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Role of EMG as a complementary tool for assessment of motor impairment

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Abstract— **Due to the aging population and increase in the number of neurological injuries, the demand for physical therapy has increased. As a result, in recent years robotic devices have been introduced to address the neuro-rehabilitation needs and have been proved to augment the recovery process. Results from a preliminary assessment study on a planar reaching task are presented in this paper. H-Man, a novel upper limb rehabilitation planar robot is employed for the study with ten healthy control subjects - divided into young and aged adults (to understand the effect of aging) and two chronic stroke patients with motor impairment. The assessment of performance was made through kinematic task parameters (smoothness of movement and time to peak velocity) and EMG signal measure (Integrated Average Value) from the upper limb muscles. This revealed significant differences between the groups. The results of the study indicated the potential use of EMG-based metric as a complementary measure to generally-used end effector robotic metrics to track the recovery process.**

Keywords—Neuro-rehabilitation robotics; Healthy aging; assessment; stroke; controller

I. INTRODUCTION

Stroke is one of the major causes for disabilities due to interruption of blood supply to the brain. This results in different neurological deficits affecting the sensorimotor and cognitive skills. Neuro-rehabilitative treatment aids in faster motor recovery, thus enhancing the quality of life of stroke-affected subjects. To meet the demands of the increasing stroke population, coupled with the limited availability of trained therapists and financial resources, an intervention of robotic devices for therapy is found to be a potential solution. In recent years, robotic devices for the training of various task-related movements of the upper extremity (UE) [1][2][3] have been developed. This was motivated by the prospect of administering repetitive training in a cost-effective manner with minimal supervision from a therapist to accelerate the neuro-recovery process.

However, the heterogeneity in stroke location and severity causes a wide variation in its effects, due to which it is difficult to define the best standard regime for therapy applicable to all stroke participants[4] .This incentivizes the need to develop a user-specific adaptive controller, which can adapt therapy routines based on the subject's performance for efficient motor learning. Most standard approaches for designing such controllers rely on kinematic parameters collected from robotic sensors. This is used to derive information about the subject's performance and adaption to the robotic feedback and training [5][6].

Muscles are the actuators of the movement, and analyzing how muscular activity is altered post-stroke could provide a basis to understand how robotic controllers can be improved. The limited studies on the effects of stroke on motor control and muscle synergy organization in the human upper extremity suggest that stroke alters the normal muscle patterns[7], [8]. Different features from EMG signals are extracted to predict the movement and to understand motor control deficits [9] [10]. These studies strongly suggest the need for an assessment of muscular activity in combination with task-space kinematic measures for developing more effective and subject-specific neuro-rehabilitation paradigms [10] along with conventional clinical scales.

In this preliminary study, we investigate how aging(by comparison of performance in healthy adult and aged group) and neurological impairment (stroke) affect the motor performance metrics of a subject during an upper limb planar reaching motion by analyzing the task kinematics and the physiological metrics based on EMG signals. The broader objective of this study is to validate if EMG-based metrics can be employed as a potential assessment tracker along with kinematics, since they provide additional information about the muscular co-ordination. Furthermore, this information can be used to model an adaptive controller for maximum therapeutic benefits.

II. METHODS

A. Participants

Ten healthy control subjects divided into young adults and age matched groups and two chronic stroke patients with upper limb motor impairment participated in the study. The demographic details of the control participants and the two stroke patients are provided in Table 1. All the control participants had corrected to normal vision, and had no

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known neuromuscular disorders. The methodology and written consent form for the experiments were approved by the Domain Specific Institutional Review Board (IRB) of the National Healthcare Group (NHG), Singapore. Stroke patients were financially reimbursed for their time and travel.

Table 1. Demographic and clinical information

	Control Adult	Control Aged	Patient 1	Patient 2
Age	26.4 (3.78)	54.9 (4.1)	56	67
Gender	3M, 2F	2M,3F	F	M
Type of lesion	-	-	Infarct	Ischemic
Side of lesion	-	-	Right	Right
Time since onset	-	-	12 months	20 months
Fugl-Meyer score	-	-	43	20

Patient 1 is a 56-year-old right-handed female who had suffered a lacunar infarct to the right hemisphere 12 months earlier. The patient had a total Fugl-Meyer Assessment (FMA) score of 43/66 with signs of motor incoordination (i.e. motor ataxia), dysmetria and intentional tremor that impaired upper extremity movements, as observed by an occupational therapist.

Patient 2 is a 67-year-old right-handed male who suffered a right hemisphere ischemic stroke 20 months prior to the baseline assessment. Clinical assessment scales showed an FMA score of 20/66. The patient did not present any associated motor incoordination or motor ataxia.

B. Apparatus

The robotic platform used for this study is the H-Man device (Figure1), a planar compact robot characterized by a simple mechanical design for post-stroke rehabilitation therapy [3]. The unique features of H-man are its homogeneous behavior across its workspace, ease of control, light weight (about 7kg), and intrinsic safety. The system can be used in a passive mode (motors off) for simple assessment tasks and in an active mode (motors on) for training and rehabilitation tasks. For a detailed description and the characteristic parameters of H-Man, as well as other studies, the reader is referred to [3], where H-Man has been previously studied with control and stroke participants[13].

The electromyography activity from the upper limb muscles was collected by the BIOPAC MP150 Data Acquisition and Analysis System using National Instrument's NI-USB 6463 device with a sampling rate of 1500Hz. Followed by adequate skin preparation, Meditrace200 surface electrodes with an inter-electrode distance of 20mm were used to acquire the EMG activity in accordance with the standard recommendations for sensor placement described under SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) [14]. The EMG activity of the following upper limb muscles: Brachioradialis (BRAC), Biceps Brachii (BICP), Triceps lateral head (TRIC), Deltoid Medial (DMID), Deltoid Anterior (DANT), Deltoid Posterior (DPOS) and Trapezius Superior (TRAP) was analyzed. Muscle selection is based on the task requirement and adapted from similar studies[15].

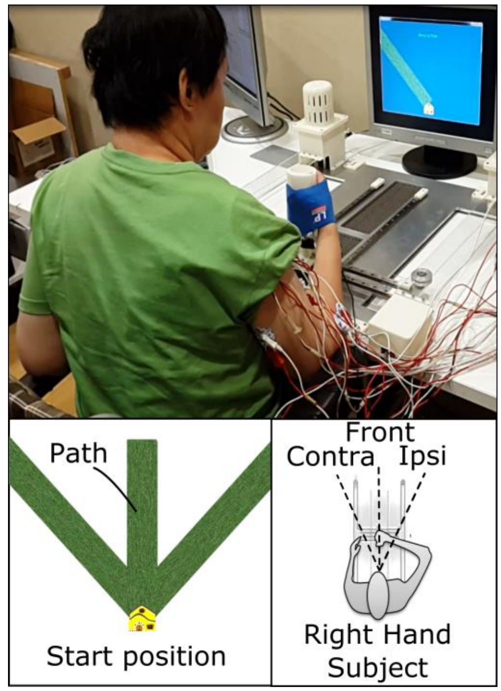

Figure 1(Top) Subject using H-Man robot for assessment task. (Bottom) Visual stimuli used for the assessment with the directions explained.

The EMG data is synchronized with the kinematic data from the H-MAN controller that contains information about velocity and position relevant to the task conditions.

C. Procedure

For robotic assessment, the subjects were asked to perform a planar reaching movement in three directions (-45°, 0° and +45°) to understand their natural motor performance (see Figure 1). Participants were seated on a chair with a back support. The H-man was placed in front of the subject on a fixed table, and a visual feedback with the movement path and the task instructions were provided on a flat screen monitor placed in front of the subject. For motivational purposes as well as a better interface, the games were designed on the commercially available platform, Unity. The equipment was adjusted with respect to the subject such that the sternum was aligned with the handle of the H-Man robot, and the elbow joint angle was 90°. The starting position of the H-Man handle was set to a distance of approximately 25 to 30cm from the sternum.

Participants were asked to move the handle as far as possible in three different directions, which were displayed randomly on the visual display, at angles of the contralateral, ipsilateral and sagittal (front) plane direction (angles of ±45° and 0° from the vertical axis). At the beginning of each trial, the target movement direction was presented with visual stimuli and participants were asked to initiate the movement in that direction. Once the participants reached the maximum range of motion, they were instructed to stay in the same position for 3 seconds (as a resting phase), which was then followed by an instruction to go back to the start position. The subjects were instructed via verbal communication to limit their trunk movements while performing the task. This was in order to assess the natural performance of the subjects and identify the compensatory movements.

Each stroke participant performed a total of 36 trials (12 in each direction in a randomized order) and each control participant completed 15 trials per direction (randomized order), for a total of 45 trials for each control subject. The entire testing session (including the placement of the EMG electrodes) took approximately 45 minutes.

D. Data Analysis

The raw kinematic data of the velocity and distance profile obtained from the robot controller was low pass filtered (Butterworth: 6th order, cut off Fc: 20Hz, Fs: 1000Hz) for further analysis. The raw EMG data acquired from the NI CARD was pre-amplified with a gain value of K=1000 and band-pass filtered (10-500Hz). The acquired raw signal was processed offline to a rectified and low pass filtered signal (Butterworth: 4th order, cut off Fc: 20Hz) to obtain an EMG envelope for further processing.

The movement data was segmented into the outward and the inward motion phase by analyzing the distance and velocity profiles along with the state of the task derived from the game (Unity). The onset time (T_{onset}) is the time instant when the tangential velocity exceeds 5% of the maximum velocity (V_{peak}); the offset time is the time when the velocity drops below the threshold of 5% of the maximum velocity (V_{peak}). The results for the outward motion in the respective three directions are presented in this paper. All signals are normalized by the maximum time taken and are interpolated to have a sample length of 5000 to account for the irregularities.

The following applied quantitative measures are assessed to provide overall information about the subject's motor performance and co-ordination for the three different subject groups. These measures assess smoothness, temporal (task) efficiency and muscular co-ordination (Integrated Average Value of EMG signals), were selected based on their significance, sensitivity and validity.

1) Spectral Arc Length:

The smoothness of each reaching motion was assessed using the Spectral Arc Length (SAL) smoothness metric developed in [16]. Spectral arc length is a dimensionless smoothness measure derived from negative arc length of the amplitude and frequency-normalized Fourier magnitude spectrum of the velocity profile over the applicable bandwidth for human actions.

$$\eta_{sal} = -\int_0^{\omega_c} \sqrt{\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2}\, d\omega \qquad (1)$$

Where $[0, \omega_c]$ is the frequency band of interest (typically up to 20 Hz for normal human movements). The Fourier magnitude spectrum $\hat{V}$ of the velocity signal $v(t)$ is given by:

$$\hat{V}\,(\omega) = \frac{V(\omega)}{V(0)} \qquad (2)$$

2) Time to Peak Velocity:

As the planar reaching task described in our assessment protocol imposes no constraints on the velocity range, time to complete the task as well as the maximum distance, a normalization of temporal measures to assess and compare across the subjects is required. The temporal measures provide an understanding of the adapted motion planning strategy as described in [17]. This is given by:

Time to Peak Velocity:

$$T_{peak} = T(V_{peak}) - T_{onset} \qquad (3)$$

Time to Peak Velocity Normalized (by time):

$$(\mathrm{T_{peakN}}) = \frac{T_{peak}}{T_{offset} - T_{onset}} \qquad (4)$$

3) EMG parameter:

To evaluate the motor performance based on the muscle recruitment pattern, the time domain EMG feature - called IAV (Integral of Absolute Value) - is calculated[12]. This measure describes the strength of the muscle activation and represents the weight of its contribution to the task. The IAV pattern is normalized to the maximum value of its group[11]. The IAV of a signal x of segment length N is given by:

$$IAV = \frac{1}{N}\sum_{i=1}^{N}|x_i| \qquad (5)$$

E. Statistical Analysis

To identify the intra subject variability across different directions [45°, 0° and +45°], a non-parametric Kruskal Wallis (K-W) test[18] was performed on each measure for the respective groups.

The statistical significant difference among the three groups [control (adult, aged) and stroke] was tested by a Wilcoxon rank sum (RS) test for all the directions and the respective measures. The critical p-value of 0.05 was selected for rejecting the null hypothesis unless stated otherwise.

III. Results

The reaching trajectory of the selected control subjects and the stroke participants is presented in Figure 2. Similar behavior is observed among both the control groups and a significant difference in performance in stroke subjects is observed from the kinematic XY profile. In stroke subjects reduced performance is observed to be in correlation with the level of impairment.

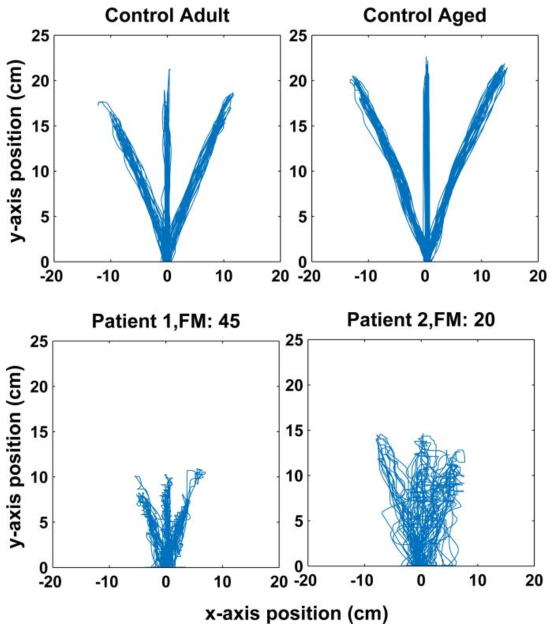

Figure 2: Reaching trajectories of four group of subjects - Control adult, control aged and two stroke participants.

A. *Smoothness of Motion*

In general, both aged and adult control participants made smoother reaching movements compared to stroke patients, irrespectively of directions (see Figure 3). This was verified by a RS test (control adults vs stroke, all directions: p<0.001

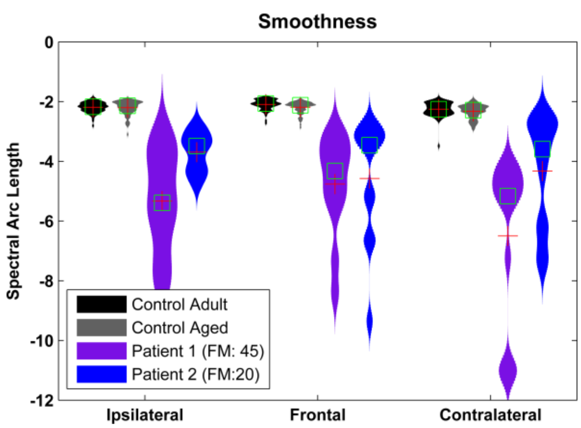

Figure 3: Spectral Arc Length distribution for combined control (adult and aged) and two stroke participants. Red crosses and green squares represent mean and median respectively.

& control aged vs stroke, all directions: p<0.001). Comparison between the ontrol adults and aged was only significant for the middle direction (control adults vs. aged, sagittal frontal direction p<0.004) with a relatively smoother movement as observed by spectral arc length measure for adults compared to aged participants.

Directional difference within each group (adult, aged, patient 1 and 2) using K-W test showed significant differences for the adult and aged healthy participants (both cases: p<0.0001). However for the two stroke participants no significant difference was found across directions (potentially due to the lower number of trials and thus increased variability).

B. *Time to peak velocity:*

Similar to the smoothness metric, significant difference was observed between the aged vs. stroke participants (all directions: p<0.0001) and adults vs. stroke participants (p<0.001 – except direction 3: p>0.05). The K-W test across directions in each individual group showed significant difference for control aged, adults (p<0.001) and stroke participant 1 (p<0.04) but was not significant for participant 2 (Figure 4).

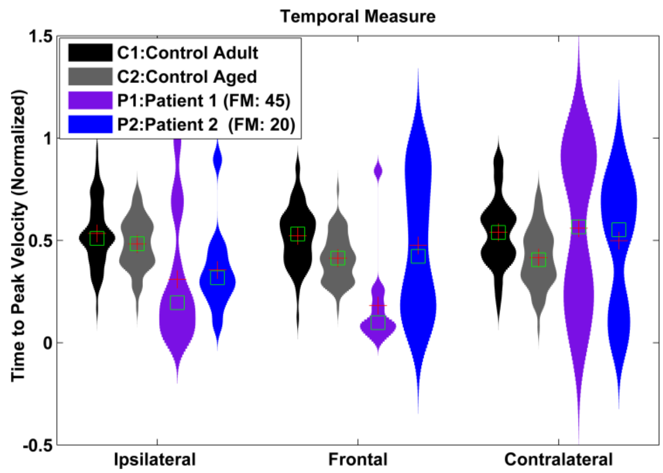

Figure 4: Temporal measure distribution for all directions for combined control (adult and aged) and two stroke participants. Red crosses and green squares represent mean and median respectively.

C. *EMG results*

The normalized Integral of Absolute Value (IAV) values of the EMG of the collected upper limb muscles are presented in Figure 5. The activation pattern across the control groups and stroke subjects can be observed from the IAV amplitude values of the measured EMG signals. From the figure and the statistical test results performed to compare across different groups (aged, adult and stroke), a high similarity in muscle recruitment in adult and aged (control group) is observed except for the case of the BIC, TRIC, DMID muscles (p>0.1). The RS test showed significant differences among the control group and both the stroke participants with in the corresponding muscles for all the cases (p<0.05) except for the DANT muscle (p>0.2). A K-W test was performed to understand the directional difference. It revealed significant differences in the muscle pattern among the directions in the control group: control aged (except for DMID and DANT; p<0.02), control adult (except for BICP and DANT; p< 0.002). For the stroke participant 1 no significant differences were observed across different directions (except for BRAC and BICP; P<0.01) whereas participant 2 showed significance in directional difference (except for DMID and DANT; p>0.01).

IV. DISCUSSION & SUMMARY

In this paper we assessed the motor performance of three groups of subjects: control adult, control aged, and stroke participants by kinematic and EMG-based metrics to understand and identify the differences across directions, subjects and their relation with the type and level of impairment.

For a preliminary assessment, the following kinematic and physiological parameters were selected for assessing a subject's ability to perform a planar reaching task within his or her workspace: 1) Smoothness of the reaching task: the ability of the participants to complete the task with a minimum number of sub movements is assessed using SAL. 2) Time to peak velocity normalized: the time taken by subjects to reach the peak of their speed profile with respect to the total time to complete the task. This measure gives the temporal efficiency and planning strategy of the subject. 3) The activation pattern of different upper limb muscles across the shoulder and elbow are also analyzed by monitoring the IAV value of their EMG activity. This provides an insight into the neuromuscular co-ordination by understanding the major and minor contributors of the task and the variability in recruiting among different groups. We briefly discuss the results of these parameters followed by directions for future work.

The kinematic end effector parameters demonstrate a clear difference in the control and stroke subject performance. Smoothness (as in SAL) is characterized as having few sub-movements spaced closely in time[16]. Control participants (both adult and aged groups) exhibited fewer sub movements as indicated by SAL values closer to zero than the stroke-affected participants (Figure 2). Similarly, when comparing corresponding directions between control and stroke

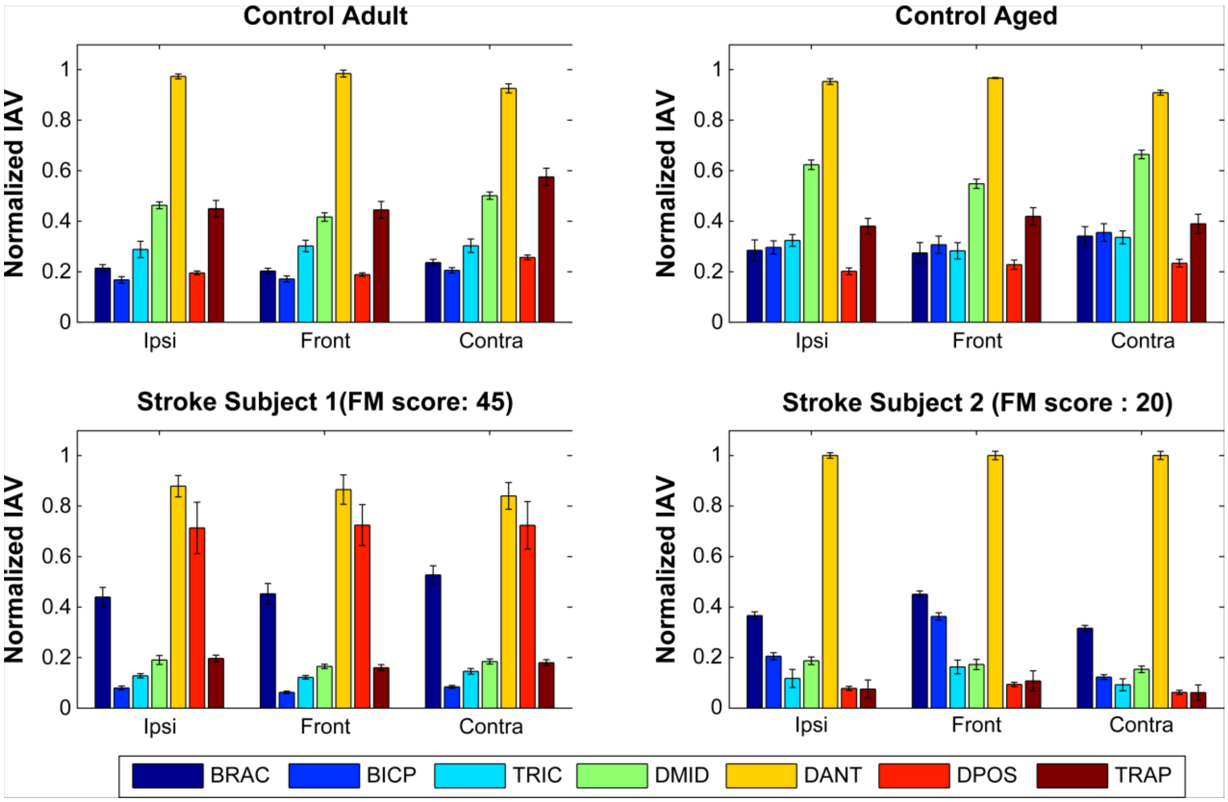

Figure 3: IAV_{EMG} value for all muscles across the three directions in control adult, control aged and two stroke participants. The data is shown for the following muscles: Brachioradialis (BRAC), Biceps Brachii (BICP), Triceps lateral head (TRIC), Deltoid Medial (DMID), Deltoid Anterior (DANT), Deltoid Posterior (DPOS) and Trapezius Superior (TRAP)

participants, a significant difference was observed. These results indicate a strong potential for using smoothness - and SAL, in particular - as a motor assessment measure, since it gives information about co-ordination at task space.

The time to peak velocity measure showed a difference in the control adult and aged group. The aged matched group shows a longer movement time to perform the reaching task when compared to the young adult group. The stroke subjects exhibited even lower values and a significant difference between the control and stroke subjects was observed. The normalized time to peak velocity is a sensitive and reliable measure and, in combination with the smoothness, can be used to get a preliminary understanding of a person's impairment and functionality.

The IAV measure of the muscles provided additional information about the subject's strategies and compensatory movements. This can be used by therapists to identify the subject's deficit and train those muscles that showed abnormal activation patterns. In general, the prime movers for the planar reaching task in control subjects for forward motion are the shoulder joint deltoid muscles (DMID, DANT) with the maximum IAV being observed in DANT, along with supportive muscles (TRIC,TRAP). The activation pattern within the control groups is similar, except that control aged group seems to have increased activity in supporting muscle (TRIC, TRAP). For patient 1, with a moderate FM score of 45, a co-contraction of the agonist-antagonist pair of the deltoid muscles (DANT, DPOS) is observed. This might be the reason for uncoordinated movement, which is a result of ataxia (the person tended to exhibit ataxia from the clinical tests). Patient 2, a severely impaired subject with a low FM score of 20 seems to use the primary mover (DANT) in greater amounts in proportion to other upper limb muscles, indicating that the subject requires more strength and uses abnormal activation patterns when compared to the control. This difference in the muscle co-ordination among stroke participants might account for the type and severity of the stroke. The limitation of using EMG signals is that EMG a highly variable signal depending on many anatomical, physiological and technical factors as given in [19] and requires expertise in electrode placement and measuring a noise free qualitative signal.

From the preliminary results it can be derived that unlike the kinematic measures that provide information about the level of incoordination, EMG-based measures provide explanations for the uncoordinated movements. EMG can highlight altered muscle patterns and helps in understanding the underlying strategies of each subject. Our results are in accordance with recent studies that showed impairment level dependent muscular activity pattern alterations among different stroke group subjects (mild, moderate and chronic) when compared to control subjects [8],[15]. This emphasizes the need for employing the EMG-based metrics or muscle synergies as indicators of impairment and to use them in assessment tests and tracking the recovery process.

This study is performed to understand the feasibility of using EMG based metrics as complementary measures to generally-used end effector metrics for assessment of stroke subjects. The results are promising and suggest the use of EMG-based metrics along with the task space parameters in developing an adaptive controller. A limitation of this study includes the limited number of stroke participants. For efficient and faster recovery, there is a need to understand the reason behind motor control deficit from a neuromuscular perspective i.e. modular organization of motor control. Future studies may aim to analyze muscle synergy patterns to understand the impaired motor coordination by adding multiple task constraints.

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REFERENCES

[1] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 1, pp. 75–87, Mar. 1998.

[2] R. Riener, T. Nef, and G. Colombo, "Robot-aided neurorehabilitation of the upper extremities," *Med. Biol. Eng. Comput.*, vol. 43, no. 1, pp. 2–10, Feb. 2005.

[3] D. Campolo, P. Tommasino, and K. Gamage, "H-Man: A planar, H-shape cabled differential robotic manipulandum for experiments on human motor control," *J. Neurosci. …*, 2014.

[4] M. C. Cirstea and M. F. Levin, "Compensatory strategies for reaching in stroke.," *Brain*, vol. 123 (Pt 5, pp. 940–953, 2000.

[5] L. Marchal-Crespo and D. J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury.," *J. Neuroeng. Rehabil.*, vol. 6, no. 1, p. 20, 2009.

[6] A. A. A. Timmermans, H. A. M. Seelen, R. D. Willmann, and H. Kingma, "Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design.," *J. Neuroeng. Rehabil.*, vol. 6, no. 1, p. 1, Jan. 2009.

[7] J. Roh, W. Z. Rymer, E. J. Perreault, S. B. Yoo, and R. F. Beer, "Alterations in upper limb muscle synergy structure in chronic stroke survivors," *J. Neurophysiol.*, vol. 109, no. 3, pp. 768–781, 2013.

[8] V. C. K. Cheung, L. Piron, M. Agostini, S. Silvoni, A. Turolla, and E. Bizzi, "Stability of muscle synergies for voluntary actions after cortical stroke in humans.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 106, no. 46, pp. 19563–19568, 2009.

[9] F. a Mussa-Ivaldi, M. Casadio, and R. Ranganathan, "The body-machine interface: a pathway for rehabilitation and assistance in people with movement disorders.," *Expert Rev. Med. Devices*, vol. 10, no. 2, pp. 145–7, 2013.

[10] R. a. R. C. Gopura, D. S. V. Bandara, J. M. P. Gunasekara, and T. S. S. Jayawardane, "Recent trends in EMG-Based control methods for assistive robots," *Electrodiagnosis New Front. Clin. Res.*, pp. 237–268, 2013.

[11] A. Avella, B. Cesqui, and F. Lacquaniti, "Converging Clinical and Engineering Research on Neurorehabilitation," vol. 1, pp. 1243–1247, 2013.

[12] B. Cesqui, P. Tropea, S. Micera, and H. Krebs, "EMG-based pattern recognition approach in post stroke robot-aided rehabilitation: a feasibility study," *J. Neuroeng. Rehabil.*, vol. 10, no. 1, p. 75, 2013.

[13] A. Hussain, W. Dailey, C. Hughes, A. Budhota, W. G. K. C. Gamage, D. A. Vishwanath, C. Kuah, K. Chua, E. Burdet, and D. Campolo, "Quantitative motor assessment of upperlimb after unilateral stroke: A preliminary feasibility study with H-Man, a planar robot," in *2015 IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2015, pp. 654–659.

[14] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, and G. Rau, "Development of recommendations for SEMG sensors and sensor placement procedures," *J. Electromyogr. Kinesiol.*, vol. 10, no. 5, pp. 361–374, 2000.

[15] P. Tropea, V. Monaco, M. Coscia, F. Posteraro, and S. Micera, "Effects of early and intensive neuro-rehabilitative treatment on muscle synergies in acute post-stroke patients: a pilot study.," *J. Neuroeng. Rehabil.*, vol. 10, no. 1, p. 103, 2013.

[16] S. Balasubramanian, R. Colombo, I. Sterpi, V. Sanguineti, and E. Burdet, "Robotic Assessment of Upper Limb Motor Function After Stroke," *Am. J. Phys. Med. Rehabil.*, vol. 91, pp. S255–S269, 2012.

[17] L. Zollo, L. Rossini, M. Bravi, G. Magrone, S. Sterzi, and E. Guglielmelli, "Quantitative evaluation of upper-limb motor control in robot-aided rehabilitation," *Med. Biol. Eng. Comput.*, vol. 49, no. 10, pp. 1131–1144, 2011.

[18] W. H. Kruskal and W. A. Wallis, "Use of Ranks in One-Criterion Variance Analysis," *Source J. Am. Stat. Assoc.*, vol. 4710087, no. 260, pp. 583–621, 1952.

[19] C. J. De Luca, "The use of surface electromyography in biomechanics," *J. Appl. Biomech.*, vol. 13, no. 2, pp. 135–163, 1997.