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Mini-Symposia Title:

Upper and Lower Extremity Rehabilitation Robotics: Current Trends and Future Directions

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Soha Saleh, Ph.D., Kessler Foundation

Theme:

○ 01. Biomedical Signal Processing
○ 02. Biomedical Imaging and Image Processing
○ 03. Micro/ Nano-bioengineering; Cellular/ Tissue Engineering &
○ 04. Computational Systems & Synthetic Biology; Multiscale modeling
○ 05. Cardiovascular and Respiratory Systems Engineering
○ 06. Neural and Rehabilitation Engineering
○ 07. Biomedical Sensors and Wearable Systems
● 08. Biorobotics and Biomechanics
○ 09. Therapeutic & Diagnostic Systems and Technologies
○ 10. Biomedical & Health Informatics
○ 11. Biomedical Engineering Education and Society
○ 12. Translational Engineering for Healthcare Innovation and

Mini-Symposia Synopsis— Max 2000 Characters

In the past decade there have been several important advances in Robotics and an expansion of the Robotics -based rehabilitation. This symposium will focus on Innovative rehabilitation robotic technologies and its impact on recovery of upper and lower extremity function in people with neurological deficits (stroke, traumatic brain injury, and spinal cord injury). The symposium will present an overview of four areas of rehabilitation technology: Development of rehabilitative and assistive robots, clinical use of robots, functional and biomechanical changes due to robotic therapy, and the corresponding adaptive induced neuroplasticity. An expert will present an overview of each area with an emphasis on patient populations that are best served by each family of technologies, progress that has been made beyond the original research, and the current directions of research in each of these fields. . Investigators will examine immediate and long term training responses for biomechanical (joint kinematics, limits of stability, 3D loading forces, center of pressure, joint torques, and metabolic), electrophysiological (EEG, fNIRs, MRI) and peripheral neural (EMG) variables in order to understand the changes in peripheral, spinal, supraspinal/ cortical control of gait. The overall focus of the symposium is to illustrate efficacy of using different powered robotics in upper and lower extremity rehabilitation for a cross section of different neurologically impaired populations.

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Ground reaction force profiles during Exoskeleton Training

Gail F. Forrest, Director, Kessler Foundation

Abstract — **This study presents preliminary data for ground reaction force for able-bodied control and SCI walking in several different exoskeletons to evaluate the temporal-spatial relationships among conditions.**

I. INTRODUCTION

Measurement, interpretation, and characterization of 3-D ground reaction force (GRF) during human walking has proven to be a crucial descriptor of pathological gait [1]. All 3-D GRF (vertical, anterior-posterior, and medial-lateral forces) are required for calculating the inverse dynamics during gait to determine the ankle, knee, and hip joint kinetics, albeit GRF's and joint torques influence proprioception, afferent input, motor control, spinal reorganization, and recovery after injury. This study aims to evaluate the vertical component of GRF when walking with different robotic exoskeletons (RE) and establish temporal-spatial relationships among conditions compared to GRF temporal-spatial profiles for able-bodied (AB) and spinal cord injury (SCI) gait.

II. METHODS

Able-bodied (AB, n=6) and SCI (n=11) individuals trained to walk with the RE devices (EksoGT^{TM}, ReWalk^{TM}, & Indego®) independently under minimal supervision. For able-bodied individuals, EksoGT^{TM} testing occurred under *Max-Assist*, *Fixed-Assist,* and *2Free* modes. After training, GRF data from multiple walks on four force plates were collected using all RE devices, as well as independent overground (OG) walking at slow (OG_{slow}), self-selected (OG_{ss}), and fast (OG_{fast}) speeds. Data were collected for the SCI group at one intervention time-point while walking with EksoGT^{TM} (Max-Assist setting only) and ReWalk^{TM}. Participants were instructed to walk multiple times along a 10m walkway. GRF data (120 Hz) recorded from four force plates (Bertec Corp, OH). Trials with clean force plate foot strikes (bilaterally on any of the four plates) were analyzed. Outcomes included GRF profile correlations (R); suitable adjustments of p-value (<.05) for multiple comparison.

III. RESULTS

Comparison of profiles for all conditions were performed by examining correlations (RE-assisted conditions for both AB and SCI groups were compared to AB overground walking (OG_{slow}, OG_{slow}, OG_{fast})(Fig. 1C,D). For the AB group, RE-assisted GRF profiles, among all devices and conditions, were strongly correlated (R = 0.92 to 0.99, p<.0001) to OG_{slow}. Indego® had strongest correlation (R = 0.99). Compared to the OG_{ss} condition, ReWalk^{TM} and Indego® still produced significantly higher correlations (R = 0.94 and 0.93, respectively, p<.0001) than EksoGT^{TM} (R = 0.77 to 0.88) with the *Max-Assist* condition, least correlated (R = 0.77). Weak correlations for RE-assisted walk for the SCI group compared to OG_{slow} (R = 0.77 to 0.97) and OG_{ss} (R = 0.62 to 0.90).

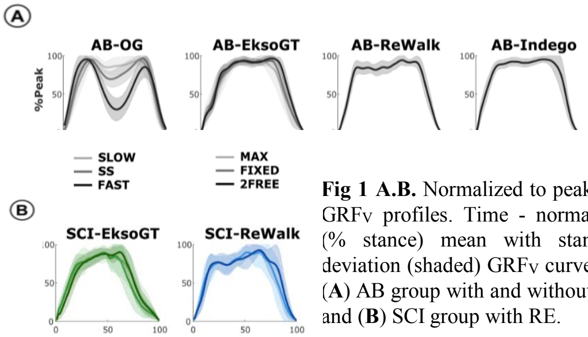

Fig 1 A.B. Normalized to peak (%) GRFv profiles. Time - normalized (% stance) mean with standard deviation (shaded) GRFv curves for (**A**) AB group with and without RE, and (**B**) SCI group with RE.

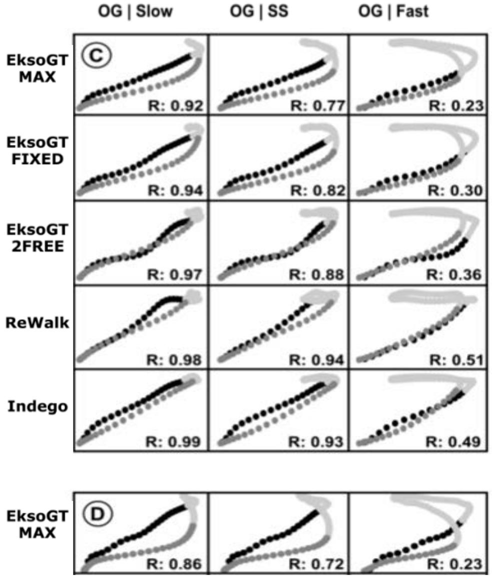

Fig1 C. D. Correlations among OG (AB) and RE-assisted walking conditions relative to normalized GRF vs stance. Graph shows: IDS, SS and TDS phases for (**C**) AB and (**D**) SCI groups.

IV. DISCUSSION & CONCLUSION

Correlation data suggests able-bodied gait walking in exoskeleton exhibit similar GRF temporal-spatial as walking overground. However, force profiles visually appear quite different. Additional analyses exploring the different phases of gait, the relationship between GRF to normalized foot pressure, and relevance to recovery should also be performed.

REFERENCES

[1] Ramanujam, A., et al.,. J Spinal Cord Med, 2018. 41(5): p. 518-528.
[2] Dumas R, Nicol E, Chèze L. *Influence of the 3D inverse dynamic method on the joint forces and moments during gait.* J Biomech Eng. 2007 Oct;129(5):786-90. doi: 10.1115/1.2768114. PMID: 17887905.

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Individualizing Robot-Assisted Gait Rehabilitation via Reinforcement Learning Control

Damiano Zanotto, Assistant Professor, Stevens Institute of Technology

***Abstract*— Assist-as-needed (AAN) control aims at promoting therapeutic outcomes in robot-assisted rehabilitation by encouraging patients' active participation. In most AAN controllers, the robot's impedance parameters are adjusted manually by a human expert or adapted online based on simplistic assumptions about the wearer's learning processes. We argue that the lack of personalization in existing AAN controllers may contribute to the modest therapeutic benefits of robot-mediated intervention over conventional exercise-based therapy. In this talk, we introduce new learning-based AAN strategies for robot-assisted gait rehabilitation that continuously shape a robot's control policy based on models of the user's motor adaptation learned on-line. The controllers are validated through gait training sessions with able-bodied individuals who learned an altered gait pattern with the assistance of a powered ankle-foot orthosis. The proposed controllers do not rely on presumptions about an individual's learning ability and can modify the control policy in real-time based on the wearer's motor responses.**

I. INTRODUCTION

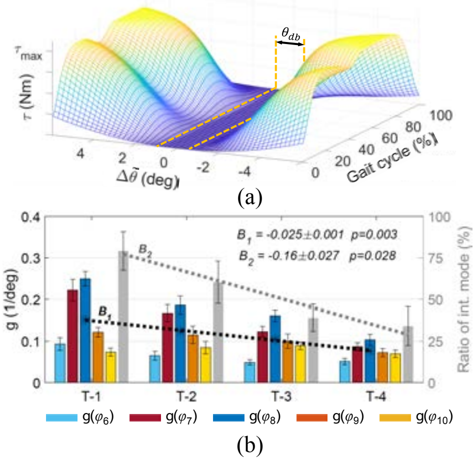
During robot-assisted training, individuals tend to let the robot "take over" the motion tasks completely – if given the opportunity – thereby reducing their physical effort. Because active effort is a critical enabler of motor learning, this "*slacking effect*" is detrimental for rehabilitation. To mitigate the slacking effect, rehabilitation robots should provide only the amount of assistance required for a subject to complete the target motion and should allow a certain level of kinematic error. Controllers designed to achieve these goals are called "*assist-as-needed*" (AAN). Most AAN controllers modulate the level of robotic assistance by following an iterative learning control (ILC) law that approximates the way the human motor control system adapts to a training task. To encourage subjects' learning, these controllers must reduce the assistive forces at a faster rate than the rate at which the wearer reduces their effort, and therefore they require time-consuming tuning processes. Simpler implementations of the AAN paradigm rely on static, error-dependent force-fields that require minimal tuning but cannot self-adapt to an individual's performance. To enable individualized assistance by a powered orthosis and eliminate the need for manual tuning, herein we introduce two model-free controllers based on the reinforcement learning (RL) paradigm. Both controllers seek to continuously balance the wearer's kinematic error and effort, in a subject-specific fashion, until the robot's assistance is no longer needed for the wearer to complete the target motion task.

II. METHODS

The impedance control law of the powered orthosis is defined as

$$\tau = \tau_{max}\left(1 - \mathrm{e}^{-(\Delta\theta\ g)^2}\right), \qquad (1)$$

where τ_{max} is the upper bound of the assistive torque τ, $\Delta\theta$ is the kinematic error, and g is the stiffness parameter. The first RL controller relies on *Action-Dependent Heuristic Dynamic Programming* (ADHDP). By correlating the actor control objective with tracking errors in the most recent gait cycles, the ADHDP-AAN controller autonomously stiffens the force-field when the subject struggles to complete the training task, and progressively increases compliance when sustained good performances are detected. This is achieved by updating g after each gait cycle. The second RL controller improves the adaptability of the former strategy by enabling individualized, phase-dependent assistance through a modified *Policy Improvement with Path Integral* (PI^2) algorithm. In the PI^2-AAN controller, g is modulated by a set of phase-locked kernel functions, resulting in a phase-dependent force field whose stiffness fades as the wearer learns the target motion (Fig. 1). The kernel weights are continuously updated to optimize the weighted sum of kinematic errors and control effort, and this cost function is updated by a hierarchical policy evaluation structure that specifies different learning objectives based on subjects' training progress.



(a)

(b)

Figure 1: (a) Individualized, phase-dependent force field generated by the PI^2 algorithm; (b) group averages (N=10) indicate that the stiffness of the powered orthosis (colored bars) decreases from the first to the last training session (T1-T4), as the subject learns the motor task.

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*Research supported by the NSF (CMMI-1944203) and by New Jersey Health Foundation (PC 6-18). D. Zanotto is with the Wearable Robotic Systems (WRS) Lab, Stevens Institute of Technology, Hoboken, NJ 07030 USA; e-mail: dzanotto@ stevens.edu).

Effect of Robotic Exoskeleton Gait Training during Acute Stroke on Functional Ambulation

Karen J. Nolan, Assistant Director, Kessler Foundation

***Abstract*— This investigation presents preliminary data utilizing rehabilitation robotics for over-ground inpatient gait training for acute post stroke functional recovery. Summary data will include distance walked during their physical therapy sessions and measures of functional ambulation.**

I. INTRODUCTION

Stroke is the leading cause of long-term functional ambulation deficits resulting in reduced quality of life. Conventional therapy produces improvements in ambulation, but may not be able to provide consistent, high dose repetition of movement, resulting in the variable recovery of functional ambulation with residual gait deviations. Research in gait rehabilitation has shown that high dose quality gait training will lead to recovery of walking function [1, 2]. Recovery of functional ambulation is dependent on the interrelationship between dosing, intensity [3], and task specific practice [4] applied during rehabilitation [5]. The objective of this preliminary prospective investigation is to evaluate the ability of a robotic exoskeleton (RE) to provide high dose physical therapy (PT), and its therapeutic effect on the functional ambulation in adults with acute stroke.

II. METHODS

Participants (n=17) were admitted to an acute inpatient rehabilitation facility (IRF), diagnosed with stroke and hemiplegia (<3 months). All participants received standard of care (SOC) PT during inpatient rehabilitation. Fourteen participants received at least two sessions per week of RE gait training during their scheduled PT using a commercially available FDA approved robotic exoskeleton (EksoGT, Ekso Bionics, Inc. Richmond, CA, USA) for the duration of their inpatient stay. Outcome measures were collected at baseline (before training sessions) and follow-up (within one week of completing the last training session) and included distance walked during their physical therapy sessions (used as a measure of dosing), ten-meter walk test (10MWT), 6-minute walk test (6MWT), and timed up and go (TUG).

III. RESULTS

Pearson's rank correlation demonstrated that with increased SOC training or reduced RE training the distance walked in PT reduces per session (r= -0.669, p<0.01) (Figure 1a). Spearman's rank correlation showed that increased RE training or reduced SOC training results in increased total distance walked during a rehabilitation therapy session (ρ= -0.589, p<0.05) (Figure 1b). Wilcoxon Signed-Ranks test showed a significant difference between baseline and follow-up in 10MWT (p<0.01), and 6 MWT (p<0.01) tests. Paired samples t-test showed a significant difference between baseline and follow-up in TUG (p<0.01). Spearman's rank correlation showed a significant correlation (p<0.01) between total distance walked and change in TUG (Figure 2a).

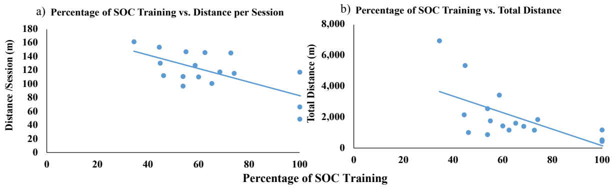

Figure 1: a) Distance walked (RE + SOC) per PT session vs. Percentage of SOC training. b) Total distance walked during PT training vs. Percentage of SOC training.

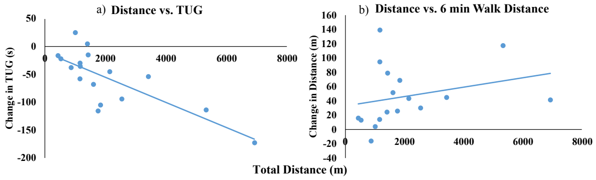

Figure 2: a) Total distance walked (RE+SOC) vs. change in TUG; b) Total distance walked (RE+SOC) vs. change in speed; c) Total distance walked (RE+SOC) vs. change in 6 minute walk distance; and d) Total distance walked (RE+SOC) vs. change in speed during 6 minute walk distance.

IV. DISCUSSION & CONCLUSION

The walking distance during PT increased with increased use of RE for individuals post stroke. This research suggests that RE can increase dosing, and may result in improved functional ambulation in adults with acute stroke. This preliminary research provides information on the ability of robotic exoskeleton to provide high dose therapy and its therapeutic effect on the functional ambulation in adults with acute stroke.

REFERENCES

[1] Lohse, KR, et al. Is more better? Using metadata to explore dose-response relationships in stroke rehabilitation. Stroke 2014.

[2] Cooke, EV, et al. The effects of increased dose of exercise-based therapies to enhance motor recovery after stroke: A systematic review and meta-analysis. BMC Med. 2010.

[3] Hornby, TG, et al. Influence of skill and exercise training parameters on locomotor recovery during stroke rehabilitation. Curr. Opin. Neurol. 2016.

[4] Krishnan, C, et al. Learning new gait patterns is enhanced by specificity of training rather than progression of task difficulty. J. Biomech. 2019

[5] Partridge, C, et al. Is dosage of physiotherapy a critical factor in deciding patterns of recovery from stroke: A pragmatic randomized controlled trial. Physiother. Res. Int. 2000.

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b)

Robotic Gait Training for Children and Young Adults with Acquired Brain Injury

Kiran K Karunakaran, Associate Research Scientist, Kessler Foundation

Abstract— **The objective of this presentation is to demonstrate the effect of 4 weeks of robotic exoskeleton gait training in children and young adults with chronic brain injury. Summary data will include the neuromechanical and cortical outcomes.**

I. INTRODUCTION

Acquired brain injury (ABI) with associated hemiparesis results in gait and balance deficits in adolescents and young adults [1], [2]. These motor deficits decrease walking speed, control and coordination, while also increasing asymmetry and almost doubling support time, leading to pathological ambulation [1], [2]. Recovery involves rehabilitation through physical therapy based on the theory that the human brain is capable of self-reorganization, through continuous, consistent, repeated practice aimed at restoring function and independence [3]. Conventional therapy alone may not be able to provide enough consistent mass practice and repetition to facilitate the neuroplasticity needed for a functional recovery. Consequently, after rehabilitation, individuals with ABI can experience variable recovery with residual gait deviations and may develop compensatory mechanisms in order to achieve ambulation [2], [3] .

Robotic exoskeletons (RE) can deliver comprehensive motor and balance training. They can provide the user with intensive, consistent, goal-directed repetition of movement and also with balance & stability [4], which is ideal to induce neuroplasticity and may lead to improved functional recovery in children and young adults with chronic ABI.

The objective of the study is to evaluate the neuromechanical and cortical outcomes after 4 weeks of RE gait training in children and young adults with chronic ABI.

II. METHODS

Seven participants with hemiplegia due to ABI between 13-28 years of age and one age-matched healthy control completed the study. The ABI group walked in the RE three days per week for 4 weeks (45 minutes/session), and participated in two assessment sessions walking with and without the RE at baseline and at 4 weeks. A licensed PT administered all RE gait training sessions, as shown in Figure 1. Data collection and analysis included neuromechanical (temporal-spatial symmetry, total vertical pressure [TVP], center of pressure, walking speed, temporal metrics, and step length) and cortical (cortical motor control network) outcome measures.

Figure 1. RE training administered using Ekso GT (Ekso Bionics) by a PT on a participant with ABI.

III. PRELIMINARY RESULTS

Initial loading of the hemiparetic limb during the initial double support (IDS) phase in 7 participants with ABI are shown in Figure 2. Following the use of the RE, an increase in linearity of loading during IDS with an associated increase in speed, step length and decrease in stance phase time was observed after 4 weeks of RE gait training. These preliminary results suggest an improvement in neuromechanical and cortical outcomes after 4 weeks of RE gait training in children and young adults with brain injury.

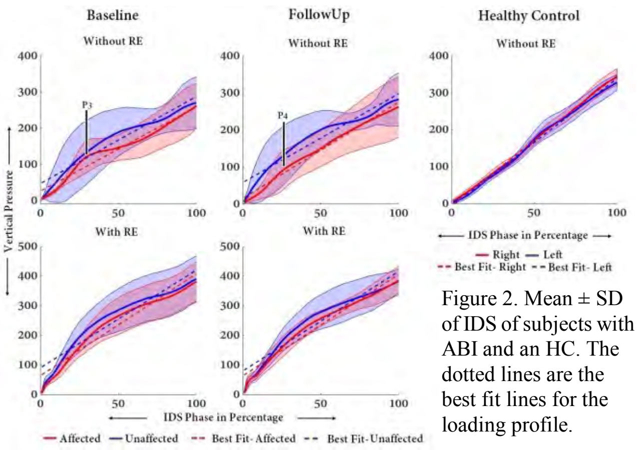

Figure 2. Mean ± SD of IDS of subjects with ABI and an HC. The dotted lines are the best fit lines for the loading profile.

REFERENCES

[1] G. Williams, M. E. Morris, A. Schache, and P. R. McCrory, "Incidence of Gait Abnormalities After Traumatic Brain Injury," *Arch. Phys. Med. Rehabil.*, 2009.

[2] M. G. Benedetti, V. Agostini, M. Knaflitz, V. Gasparroni, M. Boschi, and R. Piperno, "Self-reported gait unsteadiness in mildly impaired neurological patients: An objective assessment through statistical gait analysis," *J. Neuroeng. Rehabil.*, 2012.

[3] S. Lennon, D. Baxter, and A. Ashburn, "Physiotherapy based on the Bobath concept in stroke rehabilitation: A survey within the UK," *Disabil. Rehabil.*, vol. 23, no. 6, pp. 254–262, 2001.

[4] A. Jayaraman, S. Burt, and W. Z. Rymer, "Use of Lower-Limb Robotics to Enhance Practice and Participation in Individuals with Neurological Conditions," in *Pediatric Physical Therapy*, 2017.

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Combining Robotic Training in an Acute Rehabilitation Center and Home Based Telerehabilitation for Optimal Recovery of Hand Function after Stroke

Sergei V. Adamovich, Professor, New Jersey Institute of Technology

Abstract— **Ongoing studies investigate the feasibility and efficacy of two systems for hand rehabilitation after stroke designed by our group that combine robotics and adaptable computer games in an acute rehabilitation hospital setting and in the home of a person who has had a stroke. Preliminary results suggest that the use of both systems might be indicated to achieve optimal outcomes. We are developing affordable and easy to use haptic devices to allow individuals with severe hemiparesis to benefit from the telerehabilitation approach.**

I. INTRODUCTION

Combining haptically assisted training and customizable and adaptable exergames is a promising approach to upper extremity rehabilitation. Currently, our group is focusing on the optimization of timing and volume of this type of intervention for the recovery of hand function after stroke. Two ongoing studies investigate the use of haptic devices for hand and arm in an acute rehabilitation setting early after stroke, as well as focus on the design and development of affordable and easy to use haptic tools and computer games to provide distributed over time hand and arm telerehabilitation to individuals with moderate to severe hemiparesis during the later stages of recovery.

II. METHODS

In this ongoing single-blinded, interventional study [1, 2], subjects are randomized into one of the four groups: Two experimental groups will receive in-patient usual care therapy plus an extra 10 hours of intensive therapy focusing on the hand and initiated 5–30 days post-stroke (Early Robotic/VR Therapy, EVR) or 30–60 days post-stroke (Delayed Robotic/VR Therapy, DVR). Dose-matched usual care group (DMUC) will receive an extra 10 hours of usual care initiated 5–30 days post-stroke. Usual Care Group (UC) will receive the usual amount of physical/occupational therapy.

In an ongoing parallel study, we are testing a Home Based Rehabilitation System (HoVRS) designed by our group for hand telerehabilitation [3]. The system consists of a LEAP camera and a library of adaptive games built with the Unity engine to train movements in various degrees of freedom of the hand and arm. Admittance controlled hand exoskeleton and arm support were designed to allow stroke survivors with more severe hemiparesis to participate.

III. RESULTS

Preliminary results from the ongoing clinical trial indicate that robotic hand/arm therapy delivered during the first two months post stroke might improve the clinical and kinematic outcomes measured one month after the therapy when compared to dose-matched usual care. However, these improvements might reduce at six months post stroke.

15 individuals with chronic stroke participated in an ongoing HoVRS telerehabilitation study without any adverse events. They demonstrated a mean increase of 5.2 on the Upper Extremity Fugl-Meyer Assessment and improvements on various measures of hand kinematics.

IV. DISCUSSION & CONCLUSION

Integration of haptic devices, interactive virtual environments, and adaptive gaming algorithms is a promising approach to deliver intensive and engaging hand and arm training in subacute and chronic stroke, especially for stroke survivors with moderate to severe stroke. Further investigations are needed to determine the optimal timing and dosage of these interventions. Since delivering sufficiently large volumes of training in a clinical setting might be often difficult due to various financial and logistical limitations, combining in-clinic early intervention with a home-based, remotely supervised telerehabilitation approach might be indicated in a large subset of stroke survivors. Design and testing of simple, easy to use, and affordable haptic devices to be used at home is needed.

REFERENCES

[1] Patel J, Fluet G, Qiu Q, Yarossi M, Merians A, Tunik E, Adamovich S. Intensive virtual reality and robotic based upper limb training compared to usual care, and associated cortical reorganization, in the acute and early sub-acute periods post-stroke: a feasibility study. J Neuroeng Rehabil. 2019 Jul 17;16(1):92.

[2] Alma S. Merians,et.al. . Hand Focused Upper Extremity Rehabilitation in the Subacute Phase Post-stroke Using Interactive Virtual Environments. Front. Neurol., 26 November 2020 |https://doi.org/10.3389/fneur.2020.573642.

[3] Qiu Q, Cronce A, Patel J, Fluet GG, Mont AJ, Merians AS, Adamovich SV. Development of the Home based Virtual Rehabilitation System (HoVRS) to remotely deliver an intense and customized upper extremity training. J Neuroeng Rehabil. 2020 Nov 23;17(1):155. doi: 10.1186/s12984-020-00789-w.

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Modulation of Sensorimotor Cortex Activation in Response to Hand Focused Robot Assisted Virtual Reality Rehabilitation of Upper Extremity

Soha Saleh, *Member, EMBS*

Abstract— **In an ongoing clinical trial, hand focused, intensive training uses the Robot Assisted Virtual Reality (NJIT-RAVR) rehabilitation system. The rehabilitation starts during the first month or second month post stroke. The presentation will explain the design of the study and will describe the effects of ten hours of training on desynchronization of EEG channels during target-directed finger movements.**

I. INTRODUCTION

Both dosing and timing can affect the outcomes of stroke rehabilitation interventions. Aggressive therapies can produce exceptional results in the rehabilitation of neurologically impaired individuals [1]. Robotic assistance can allow administering aggressive therapy early on after stroke, before maladaptive plasticity occurs or strengthens, which makes it harder to achieve complete recovery with traditional therapy. In the chronic phase of stroke rehabilitation, it is common to focus on compensation, assuming that motor recovery has reached a plateau. As a result, termination of motor rehabilitation is often recommended, and patients are left with the disabling effects of stroke, challenging their reintegration into the community [2]. This ongoing study aims to deliver arm and hand rehabilitation during the early period of heightened neuroplasticity using robot assistance and virtual reality simulations to facilitate the delivery of increased intensity [3]. Brain activation data are acquired before and after ten rehabilitation sessions, and at four months post stroke using EEG. We hypothesize weak desynchronization of EEG channels covering contralateral sensorimotor cortical brain regions before training and an increase in desynchronization after training with RAVR when compared to usual care.

II. METHODS

Subjects are randomized into early (EVR, starts training 5-30 days post stroke) and delayed (DVR, starts training 30-60 days post stroke) groups. Both groups receive state-of-the-art usual care therapy plus extra 10 hours (1 hr/day) of intensive therapy focusing on the hand using robotically facilitated rehabilitation interventions presented in virtual environments using the NJIT-RAVR (robot assisted virtual reality) system [4]. A third group receives usual care plus ten extra hours of usual care and serves as a control for EVR and DVR groups. Resting-State and Task-Based Brain activation are evaluated using EEG. Channels showing significant EEG desynchronization in alpha (8-12 Hz) and beta (12-30 Hz) bands during the tasks will be identified and used in subsequent EEG connectivity analysis to explore within-brain connectivity. The experiment conditions (tasks) during EEG data collection are: (1) simple target-directed finger flexion/extension of the affected hand, and (2) simple finger flexion/extension of the unaffected hand with a randomized veridical or mirrored feedback of the virtual hand.

III. PRELIMINARY RESULTS

The presentation will discuss data acquired in the first two years of the ongoing five-year clinical trial. Figure 1 shows preliminary results in a representative subject from the EVR group. The data show a training effect on activation and laterality of the sensorimotor cortex; earlier and higher beta frequency desynchronization of the ipsilesional sensorimotor (SM) area during affected hand movement at 6 months post stroke and during unaffected hand movement with mirrored visual feedback after training and at 6 months post stroke.

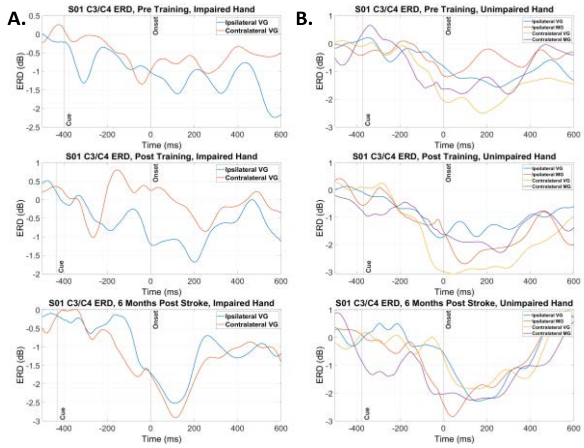

Figure 1. **A.** During target-directed finger movement of affected impaired hand with veridical visual feedback, subject shows higher and earlier beta frequency desynchronization in the sensorimotor (SM) area contralateral to movement (orange curve) at 6 months post stroke. **B.** In response to mirrored visual feedback during movement of unaffected hand, participant data shows higher beta frequency desynchronization in the SM region ipsilateral to movement (ipsilesional, orange curve) after 2 weeks of training and at 6 months post stroke.

REFERENCES

[1] A. W. Dromerick, P. S. Lum, and J. Hidler, "Activity-based therapies," *NeuroRx*, vol. 3, no. 4, pp. 428–438, 2006.

[2] S. J. Page, D. R. Gater, and Y. R. P. Bach, "Reconsidering the motor recovery plateau in stroke rehabilitation," *Arch Phys Med Rehabil*, vol. 85, no. 8, pp. 1377–1381, 2004.

[3] A. S. Merians *et al.*, "Hand Focused Upper Extremity Rehabilitation in the Subacute Phase Post-stroke Using Interactive Virtual Environments," *Front. Neurol.*, vol. 11, p. 1449, 2020.

[4] S. V. Adamovich, G. G. Fluet, A. S. Merians, A. Mathai, and Q. Qiu, "Incorporating haptic effects into three-dimensional virtual environments to train the hemiparetic upper extremity," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 17, no. 5, pp. 512–520, 2009.

[*] Research supported by NIH/NICHD grant R01HD058301 and NIDILRR RERC 90RE5021. S. Saleh is with the Kessler Foundation, West Orange, NJ, USA, and, Rutgers –NJMS, Newark, NJ (corresponding author, phone: 973-324-3520; email: ssaleh@kesslerfoundation.org).