorded signals were decomposed twice, by Convolution Kernel Compensation (CKC) [1] algorithm with standard GSO and by CKC algorithm with novel orthogonalization. Pulse-to-Noise Ratio (PNR) [1] was used to assess the accuracy of MU identification. RESULTS: CKC with novel orthogonalization identified 4.6±0.7, 8.2±2.1 and 13.7±4.6 MUs with PNR>30 dB (accuracy>90%) in the first 5, 10 and 20 decomposition runs, respectively. In the same conditions, CKC with GSO identified 4.4±1.1, 5.3±1.9 and 5.4±1.9 MUs. In 10 and 20 decomposition runs, the number of identified MUs was significantly lager with new orthogonalization scheme than with GSO (Wilcoxon signed rank test, $p<0.0001$). CONCLUSIONS: Proposed convolutive orthogonalization efficiently protects against multiple convergences to the same MU discharge pattern and is not sensitive to errors in MUAP train estimation. As such, it effectively reduces the decomposition time and boosts the number of identified MUs. Both aspects are of paramount importance in studies of MU populations. This study was supported by Slovenian Research Agency (projects L5-5550 and J2-7357). [1] Holobar A et al. 2014, J Neural Eng. 11(1):016008 [2] Chen

M, Zhou P 2016, IEEE Trans Neural Syst Rehabil Eng. 24(1):117-27, doi: 10.1109/TNSRE.2015.24120

High-density surface electromyograms: do they sample representative muscle active?

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The possibility of sampling the activity of muscles other than that of interest with surface electrodes (i.e., cross-talk) has been of marked concern in the scientific and clinical community. Less disseminated though is the possibility of sampling EMGs from unrepresentative muscle regions. Specifically, users of surface electromyography are rarely aware that some, or even most, of the active muscle fibres might locate outside the pick-up volume of electrodes. Under these circumstances, muscle activity may be not genuinely represented in the detected signals and, consequently, attributing changes in EMG features to physiological muscle changes may be not possible. The issue of representativeness in surface EMG, although opposite to cross-talk and apparently incipient, is equally critical. In a continued attempt to attenuate cross-talk, manufacturers have reduced inter-electrode distance and electrode size considerably, further biasing the representation of muscle activity in the EMGs. On one hand, collecting surface EMGs with a grid of electrodes rather than with the conventional bipolar electrodes provides a more global muscle view. On the other hand, it is often not viable to use grids of electrodes to sample activity from different muscles. Ideally, one could propose the bipolar electrodes must be sensitive to the most possibly localised changes in muscle activity whereas grids of electrodes must resolve them. In both cases, whether EMGs fully represent muscle activation depends not only on electrodes? pick-up volume but also on how locally changes in muscle activity might manifest? The size and the location of the active muscle volume are currently not predictable. Also unclear is the relation between the location and size of active muscle volume and its associated spatial representation in the surface EMG. Compelling evidence from different research centres suggests the spatial distribution of muscle activity depends on the task performed, force direction, muscle architecture, fatigue, contraction intensity, and on several other factors. Anthropometric differences, although apparently undocumented, likely account for the relative spatial changes in EMGs between individuals. It appears obvious after all that a unique system of electrodes, be it bipolar or high-density, would rarely suffice for the unambiguous sampling of representative activity from different muscles. Identifying the causes and consequences of not sampling representative muscle activity with surface electrodes, as dealt with in this speech, is a potentially promising approach for the design of systems able to circumvent this issue.

Topographical characteristics of motor units of the complete facial musculature determined by means of high-density surface EMG.

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INTRODUCTION: The facial musculature participates in many important functions such as speech, food intake and mediation of emotional and affective states. Therefore, functional investigation of the facial motor system by means of conventional surface EMG techniques is relevant in several medical disciplines. Moreover, systematic topographical data on the facial musculature at a single motor unit (MU) level was lacking. AIM: To topographically characterize the MUs of the upper, midfacial and lower facial muscle subcomponents including the periorbital and lip musculature. METHODS: High-density surface EMG (HDsEMG) was recorded in five separate measurement sessions from 21 individual facial muscle subcomponents using 0.3mm-thin multi-electrode grids with a maximum of 256 channels. In total, thirty-nine healthy adult subjects were trained to be able to perform slight to moderate (attempted) selective contractions of investigated muscle subcomponents. Multichannel motor unit action potentials (MUAPs) were decomposed by convolution kernel compensation technique (Holobar et al., 2007). For each MUAP, the initiation and propagation of the potential were topographically identified in the time sequence of the interpolated monopolar amplitude maps to determine motor endplate zones and muscle fiber directions. RESULTS: Generally, our findings confirm previous anatomic studies demonstrating high inter-individual variability in the anatomy of the facial musculature with absence of certain muscle subcomponents in some individuals and varying fiber architecture and innervation

zone locations. Decomposed MUAPs reveal the distinctive topographical characteristics of facial MUs, such as overlapping territories of MUs belonging to different muscles and the occurrence of asymmetrically located endplate zones within single muscles. In the upper facial muscles as well as the orbicularis oculi we found widely distributed motor endplate locations over the muscle. In the other subcomponents, clustering of endplate zone locations has been found at least to a certain extent with more or less varying locations of endplate clusters between individuals. CONCLUSIONS: Results of this series of studies are unique with regard to the fact that topographical information has been obtained at the level of the smallest functional neuromuscular units (i.e., the MUs) from a relatively large group of healthy individuals without dissection of human cadavers. This allows the use of the individual results for optimizing functional investigations, e.g. establishing electrode placement guidelines for speech and psychophysiologic research, and for endplate-targeted Botulinum neurotoxin injection with reduced side-effects. Beyond this practical and clinical relevance, the systematic topographical data on the architecture of the whole facial muscle system adds substantially to the sparse neurophysiological and anatomical knowledge at the level of the smallest functional units.

Longitudinal tracking of individual motor units using high-density surface electromyography

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BACKGROUND AND AIM: The possibility to identify the same motor units (MU) across multiple sessions of an experimental protocol may open new avenues in the neurophysiological investigation of motor neurons. However, this is not possible with classic recording techniques of intramuscular fine wire EMG. This recording method is indeed characterized by high selectivity, so that the waveform shapes of action potentials MUAPs of the same MUs are substantially different when the wires are inserted in the muscle multiple times. Therefore, in this study, we aimed to develop a methodology to track individual MUs using the combination of high-density surface EMG (HDEMG) recordings and convolutive blind source separation methods.

METHODS: We used two-dimensional arrays of 64 EMG electrodes to increase the spatial representation of the MUAPs. The recordings were performed from a decerebrated cat preparation as well as in healthy human volunteers. In the cat experiments, the MU tracking was attempted in the same experimental session, but on different trials with repositioning of the electrodes. The EMG signals were recorded on the gastrocnemius and soleus muscles. Due to the instability of the recordings, this type of experiment creates a considerable challenge for the MU tracking. In the human experiment, the signals were collected on 10 subjects in three days over different weeks. The MU were tracked along the three sessions. The participants were asked to perform two submaximal (10-70% of the maximal force) isometric knee extensions with HDEMG recordings placed on the vastus lateralis (VL) and medialis (VM) muscles. In both the cat and human experiments, blind source separation (Holobar et al., 2007; Negro et al., 2016) was applied to each individual recording for the identification of MU activity and the spatial signature of their MUAPs was used to track the same MU across trials. The spatial signatures were compared using 2D cross-correlation and normalized Euclidean distance. RESULTS: In the cat experiments, a total of 44 unique MUs was identified in all trials. Of these, 27 were tracked longitudinally across two trials, 16 across five trials, and 7 across nine trials. The tracked motor units showed a good consistency of peak-to-peak amplitude and conduction velocity estimates, with coefficient of variations of these variables <10%. Similarly, in the human experiment, the number of tracked MUs across two sessions varied (over the 10 subjects) between 21(6-34) and 23(6-40), while for three sessions it was possible to track between 11(8-17) and 11(1-16) MUs for VM and VL, respectively, across all force levels. CONCLUSIONS: The results demonstrates the possibility to track individual MUs longitudinally across trials performed in the same or different days using HDEMG, with repositioning of the electrodes. The methodology may be used to study the changes in the properties of individual MUs during intervention and progressive neuromuscular diseases.

Differences in motor unit discharge characteristics among proximal and distal muscles of the upper limb in individuals with chronic hemiparetic stroke

Laura Miller McPherson[1], Francesco Negro[2], Chris Thompson[3], CJ Heckman[4], Dario Farina[2], Jules Dewald[4]

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BACKGROUND AND AIM: Proximal and distal muscles serve different roles during functional tasks. In the upper limb, proximal muscles are typically used for postural control, and distal muscles are typically used for fine motor control. Differences in neural inputs to the muscles likely exist, but they have not been studied extensively. Analysis of motor unit (MU) discharge can help elucidate neural organization to a muscle in both the healthy and neurologically injured state. However, until recently, it has not been feasible to efficiently measure MU discharge in multiple muscles. Multi-channel surface EMG is a novel approach for extracting MU discharge that provides improved efficiency and automation. Using this approach in healthy controls (N=9) and those with chronic hemiparetic stroke (N=12, moderate-to-severe impairment), we examined the number of MU extracted (yield) and MU discharge characteristics (discharge rate, rate modulation, common drive) in proximal and distal arm muscles.
METHODS: Participants were seated with the arm affixed to an isometric apparatus to measure shoulder, elbow, and finger joint torques. 64-channel EMG grids were placed on the surface of deltoid (DELT), biceps (BIC), and finger flexors (FF). Separate isometric contractions of shoulder abduction, elbow flexion, and finger flexion were performed at efforts ranging from 10 - 40% maximum torque. EMG data were decomposed into MU spike trains. Mean MU discharge rate (MDR) was calculated and compared against torque to estimate rate modulation. Coherence was calculated on composite spike trains and pooled across torque levels for each participant group. Z-transformed values for frequencies at 1-2 Hz were used to quantify common drive.
RESULTS: Differences were found across muscles and/or groups for all metrics. Mean MU yield was highest at FF for both groups (Stroke: DELT: 5.6, BIC: 6.9, FF: 9.6; Control: DELT: 4.3, BIC: 3.8, FF: 12.0). For overall MDR, values were similar across muscles in controls (DELT: 13.7, BIC: 13.9, FF: 13.4 pps) but decreased from proximal to distal post-stroke (DELT: 11.4, BIC: 10.7, FF: 8.5 pps). Differences in rate modulation were also observed between groups. In controls, rate modulation was demonstrated by a positive relationship between MDR and torque in all muscles, and the slope between the variables increased from proximal to distal (DELT: 7.5, BIC: 16.6, FF 21.5 pps/%MVT). Post-stroke, however, rate modulation decreased from proximal to distal, and it was absent in FF (DELT: 7.9, BIC: 5.4, FF: -0.6 pps/%MVT). Common drive values were highest in FF for controls (DELT: 31.4, BIC: 30.4, FF: 51.6) but lowest for FF

in stroke (DELT: 63.8, BIC: 56.2, FF: 49.9). CONCLUSIONS: Results demonstrate differences in MU behavior among DELT, BIC, and FF and that the relationships between the muscles changes post-stroke. Findings underscore the need to record from multiple muscles when using MU analysis to examine neural organization to the upper limb.

How synaptic organization shapes the motoneuron to EMG transform

CJ Heckman[1], Randy Powers[2]

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The motor commands that produce EMG and movement comprise 3 components. Excitation and inhibition are of course fundamental. Yet motoneurons also have extremely potent neuromodulatory inputs via neurotransmitter systems that act on G-protein coupled receptors. This 3rd component of motor commands acts to control the excitability of motoneurons, i.e. their "state". Thus the response of a motoneuron to excitation or inhibition varies dramatically depending on its neuromodulatory state. There are multiple neuromodulators, but our emphasis is on serotonin (5HT) or norepinephrine (NE), which originate in the brainstem and are especially potent in their actions on motoneurons. By comparing our realistic computer simulations of these neuromodulatory actions to detailed surface array recordings of motor unit firing patterns, we are able to identify the relationship between the temporal pattern of EMG and the temporal pattern of all 3 components of motor commands. This identification is part of a systematic effort to reverse engineer the firing patterns of human motor units. Our result show a remarkable flexibility in the command to EMG transform, which has important implications for understanding to what degree EMG patterns reflect motor command patterns.

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S.16. *Mobilizing Data: Research at the Intersection of Data Science and Biomechanics*

The Mobilize Center: accelerating movement science with big data

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Mobility is essential for human health. Unfortunately, many conditions, including cerebral palsy, osteoarthritis, obesity, running injuries, and stroke, limit mobility at a great cost to public health and personal well-being. The proliferation of devices monitoring human activity, including mobile phones and an ever-growing array of wearable sensors, is generating unprecedented quantities of data describing human movement, behaviors, and health. Mobility data is also being collected daily by hundreds of clinical centers and research laboratories around the world. The mission of the Mobilize Center (mobilize.stanford.edu), one of 11 NIH Big Data to Knowledge (BD2K) Centers of Excellence, is to overcome the data science challenges facing this mobility big data to improve human movement across the wide range of conditions that limit mobility. In this talk we will provide an overview of the Center's research, training, and dissemination activities and share specific ways that the biomechanics community can participate in the Center.

Four Data Science Cores focus the Mobilize Center's data science research efforts. Our Biomechanical Modeling core is focused on developing robust, flexible, and automated optimization tools for generating personalized biomechanical models and simulations from diverse experimental movement data. Through our Statistical Learning Core, we are creating algorithms to make predictions and classifications and identify insightful correlations from large sets of noisy, sparse, and complex data, whether discrete or time-varying. The Behavioral and Social Modeling Core is focused on developing tools to model the role of behavioral and social dynamics in human health based on information collected with smartphones and wearable activity monitors. Finally, the Integrative Modeling Core is bringing the three approaches together to establish machine learning systems that integrate diverse data sources and modeling approaches to aid clinical decision-making and transparently communicate with clinicians.

To ensure that our data science research has a significant impact on important health issues, we are focusing the activities of the center on three Driving Biomedical Problems. First, we are analyzing mobility data collected at Gillette Children's Specialty Healthcare to predict and improve the outcomes of surgeries in children with cerebral palsy and gait pathology. Second, we are integrating data from biomechanics labs and hospitals to identify new approaches to optimize mobility in individuals with osteoarthritis, running injuries, and other movement impairments. Third, we are analyzing wearable sensor data from millions of people to discover methods that motivate individuals to move more.

In addition to the research, the Center is also training scientists at the intersection of data science and biomechanics and sharing new tools with the data science and biomechanics communities. Our Massive Open Online Courses (MOOCs) train tens of thousands of students and researchers on topics such as Mining Massive Datasets, Statistical Learning, and Convex Optimization. We have established a Distinguished Postdoctoral Fellows and graduate student research program to create leaders in biomedical big data analytics. We also develop and disseminate general, open source tools for biomedical big data science including optimization, statistical learning, biomechanical modeling, and machine learning packages.

Stepping forward? Patient-specific measures of altered control to improve treatment outcomes in cerebral palsy

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Background: Improving movement after brain injury remains a formidable challenge, requiring new methods for enhancing rehabilitation and recovery. Every brain injury is unique and clinicians struggle to determine the optimal course of treatment for each individual. For example, cerebral palsy (CP) is caused by an injury to the brain at or near the time of birth and impairs movement and coordination. To improve movement, individuals with CP receive a wide variety of treatments such as orthopaedic surgery; however, only 50% of patients improve walking ability after various treatments. New methods are needed to optimize patient-specific treatment and improve quality of life. Aim: A long-held clinical belief is that variability in treatment outcomes is due to differences in motor control between individuals. However, no methods currently exist to quantify patient-specific changes in motor control. The goal of this research was to retrospectively evaluate whether motor control, measured by muscle synergies, was associated with treatment outcomes in CP. Methods: We analyzed 473 children with CP who had previously undergone treatment at Gillette Children's Specialty Healthcare and received pre- and postoperative gait analyses. Electromyography data from each gait analysis was processed using nonnegative matrix factorization to identify weighted groups of muscles consistently activated together (synergies). We defined the dynamic motor control index during walking (walk-DMC) as the variance accounted for by one synergy, scaled relative to synergies from 84 typically-developing (TD) children. Among the TD children, 100 is the average walk-DMC and 10 points is one standard deviation. Values less than 100 indicate a more simplified control, in which a single synergy describes more muscle coordination than in TD children. Stepwise linear regression models were computed, predicting changes in Gait Deviation Index (GDI), gait speed, and oxygen cost after treatment ($p < 0.05$ for variable entry, and $p > 0.10$ for variable removal). Results: The final regression models indicated that walk-DMC was correlated with post-operative GDI ($r2 = .42$) and gait speed ($r2 = .53$), but not oxygen costs. Thus, even after controlling for pre-operative GDI and speed, synergies provided a unique factor associated with improvements in gait. Individuals with a walk-DMC more similar to TD (closer to 100) were more likely to have improvements in gait after treatment. More aggressive treatments (orthopaedic surgery/rhizotomy) resulted in larger positive changes, but the effect size of treatment group was significantly smaller than walk-DMC effects. Conclusions: Muscle synergies were associated with treatment outcomes in CP and provided unique information beyond traditional gait analysis. These results confirm and provide a quantitative measure of clinicians' long-held belief that "motor control matters" for optimizing treatment in CP.

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Detecting foot strike from kinematics, a case study in the debate between hypothesis-first and data-first methods

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BACKGROUND AND AIM: Recently, technological advances have provided researchers with sophisticated data analysis procedures. These techniques afford new research opportunities, whereby large amounts of data can be explored for meaningful patterns. This approach, often referred to as data-driven or "data-first", contrasts sharply with a traditional hypothesis-driven or "hypothesis-first" approach. In turn, a debate has begun over the fundamental place of each of these approaches, in fields such as cancer genetics [1,2]. In human movement science, meaningful discussion is also timely in determining how we integrate these new techniques. Two recently published papers provide a case study which crystalizes this debate. The studies both address a common biomechanical problem, the detection of foot touchdown events from kinematics, along with two solutions: a hypothesis-first method, and a data-first approach. The aim of the current case study was to place these two approaches in the same problem context, and contrast them to provide insight into both. METHODS: Using a large database of running biomechanics, touchdowns were detected with: 1) a hypothesis-first method using peak downward velocity of the centre-of-mass [3], and 2) a data-first method based on angular accelerations at the foot, ankle, knee and hip, and using principal component analysis (PCA) -based machine learning [4]. Each method was then similarly applied to the detection of touchdowns for walking, which was a completely novel task for both. Performance in all cases was evaluated using gold-standard touchdowns from a rising-threshold of vertical ground reaction force exceeding 10 N. RESULTS: Both methods demonstrated very similar standard deviations of error in touchdown detections for running (hypothesis-first: 8.6 ms, data-first: 8.8 ms). However, attempts to extend the hypothesis-first method for walking demonstrated higher standard deviations of error (hypothesis-first: 20 ms, data-first: 8.3 ms). CONCLUSIONS: The hypothesis-first method relied on a narrowly-chosen sample, variable set, and movement task to produce results specifically applicable within those parameters. In contrast, the data-first method produced a generalized model that was independent of the specific sample and movement. This distinction is reflected in the view taken

when hypothesizing the outcome. In the hypothesis-first method, the authors created a fully-defined hypothesis, in which groups of subjects and variables of interest were pre-defined. In contrast, the data-first method utilized a general principle (Newtonian mechanics) to define a data boundary, within which variables of interest were thought to exist, but were not pre-defined. Other important contrasts are presented in Table 1. [1] R. Weinberg, Nature 464:678, 2010. [2] T. Golub, Nature 464:679, 2010. [3] C.E. Milner and M.R. Paquette, J Biomech 48:3502-5, 2015. [4] S.T. Osis, B.A. Hettinga, J. Leitch and R. Ferber, J Biomech 47:2786-9, 2014.

Characterizing Clinically Meaningful Phenotypes of Osteoarthritis Progression: Eight-Year Data from the Osteoarthritis Initiative

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BACKGROUND AND AIM: Osteoarthritis (OA) is one of few major chronic diseases that we still cannot treat. Stagnation in the development of robust preventative measures and disease-modifying treatments is partly due to poor characterization of the different types of osteoarthritis. Disease heterogeneity remains a confounder not only in the clinic, but also in the design of case-control studies that aim to advance our knowledge of disease progression. Diagnostic tools that predict clinically meaningful OA phenotypes are needed to facilitate the design and implementation of targeted and efficacious interventions. The leading aim of this study was to characterize distinct, clinically meaningful phenotypes of osteoarthritis progression. Secondarily, we sought to identify patient characteristics and short-term outcomes that are predictive of long-term progression. METHODS: We used publicly available data from the OA Initiative. To characterize progression phenotypes, we used joint space narrowing and pain progression on both knees, over eight years, for subjects who had or were at high risk of developing OA (n=2165). Each subject was represented by a vector of the changes in outcomes from baseline to each consecutive year, for both knees (ordered by most affected). A k-means clustering algorithm was used to identify distinct clusters of progression. Subject characteristics and outcomes for the first year were then used to predict the clusters. To identify the best predictive variables, we used least absolute shrinkage and selection operator logistic regression, with five-fold cross validation both for model selection and

validation, along with a bootstrapping approach for variable importance. RESULTS: A final number of three clusters was adopted after visual inspection to ensure that the clusters represented clinically meaningful paths of progression. The first cluster contained subjects who exhibited slow joint space narrowing and constant pain (typical phenotype); the second cluster contained subjects who had slow joint space narrowing and decreasing pain; the third included subjects with fast joint space narrowing and constant pain (Fig. 1). Accordingly, instead of one-versus all logistic regressions, we performed atypical phenotype vs. typical phenotype logistic regressions. Subject characteristics, such as demographics and comorbidities, predicted atypical progression phenotypes with over 60% accuracy. When change in joint space width and pain from baseline to the first year were included, predictive accuracy increased to over 80%. CONCLUSIONS: OA is increasingly recognized as a collection of diseases with a common clinical endpoint, but prevention, development of effective disease-modifying drugs, and optimal interventions are currently hindered by the agglomeration of patients into one category. The identification of clinically meaningful phenotypes of OA progression will enable faster progress towards treatment and prevention.

Data and data management for finite element analysis in joint biomechanics

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In biomechanics, finite element analysis provides a computational modeling and simulation platform to quantify the mechanics of the body, organs, joints, tissues, and cells in high level of detail. This modeling strategy enables the understanding of form-function relationships and also establishes the pathway through which loads of the higher spatial scales of joints and organs are reflected upon the mechanical environment of the tissues and their constituents. In this regard, finite element analysis provides the means to establish biomechanical markers for diagnostics and for evaluation of interventions, which have the potential to lead to individualized care. Like in any other simulation strategy, good models and reliable interpretation of predictions necessitate good input data. Finite element analysis is data rich. It requires representation of of anatomical properties, e.g., geometry of the knee and its tissue structures, representation of physiological properties, e.g., tissue material properties such as elastic modulus of cartilage, and prescription of loads and boundary conditions acting on the structures of interest, e.g., forces applied to the knee. In return, simulations can predict the response of the system (for the case of the knee, tissue stresses and strains, and joint movement), a rich output set that needs further mining for appropriate scientific and clinical interpretation. Ideally, if input data are personalized, predictions can be specific to the individual, an important aspect of individualized medicine. Towards that direction, many data challenges in finite element analysis need to be resolved. These challenges are at various levels throughout the lifecycle of the model; among many are the availability of data, acquisition of missing data; merging of existing data to approximate missing data, documentation and organization of raw and derivative data and simulation results, dissemination and re-use of data, models and simulation results. The goals of this study were i) to provide an overview of data needs for finite element analysis, with specific attention to joint biomechanics, and ii) to describe data management strategies for effective modeling promoting reproducibility and reusability. The Open Knee(s) project was used as an example. This activity aims for the development of completely specimen-specific (anatomically and mechanically) models of knee joints as a virtual knee population. The project acquires and blends heterogeneous data sets - imaging, joint mechanical testing, tissue testing, with ongoing documentation and prompt dissemination. This project is funded by the National Institute of General Medical Sciences, National Institutes of Health (1R01GM104139 - Principal Investigator: Ahmet Erdemir).

Moving Forward: From Physical Activity Monitoring to Physical Performance Monitoring

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BACKGROUND AND AIM: Mobility impairment is a key feature of osteoarthritis (OA) and lumbar spinal stenosis (LSS), yet efforts aimed at this are hampered by the lack of an objective measure. Here, physical activity monitoring seems a logical solution. Surprisingly, accelerometer-based studies in these populations reveal few, if any deficits relative to controls. The identification of objective and quantifiable measures of function would improve disease classification, evaluation and treatment. The goal of this study is to apply recently developed accelerometry measures along with novel analytics in populations with OA and LSS. We aimed to use these methods to 1) identify characteristic movement patterns (physical performance "PP" phenotypes) that are unique to individuals with OA and LSS, and 2) determine optimal methods to differentiate between the conditions. METHODS: We previously uncovered novel accelerometry signals of regional-body pain from a population-based sample, and empirically derived thresholds for accelerometry analysis tuned to the impact of musculoskeletal pain (called the physical performance "PP" analysis). In this study, we interrogate 3 datasets: the Osteoarthritis Initiative (OAI), the National Health and Nutrition Examination Survey (NHANES), and the Lumbar Spinal Stenosis Accelerometry Database (LSSAD). To characterize the unique accelerometry signals in all 3 groups, we tested the existing Freedson intervals for movement frequency and novel features of movement from the PP analysis. We then evaluated the significance of each feature alone in discriminating (pairwise) between groups. Finally, we determined which set of features best classifies individuals between groups (the PP phenotypes). RESULTS: All features were significant at $p<.05$ after accounting for multiple hypothesis testing, except for the following intervals: Freedson moderate, Freedson vigorous. Also, Freedson vigorous was not significant between LSSAD and OAI, nor was PP moderate-vigorous between LSSAD and NHANES. The PP phenotype classification rates for OA and LSS demonstrated roughly 80% accuracy (pairwise) relative to the pain-free population, given age and gender. The most important distinguishing features corresponded to sedentary and light activity. The subtler classification between diseased populations (OA vs. LSS) was at 72%, with moderate activity as the prominent distinguishing feature. CONCLUSIONS: We show it is possible to derive new insights from accelerometry data by developing a novel set of features that characterize the movement patterns of OA and LSS (called "physical performance" phenotypes). These features were found to be statistically significant in discriminating between populations. Furthermore, our approach determines a key set of discriminatory features, resulting in a framework for classifying musculoskeletal diseases, and provides a comprehensive quantitative analysis of real-life physical performance.

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S.17. ***Practical Application of Electrophysiology and Kinesiology***

Application of multi-channel surface EMG technique to researches of aging and lifestyle-related diseases

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In Japan, aged members of the population (> 65 ys old) made up 25.1% in 2105, and this percentage is the highest in the world. We should note that Japanese people spend, on average, 9 years of their life receiving nursing care. Also, number of lifestyle-related disease patients, such as those with type 2 diabetes mellitus (T2DM), recently markedly increased in Asia-Pacific countries including Japan. For the prevention and management of age-related physical dysfunctions and lifestyle-related diseases, exercise for improving muscle strength and/or muscle hypertrophy has been strongly recommended. However, physiological responses of the neuromuscular system in the elderly and lifestyle-related disease patients during exercise have not been fully elucidated. Here we introduce our recent research applying multi-channel surface electromyography (SEMG) to investigate the effect of aging and lifestyle-related diseases on neuromuscular functions. We recorded multi-channel SEMG from the vastus lateralis muscle of the elderly and T2DM patients using a two-dimensional grid of 64 electrodes. Spatial distribution SEMG patterns and decomposed individual motor unit action potentials, analyzed by the Convolution Kernel Compensation technique (Holobar et al. Clin Neurophysiol 2009) were assessed to investigate motor unit recruitment and firing patterns (Watanabe et al. J Electromyogr Kinesiol 2012; Diabetes Res Clin Pract 2012; Muscle nerve 2013). Our results suggest that motor unit recruitment/firing strategies are modified in the elderly and T2DM patients during force production. We also investigated mechanisms of age-related dysfunction in locomotion using a multi-channel SEMG. During the swing phase of the gait, in the rectus femoris (RF) muscle, the proximal region is selectively activated (Watanabe et al. J Biomech 2014). This phenomenon can be explained by region-specific functional roles within a muscle, i.e., proximal regions of the RF muscle mainly contribute to hip flexion, while all regions of this muscle contribute to knee extension (Watanabe et al. J Electromyogr Kinesiol 2012).

In the elderly, this regional activation during the swing phase was attenuated (Watanabe et al. J Biomech 2015). We suggest that region-specific functional roles within a muscle may be a key to age-related dysfunction in locomotion. The knowledges derived from multi-channel SEMG proves new insights into how the neuromuscular function is altered due to aging and lifestyle-related diseases, and may help to establish effective exercise programs for the elderly and patients with such diseases.

Rehabilitation robot using muscle activity and neural decoding

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[1]Tokyo Institute of Technology

BACKGROUND AND AIM: Non-invasive measurement method, such as EEG, fMRI or NIRS, has been used for brain-machine interface (BMI). EEG has nice temporal resolution, and it is often used for BMI. Recently, electrocorticography (ECoG) is used as an alternative approach to less invasive BMIs. Since ECoG records directly from neuronal activities on the cortical surface, ECoG has higher spatio-temporal resolution with better signal-to-noise ratio than scalp EEG. Several studies using ECoG have already succeeded in the classification of movement direction, grasp type, and prediction of hand trajectory. Despite these successes, however, there still remains considerable work for the realization of ECoG-based prosthesis. Additionally, recent studies using electromyography (EMG) have suggested that many muscles in a human body are controlled by combination of fewer activation patterns, called muscle synergies. It is also known that motor impairments following neuronal damages are related to partial changes of the muscle synergies. METHODS: The human neuromuscular system naturally modulates mechanical stiffness and viscosity to achieve proper interaction with the environment. Current rehabilitation robots can perform sophisticated operations including stiffness control. Our model is constructed with the musculo-skeletal model which can predict the angle, torque, and stiffness of joints from muscle activity. Our BMI system decode muscle activity and estimate the motion using musculo-skeletal model. RESULTS: We introduce our researches on estimating mechanical properties of musculo-skeletal system from EMG signals, and its application to robot control (Shin et al., 2009; Kawase et al.,

2012). Then we introduce BMI using muscle activity decoded from EEG and ECoG recordings (Yoshimura et al., 2012; Shin et al., 2012; Nakanishi et al., 2013; Chen et al., 2014). Finally, we introduce our recent results of muscle synergy analysis in patients with hemiparesis, and its potential application to rehabilitation robots using muscle activity. CONCLUSIONS: Decoding muscle activity is an important component for realizing BMI systems capable of controlling interaction force or stiffness. Understanding the relationship between the synergies and motor impairments may enhance possibilities of robot-aided rehabilitation using measured or decoded muscle activity. ACKNOWLEDGEMENT: A part of this study was the result of "Brain Machine Interface Development" carried out under the Strategic Research Program for Brain Sciences by MEXT/AMED. This work was supported in part by Grant-in-Aid for Scientific Research on Innovative Areas (26112004) from MEXT.

Ubiquitous approach for health and sport

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[1]Osaka Electro-Communication University

Now Japan is super aged society, and the ratio of senior citizen for the population will reach a peak in 2025. It is important to the society that a senior citizen lives healthy. The need of their health care increases to live a healthy life. It is important to measure biological information every day and to predict a change of the health condition from the tendency. We received the support of Ministry of Education, Culture, Sports, Science and Technology since 2011 and started the research of the unconscious biomedical measurement in the daily life. The purpose of this study is to develop the system to measure the biomedical information during daily life, to analyze them and to transfer the results to a medical institution. The developed system enabled an unconscious measurement of a heart rate, blood pressure, exercise and the body temperature. For heart rate measurement, we developed two system. One was a photoplethysmography using green light. This is not affected by the motion artifact. The other was the system using electrocardiogram which was led non-contactly from a sheet on a bed. We developed a chair for cuffless real-time estimation of systolic blood pressure based on pulse transit time. Furthermore, using an unconscious exercise monitoring system, we developed the remote instruction system for the rehabilitation at home. The noninvasive wearable deep body thermometer was also developed. This thermometer is helpful for a person having difficulty in body temperature adjustment.

A Remote and Non-Contact Monitoring System of Physiological Indices to Cope with Visually Induced Motion Sickness

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[Background] Head mounted displays or three dimensional wide screen television sets are frequently used for not only video games but also virtual reality rehabilitation. However, these displays sometimes cause visually induced motion sickness (VIMS). To cope with VIMS, it is important to quantify the degree of VIMS by extracting physiological indices from viewers. Physiological indices can be obtained from electrocardiograms, blood pressure, pulse waves (sphygmograms), galvanic skin responses, and so on. However, contact-type sensors are required to measure these parameters. On the other hand, it has been reported that pulse waves can be obtained in a non-contact and remote fashion by processing video signals taken by usual video cameras. In addition, it is possible to take information on blood flow or blood pressure at once because video signals are related to two dimensional information on blood volume under the skin. [Objectives] The purpose of the present study is to develop a remote and non-contact monitoring system for extracting physiological indices from viewers watching a video display to cope with VIMS. [Methods] Hemoglobin included in blood well absorbs the green components of ambient light, and thus the green video signal reflected from the human skin has information on blood volume under the skin. By using this fact, the pulse waves can be obtained to extract physiological indices as follows: 1) The region of interest on the video image is tracked by using face recognition or skin color identification and divided into plural small segments. 2) Mean brightness intensity of green components over each small segment is calculated and memorized as a time series. 3) Band-pass filtering with the pass-band of 0.5-2Hz with FFT and inverse FFT is applied to each time series data to remain only heart beat components. 4) The phase difference in mean intensity between proximal and distal areas from the heart is

calculated, and then the pulse wave transit time is obtained from the phase difference. [Results] A laptop personal computer with a front camera was used to operate the monitoring system developed with C++ and OpenCV. Fig.1 shows a snapshot of the movie image (20fps) of the monitoring system. In Fig.1a), mosaic images corresponding to intensity of the video pulse are superimposed on the subjectýfs face image. Fig.1b) shows pulse waves before and after filtering, and Fig.1c) shows heart rate. The phase difference was obtained as the difference time between the local maxima and minima of time series corresponding to two areas shown in Fig.1a). [Discussion and Conclusion] On the basis of the video pulse signals obtained above, several physiological indices such as the ratios of LF/HF of heart rate and the pulse amplitude, and so on will be estimated. However, the video pulse wave includes more noises than that measured with contact-type photo sensors and the frame rate should be higher to take more accurate phase difference information

Brain-muscle-machine interface: controlling a prosthetic hand

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To develop brain-muscle-machine interfaces, many Japanese researchers have proposed methods to approximate fine hand movements using electromyograms and cranial nerve signals. The applications toward realizing electric prosthetic hands are particularly remarkable. Our group has developed a multi-DOF myoelectric hand using three myoelectric sensors, which can produce eleven types of hand-finger movements (YK-Hand), enabling people who have lost their forearm to regain their freedom in daily living. This presentation introduces the current state of myoelectric hands in Japan, our multi-DOF myoelectric hand (YK-Hand), and other methods to estimate hand movements based on adaptive learning of individual differences and time-variances in myoelectric features. There are two types of YK-Hands: the multi-DOF and the practical/simple type. The former uses a wire-driven robot hand to approximate the biarticular muscle structure of a human hand, while the latter uses a two direct-drive actuator capable of three basic movements (grasping, tripod pinching, and lateral pinching). The adaptive learning method to estimate hand motions consist two components: motion-discrimination unit and on-line learning unit. The motion-discrimination unit discriminates classes of various hand motions

using myoelectric frequency characteristics and a neural network. The on-line learning unit learns/modifies training data for motion discrimination based on the continuity of the discrimination results and an information entropy representing the similarity of myoelectric features of different classes of movements. A high discrimination rate (> 85%) is possible for eleven types of hand movements, even after nine hours of continuous prosthetic hand use. To investigate how users become proficient and adapt to a myoelectric hand, we measured the brain activity of a user during continuous use by fMRI and evaluated the changes in brain activity. Our results show that the primary motor and sensory cortex are activated concomitant with proficiency of prosthetic hand use. Additionally, for a user to stably control various types of hand motions, much muscle strength must be exerted. Consequently, a prosthetic hand may feel unnatural and cause physical fatigue. To combat these issues and help users have a more natural experience, we propose a new control method for a myoelectric hand using a hand-motion discrimination method based on electromyograms during pre-shaping movements and a grip speed control method using estimates of object-based attention from electric signals originating in the eye. Our method reduces the muscle activity to one-third the previous value. Moreover, the control grip can control the grip speed, which can be decreased by increased focus on an object by the user (e.g., when gripping a small object). By controlling the approach movement prior to gripping on object, we achieved a more stable and closer approximation to natural hand movements.

S.18. *Intermittent control*

Intermittent Control provides a deterministic explanation of linear and remnant components of human stance control without injection of random noise.

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BACKGROUND AND AIM: Traditional models on human stance control explain our irregular sway pattern by injecting random (sensor and/or motor) noise acting,

closed-loop, on a continuously operating circuit. Here we present a deterministic explanation that, as a consequence of intermittent event triggered decision making, reproduces the non-linear remnant and the linear frequency response as well as a continuous controller with added noise. METHODS: Data in the context of controlling a human-in-the-loop system was collected in 9 participants who were strapped to a single segmental inverted pendulum structure pivoting around the ankle joint. Stance control of the human-attached-to-pendulum system was achieved by feeding a control signal derived from EMG signals measured at the Tibialis Anterior and calf muscles to the virtual unstable inertial second-order system whose output (sway movement) was transmitted via a very strong actuator to the controlled system. Participants used all available sensory feedback to reject a multi sine input disturbance under three levels of disturbance amplitude (small, medium, large) applied to the system. Our method of analysis consisted of two stages. In the first stage, we fitted linear time-invariant control parameters to the excited frequency response (CC). In the second stage, to provide a benchmark, we improved the fitted power at all frequencies by adding noise derived by calculation of the non-linear remnant (CCn) and, to test the intermittent control explanation (IC), we adjusted four parameters of the intermittent controller (Sampling Delay, Event Thresholds on position, velocity and force states) . RESULTS: Our results show that, unsurprisingly, the continuous model fits the experimental power at all frequencies when a customised noise spectrum for each disturbance amplitude level was added. The key finding is that also the Intermittent Controller fitted the observed variability using a physical model without additional noise. At the high disturbance amplitude level, the distribution of Open Loop Intervals shows small values. At the low disturbance amplitude level, we found substantial Open Loop Intervals (of more than 1 second). CONCLUSIONS: Our findings indicate that when disturbances are low, and sway is predictable, continuous sensory feedback is not required. The key conclusion is that intermittent use of sensory information using thresholds on state prediction errors can explain human stance control as well as a traditional linear model with added noise.

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Intermittent control: a general paradigm for understanding sensorimotor control

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BACKGROUND AND AIM: Human motor control is constructed through central processes of selection and reinforcement learning. Our ability to investigate mechanisms is linked to the tools available. The collection of control principles, theoretical models, system identification methodologies, behavioural and neural data collectively forms a paradigm within with investigation occurs. METHODS: Continuous feedback provides the predominant paradigm for sensorimotor control. Within the continuous control paradigm discrete decision making is restricted typically to an undeclared, higher process which passes optimised control parameters to a lower continuous regulatory loop. The continuous regulatory loop models the fast, reflexive spinal, brainstem and trans-cortical responses that have been studied extensively physiologists. The intermittent rather than continuous use of sensory information to update control signals implies an event trigger determining when to use sensory information, a discrete sampling/initialisation process and a hold process constructing a time varying control trajectory (Figure 1). The effect of the open loop interval is to reduce the control bandwidth. The benefit is (i) the event related possibility to iteratively reinitialise the control basis and (ii) the availability of predictively stabilised open loop time to provide state dependent optimisation. In short, intermittent v. continuous control trades online flexibility for control bandwidth. Recent theoretical and methodological advances have provided new behavioural evidence of sequential, refractory response selection during sustained sensorimotor control. While including continuous control as a special case omitting the discrete sampling and hold processes (green blocks in Figure 1), intermittent control provides a more general paradigm in which discrete refractory selection occurs as a serial, sequential, single channel process within the main feedback loop. RESULTS: Intermittent control has been considered, increasingly extensively, as a paradigm for studying motor control, adaptation and learning in man and in robotics applications. Distinguishing intermittent from continuous control is confounded by the masquerading property of intermittent control. With experience, human control is smooth even if it is constructed sequentially. While continuous control is well established for studying reflexive sensorimotor control, when motor decision making, learning and adaptation are considered, intermittent control becomes more relevant. This talk introduces the symposium to show how the intermittent control paradigm is becoming increasingly established and plausible from all aspects - control theory, principles, system identification methodology, behavioural data and neural substrates. CONCLUSIONS: This paradigm has value for basic science, for interfacing humans with machine devices, for informing diagnosis of sensorimotor impairments and for informing rehabilitation.

A machine learning model of intermittent control

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BACKGROUND AND AIM: There is considerable evidence that the human central nervous system uses intermittent control to control movement. If this were the case, one can hypothesise that intermittent control is necessary; therefore one might ask why does the CNS need intermittent control? The current consensus is that the human brain needs 'thinking time' to couple motor actions with state representations when decisions and actions are sufficiently complex. We present a novel machine learning framework for studying intermittency in the human brain. METHODS: State feedback is fed into a state representation, which is fed into a complex, interconnected layer of neurons (proposed) called intermittent long short-term memory (iLSTM). Based on LSTM, these neurons can store sensory information for many time steps, which can be used to influence the rest of the system; in contrast to LSTM they predict the state input one continuous time step ahead. iLSTM neurons are controlled by gated (black circles) connections; node d switches between state information a or a model prediction of the state c by excitatory (blue), and inhibitory (red) connections. The state input has a self-recurrent connection, gated by a reset node h which controls the proportion of a that is retained over time. The main input node g is controlled by a gated connection to f, which controls the proportion of g which is written to a. The coloured connections are fixed, while the black connections are adaptive, and can be learned using back-propagation through time, given a desired state and a state error. The state (predicted/measured) is fed into the rest of the network, then into an action representation, which encodes the actual control signal. The many recurrent connections are analogous to the 'thinking time' believed to be a possible reason behind intermittent control. The system can block access to sensory data, and use a model prediction, then cycle many times through the network, to produce the appropriate control response. Symbols within the nodes indicate linear and nonlinear. RESULTS: Our approach gives investigators the ability to model control systems without explicitly designing delay parameters, intermittent intervals, or indeed whether open loop or closed loop control would provide the best solution to a given problem. Our approach also provides a framework for investigating intermittency in control systems, with respect to whether intermittency is required, and if so, which situations it is required for and why. By learning only from a state representation and a desired state, the network can learn optimal parameters on node d controlling the output gate. Our hypothesis is that if intermittent feedback is necessary for a given system, then the network will learn to use sensory input intermittently, and only for learned intermittent intervals. CONCLUSIONS: We present our on-going investigations using this framework to identify systems hypothesised to be intermittent.

Remnant response in visual-manual tasks and intermittent control

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BACKGROUND AND AIM: Variability, together with non-linearity, are fundamental features of human movement. They are associated with the response component which is not linearly related to the input, i.e. the remnant response. The conventional explanation attributes the main source of remnant to stochastic noise imposed on a continuously operating feedback loop, and the resulting variability is usually regarded as a nuisance. We explore an additional explanation in which the remnant response is an inherent mechanistic feature arising from an event-driven intermittent control loop. We present a two stage frequency domain approach which is used to identify, from experimental data, a continuous controller with added suitably coloured sensory noise, or, alternatively, an event-driven intermittent controller. METHODS: We considered a manual control task to balance an unstable system with dynamics similar to an upright human, where 11 participants were given visual feedback to follow different control priorities, while the control signal is disturbed by an external multi-sine periodic disturbance with components at discrete frequencies. In stage 1 of our identification procedure (see figure), a linear continuous control model (CC) was fitted to the periodic component by averaging the complex frequency response over all periods. In the 2nd stage, the analysis period was extended, allowing us to differentiate between the responses at non-excited frequencies (the remnant) and at excited frequencies (which include the linear, periodic response and a remnant component). The remnant was modelled by either adding suitably coloured sensory noise (based on the response at non-excited frequencies) to the continuous controller (CC+noise), or by using an event-driven intermittent controller (IC), based on the CC design from stage 1, with appropriately optimised threshold parameters. using a cost function which includes the PSD at excited and non-excited frequencies to ensures that the total power of the response is fitted. Simulated data from these two explanation were also used to explore whether our approach could differentiate between a CC or IC explanation. RESULTS: The CC+noise can explain the experimental data well, but the added noise spectra are highly dependent on the experimental instructions. The IC can explain the frequency responses equally well, but only requires the adjustment of the parameters of the intermittent event detector. The values of these thresholds are related to the instructions, e.g. precise position control is associated with small thresholds, whereas relaxed instructions result in larger thresholds. CONCLUSIONS: An identification approach has been developed which demonstrates that event-driven IC can reliably fit the remnant spectrum of manual-visual control, suggesting that purely mechanistic features of the controller may play an important role as a source of variability in human movement.

Sensorimotor dynamics in the brain during intermittent control of goal-directed movements

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BACKGROUND AND AIM: Regulation of limb position in response to intermittent disturbances has been shown to occur over short and long timescales. FMRI studies indicate overlapping brain networks contribute to sensorimotor corrections over

these time scales, but the temporal dynamics mediating intermittent corrections remain unclear. We examined cortical network dynamics associated with intermittent closed-loop control and impairments that arise when feedback timing is disrupted. METHODS: We used 64-channel EEG to probe temporal dynamics of error correction in cortical networks. Healthy people (N=7) used a 1-D wrist robot to perform pursuit tracking of a moving visual target. Subjects generated intermittent corrections to performance errors induced by forces applied to the wrist (proprioceptive "P trials") or visual displacements of the cursor (visual "V trials"). Distributed source modeling identified cortical contributions to average EEG activity. We used the same setup to examine how demyelination and delays in feedback (esp. visual) in multiple sclerosis (MS) contribute to sensorimotor impairment. Sixteen subjects (8 with MS and tremor; 8 controls) regulated cursor position relative to a stationary visual target in response to band-limited visual or torque perturbations to the cursor or arm. RESULTS: In P trials, current source maps reveal early somatosensory, premotor, motor, and frontal activity ranging from 43±5 ms to 48±6 ms post-perturbation, followed by parietal activity at 70±8 ms. In V trials, parietal activity (113±8 ms) was followed by sensory, motor/premotor activity (123±42 ms to 131±22 ms). This reflects differential processing of proprioceptive and visually perceived errors. In the absence of visual feedback, errors are first computed in (and acted upon by) premotor/motor areas before a parietal estimate of error is available. When visual feedback is present, performance errors are first computed in parietal regions before being processed in motor areas. In MS subjects, we postulated that submovement intervals (derived from velocity profiles) correspond to an internal prediction of feedback delay. Consistent with this, V trial submovement intervals and response delays did not differ for control subjects ($t(9)<1.4$, $p>0.05$). By contrast, MS subjects with moderate to severe tremor (4 of 8) had V trial response delays much greater than controls ($t(7)=2.55$, $p=0.038$). In P trials, where feedback delays are much shorter, submovement intervals and response delays did not differ across groups ($t(9)<1.6$, $p>0.05$). CONCLUSION: These studies suggest that intermittent control is mediated by short and long feedback loops utilizing overlapping brain areas with different temporal dynamics. Altered timing of feedback through these networks leads to mismatches between predicted and actual delays, resulting in motor impairment. Future studies will explore how intermittent control is synchronized across the senses to maintain closed-loop stability.

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A dual Kalman filter approach to adaptation in intermittent control

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BACKGROUND AND AIM: Intermittent Control (IC) has been used to describe the modular architecture that underlies human motor control. Recent studies on human motion indicate that the parallel flow of sensory information converges to a serial ballistic process which includes the planning and selection of desired motor responses, suggesting that such a process is beneficial when complex optimization or flexible adaptation is needed to compute optimal motor output. These ideas allow us to hypothesize that adjusting our control actions to compensate for changes in the system that is being controlled could be modelled by incorporating adaptation strategies into this framework, which exploit the advantages of having open-loop intervals punctuated by instances of intermittent feedback. By designing an adaptive, self-tuning, intermittent controller based on Kalman filtering estimation principles, this study aimed to examine the effects of using adaptation techniques on a postural balance model and the possible extensions to other engineering systems. METHODS: The concept of a self-tuning regulator provides the foundations for our adaptive intermittent controller. First, an estimate of the time-varying parameters of the system is obtained in order to redesign the controller at a later step. The estimation procedure, for both, states and parameters, is performed by a dual Kalman filter that runs continuously. The estimated parameters are only used to update the control law when an event is triggered by an error exceeding a predefined threshold, using optimal control techniques. In other words, sensory information is updated continuously, but only used when needed to adjust the control strategy. The open-loop interval serves as an ideal time frame to estimate the changes in the system. This intermittent moving time-horizon allows slow optimization procedures to take place simultaneously with fast control actions, increasing the computational time for adaptation. The fact that during the open-loop period, the controller uses a predefined control trajectory (computed at every feedback instant), provides time to run online identification procedures without this representing a heavy computational burden. RESULTS: This controller was applied to a dynamical model of human balance, and compared to a corresponding continuous controller (CC). Fig. 1 shows

the estimates obtained by both controllers when one of the parameters changes suddenly. When IC is used, the estimate converges to the real parameter at a faster pace, reaching 80% of the value in less than 0.1s compared to up to 0.3s for the CC. The CC approach updates the control law at every sample whereas IC only does it when an event is triggered. CONCLUSIONS: Our results suggest that the proposed methodology is a good candidate to model online adaptation processes within the IC framework, providing a flexible algorithm that could potentially be used to reproduce human behaviour.

Intermittency using boundary control

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BACKGROUND AND AIM: Many research studies have attempted to approximate how people move using optimal control modeling approaches. However, more functional tasks tend to have flexibility of movement choice, rendering optimal solutions arbitrary. For example, there are a variety of ways one might catch an incoming object. An alternative method of action planning would be to simply avoid adverse situations, allowing all other forms of activity to be possible. Such control approaches open up new possibilities and also allows intermittency in the controller. METHODS: Our demonstration experiment required subjects to intercept objects anywhere along their trajectory. We also added robotic limit-push forces that pushed the hand further away once it exited an invisible region. RESULTS: With practice, subjects distributed their actions more uniformly within these boundaries. We will show that control variables such as distance- and time-to-edge of these boundaries increase with practice, supporting the notion that the nervous system attends carefully to their control. A simple computational model demonstrated that such a controller can intermittently turn its attention to other matters for a few moments. CONCLUSIONS: We speculate on the general idea that all other formulations of control might be instances of this type of control. This concept of "avoiding bad" makes it possible to easily execute intermittent control in complex activities, and also can be used to explain the wide variance of actions seen in some behavior.