Quantitative Motor Assessment of Upperlimb after Unilateral Stroke: A Preliminary Feasibility Study with H-Man, a Planar Robot

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***Abstract*— This paper presents the results of a preliminary assessment study to investigate baseline performance measures and differences between control and stroke participants during reaching tasks in three directions. H-Man, planar robot is, used for this purpose. Thirteen healthy and two chronic stroke patients with upper limb motor impairment participated in the study. Assessment of performance was made through three task parameters (smoothness of movement, peak velocity, and time to peak velocity). The results from healthy subjects indicate no significant difference between different directions, however significant differences are observed in stroke participants across different directions for smoothness measure (Spectral Arc Length). All the three measures show significant differences between control and Stroke participants for corresponding directions.**

Keywords—Neurorehabilitation; robotics; assessment; stroke

I. Introduction

Neurorehabilitation is emerging as an important area of research. Due in part to an ageing population, an increasing number of people are affected by neurological injuries (e.g. stroke, multiple sclerosis, Parkinson’s disease) resulting in sensorimotor disabilities. For instance, stroke (also referred to as a cerebrovascular accident) is the leading cause of disability for adults in the developed countries. It is estimated that the stroke affected population will increase further by 30% between 2000 and 2025 [1]. This growth in size of the stroke population in developed and developing countries worldwide, coupled with the limited availability of trained therapists and financial resources, means that patients don’t always get the required amount of therapy. This limitation is reflected in the progressive reduction of in-hospital rehabilitation during the acute stages of stroke [2], and the rising trend towards delivering therapy in the community through stroke follow-up clinics.

This high demand for physical therapy has stimulated particular interest in using technology assisted systems for rehabilitation with the objectives to decrease the therapist's workload and facilitate training with minimal supervision at an affordable cost. Different types of technology-based solutions have been proposed in recent decades and have shown promising results. A significant amount of this work has been in the development of robotic devices to train various task-related movements of the upper extremity (UE) [3]–[6]. Robot-assisted therapy was motivated by the prospect of administering repetitive training in a cost effective manner with minimal supervision from a therapist. To date, clinical studies have shown that robot assisted therapy of the UE is at least as effective as conventional rehabilitation therapy in terms of reducing motor impairments [5], [7]–[9]. Hence, it can be used to complement and potentially improve the overall recovery process. However, an arguably equally, if not more important aspect of using technology for assessment of sensory motor functions has been explored less thoroughly. The assessment of functional impairments is crucial as it helps in determining the type and level of treatment/therapy.

Conventional assessment of motor functions is carried out by therapists using ordinal clinical scales to investigate specific aspects of a subject’s motor behavior [10]–[12]. Although these measures are widely accepted, standardized and validated, they are still subjective and suffer from low resolution (insensitive to small but significant changes) which is typical of ordinal scales. Furthermore, the time required to perform manual assessment discourages their regular administration to track and understand motor recovery in affected population.

Robot-aided assessment using integrated sensors offers the possibility to have more continuous (high resolution measures) and does not require additional time because sensory information can be collected simultaneously during regular therapy. These systems are (semi-)autonomous, are potentially more objective (therapist independent), and less prone to human error/subjectivity [13], [14].

In this paper we present the preliminary results of thirteen healthy and two stroke participants’ motor performance during planar reaching movements with a robotic manipulandum. The broader objective of the study is to derive measures which are sensitive to motor impairments and can help in clearly understanding different level of functioning disability as defined by International classification of Health and Disability (ICF) [15] as a step toward more objective and reliable assessment.

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II. Methods

A. Participants

All demographic details and clinical data from control participants and stroke patients are given in Table 1. Thirteen individuals (mean age = 25.92, SD = 3.62, 10 men and 3 women) participated as healthy control participants. Handedness was assessed using the Revised Edinburgh Handedness Inventory [16], which ranks handedness in a battery of common tasks on a scale ranging from −1 (strongly left-handed) to 1 (strongly right-handed). All participants were rated as strongly right-handed (mean score = 0.977, SD = 0.0832). All participants had normal or corrected to normal vision, and had no known neuromuscular disorders. The methodology and written consent form was approved by the ethics committee at Nanyang Technological University.

Table 1. Demographic and clinical information

	Control participants	Patient 1	Patient 2
Age	25.92 (3.62)	47	53
Gender	10 M, 3 F	M	M
Type of lesion	-	Ischemic	Ischemic
Side of lesion	-	Left	Left
Time since onset	-	7 months	23 months
Fugl-Meyer total score	-	21	60

Patient 1 is a 47-year-old right-handed male who suffered a lacunar infarct to the left hemisphere 7 months earlier. The patient had a total Fugl-Meyer Assessment (FMA) score of 21/66, with scores of 15/42 on the shoulder-elbow coordination subscale, 4/24 on the wrist-hand function subscale. The patient does not present any associated motor incoordination or motor ataxia, visual impairment, hemispatial neglect, or homonymous hemianopia.

Patient 2 is a 53-year-old right-handed male who suffered a left hemisphere lacunar infarct 23 months prior to testing. He obtained a total FMA score of 60/66 (shoulder-elbow coordination = 30/42, wrist-hand function = 23/24). Although he does not show signs of motor function impairment, he does exhibit signs of motor incoordination (i.e. motor ataxia), dysmetria, and intentional tremor that impaired his upper extremity movements. The patient does not present with any associated visual impairment, hemispatial neglect, or homonymous hemianopia.

The methodology and written consent form for experiments with the stroke patients were approved by the Domain Specific Review Board of the National Healthcare Group (NHG). Stroke patients were financially reimbursed for their time and travel.

B. Apparatus

The experimental apparatus used for the study is shown in Figure 1. H-Man is a compact robot designed for the rehabilitation/training of planar arm movements [17]. It can provide forces of up to 30 N at the end-effector (handle) in any specified direction in a planar workspace to assist or resist the motion of the user and can be easily built using off

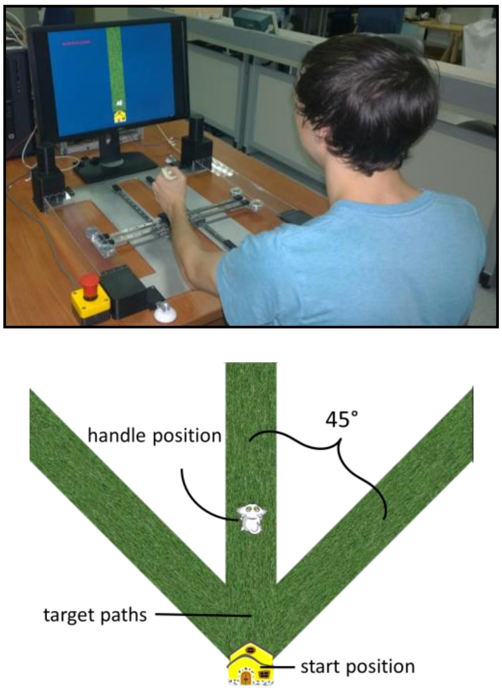

Figure 1: (Top) Participant using H-Man, a compact robot designed for the rehabilitation/training of upper-limb. (Bottom) Visual Stimuli used for the assessment using H-Man.

the shelf components. The reader is referred to [17] for a detailed description of H-Man.

C. Procedure

Participants were seated on a chair with a back support. H-Man was placed in front of the subject on a fixed table. A flat screen monitor was placed in front of the H-Man device and delivered visual feedback throughout the experiment. The visual stimuli consisted of a required movement path and the task instructions. 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 bent at 90°. The starting position of the H-Man handle was set at approximately 25 to 30 cm from the sternum.

Participants were asked to reach as far as possible in three different directions, which were displayed randomly on the visual display, at angles of -45°, 0° and +45° from the vertical axis. At the beginning of each trial the target movement direction was presented and participants were asked to initiate their reaching movement. Participants were instructed to move as far as possible on the displayed path in a direct path and then hold that position for 3 seconds. No physical trunk restraint was used during the experiment. However, the subjects were instructed to limit their trunk movements while performing the task.

Participants performed 8 or more trials in each direction, with the presentation of direction randomized, with the maximum number of trials set to 36. However, control participants completed 25 trials per direction, or a total of 75 trials for each subject

D. Data Analysis

1) Smoothness of Motion: The smoothness of each reaching motion was assessed using the Spectral Arc Length (SAL) smoothness metric developed in [18]. SAL is a dimensionless measure of the length of the frequency spectrum curve of a speed profile over the bandwidth appropriate for the action. SAL is defined as follows:

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

where $[0, \omega_c]$ is the frequency band of interest (typically up to 20 Hz for normal human movement) and the Fourier magnitude spectrum of the velocity signal $s(t)$ is given by:

$$\hat{S}(\omega) = \frac{S(\omega)}{S(0)}$$

2) Peak Velocity: The maximum velocity attained during the reaching movement, given by:

$$V_{peak} = \max\{v(t)\}$$

where $v(t)$ is the mean magnitude velocity profile for a given reaching motion.

3) Time to Peak Velocity: The time, T_{peak} taken to reach the peak velocity is given by the difference between the time at which V_{peak} is reached and the time at which velocity first exceeds during a given reaching motion.

Normal reaching movements are typically characterized by a single-peaked profile bell-shaped speed profile [19].

E. Statistical Analysis

A non-parametric Kruskal-Wallis (KW) test was used on the data of healthy subjects (trials from all subjects combined) to investigate the difference between the three different directions. Similarly, the KW test was used for each stroke participant to investigate differences between directions. The Wilcoxon Rank-Sum (RS) test was used to compare between each stroke participant's directional movements with those of the control participants (all control participants were grouped as one set with three directions). Rank Sum and Kruskal-Wallis tests are used because of the limited number of subjects. The critical p-value of 0.05 was selected for rejecting the null hypothesis unless stated otherwise.

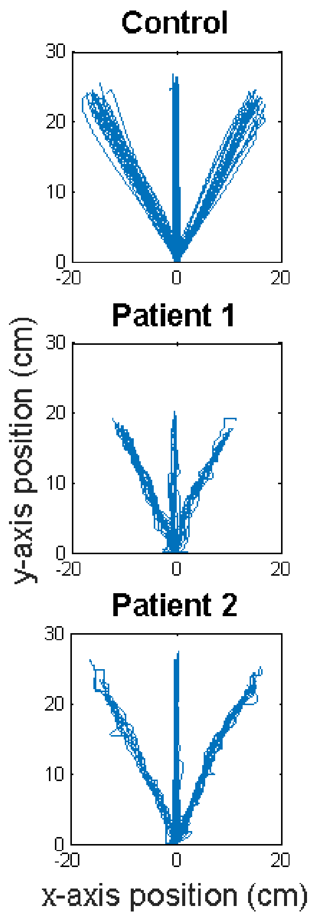

Figure 2: Reaching trajectories of a healthy (control) participant and two stroke participants.

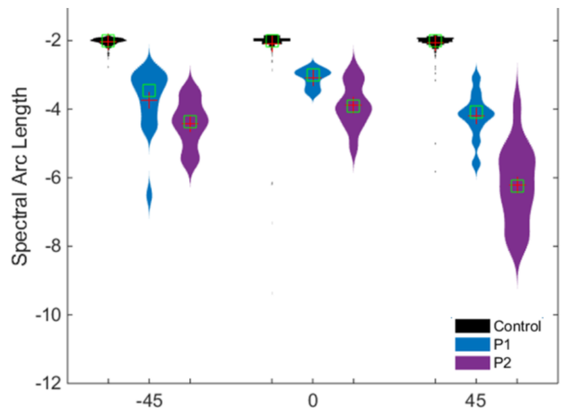

Figure 3: The distribution of spectral arc length measure for all directions for control (combined) and two stroke

III. Results

A. Smoothness of Motion

In general, control participants made smoother reaching movements compared to stroke patients, irrespective of direction (see Fig. 3). Within the control population no significant difference was observed between directions using

Table 2: Summary of assessed measures.

Measure	Group	Direction		
		-45°	**0**	**+45°**
SAL	Control	-2.028 (0.114)	-2.084 (0.7364)	-2.056 (0.304)
	P1	-3.728 (0.918)	-3.091 (0.271)	-4.202 (0.671)
	P2	-4.421 (0.697)	-3.895 (0.657)	-6.213 (1.158)
Peak Velocity	Control	0.321 (0.122)	0.324 (0.106)	0.322 (0.128)
	P1	0.094 (0.014)	0.099 (0.013)	0.103 (0.022)
	P2	0.092 (0.029)	0.096 (0.026)	0.097 (0.021)
Time to Peak	Control	0.568 (0.230)	0.590 (1.094)	0.534 (0.230)
	P1	3.188 (4.137)	1.278 (0.632)	1.685 (1.238)
	P2	2.496 (3.872)	2.953 (1.634)	1.871 (1.864)

the non-parametric KW test (p>0.02). There were, however, significant differences between directions for stroke participants (Fig. 3) which was verified using KW (P1: p<0.0001 and P2: p<0.0026). When compared with control the SAL values of both patients were significantly less (RS test) than the control participants for corresponding directions (All directions – P1: p<0.001, P2: p<0.001).

B. *Peak Velocity*

Peak velocity values were significantly higher for control participants compared to patients with stroke having

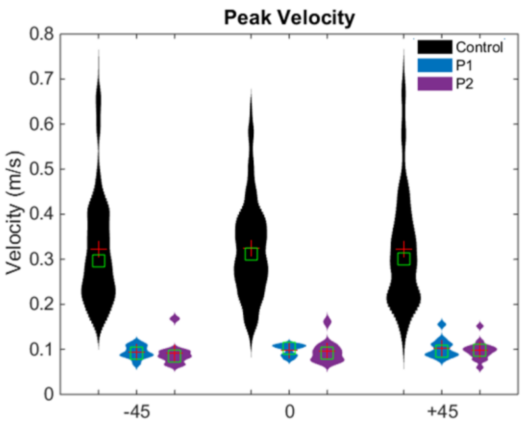

Figure 4: The distribution of peak velocity measure for all directions for control and two stroke participants. Control participants show higher peak velocity and larger variability.

a lower degree of variability (see table 2). Like SAL, within control participants no signifcant difference was observed between directions (p>0.02) . However unlike SAL, within stroke participants no significant difference was observed using KW test (P1: p>0.5; P2: p>0.4). When compared to control movments, significant a difference was observed for corrosponding directions using RS test (All directions – P1: p<0.001, P2: p<0.001).

C. *Time to Peak Velocity*

Like Peak velocity, no significant difference was observed across different directions for control population using KW test (p>0.6). Similarly no significant difference was observed across directions for the two stroke participants (P1: p>0.4, P2: p>0.1). However, higher time to peak velocity values were observed for stroke participants when compared with control subjects for corresponding directions, using rank sum test significant difference were observed for all direction for Patient 1 (P1: p<0.001) for all directions, however for stroke Patient 2 significant difference was only observed for direction 1 (0°) (P1: 0°, p<0.001; ±45°, p>0.09).

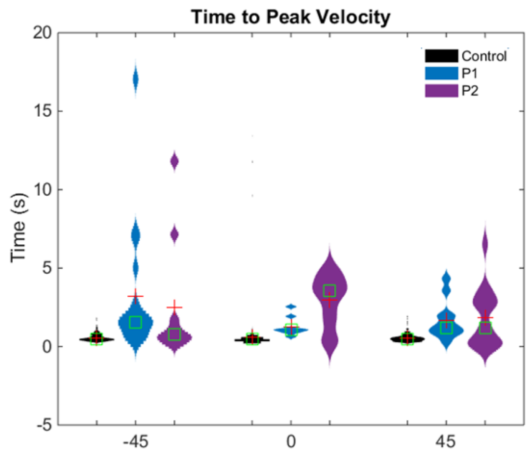

Figure 5: The distribution of time to peak velocity measure for all directions for control and two stroke participants. Control participants reach peak velocity in small time and have limited variability when compared with stroke.

IV. Discussion

In this preliminary feasibility study, we assessed H-Man as a potential tool for the assessment of motor functions by examining movement data during reaching tasks for thirteen healthy and two stroke participants. The broader/long term aim of the study is to identify quantitative clinical scales that have a higher resolution and greater reliability for clinical use. Furthermore, we seek to examine if technology can offer an alternative to conventionally used ordinal scales, which despite being the current gold standard, do not give the complete picture of a person's impairment and functionality. For preliminary assessment we selected the following parameters for assessing a subject's ability to perform tasks within his or her workspace 1) smoothness of reaching task, the ability of participants to complete the task in an efficient manner, 2) peak velocity, the highest velocity reached during the task, and 3) time to peak velocity, the time taken by subjects to reach the peak of their speed profile. We briefly discuss the results of these parameters followed by directions for future work.

Smoother movements can be characterized as having few sub-movements spaced closely in time, while less smooth motions will have a greater number of sub-movements with loose temporal locality[18]. The results from the assessment clearly demonstrate that control participants generally tend to follow this rule and have fewer sub movements as indicated by SAL measures closer to zero than the stroke-affected participants (Fig. 2 and 3). Furthermore, across directions the level of smoothness varied significantly in the two stroke participants. This is evident for both stroke participants in Fig. 3. Similarly, when comparing corresponding directions between control and stroke participants a significant difference was observed. These results indicate a strong potential for using smoothness and SAL in particular as a motor assessment measure, though it remains to be seen how sensitive SAL is to changes in coordination.

Peak velocity has been used in number of different studies as a measure of assessment. Here we try to validate its reliability using H-MAN. As with the SAL results, the peak velocities of the control participants show no significant difference between directions, but do show a larger degree of variability. Further, no significant difference was observed within different directions of stroke participants indicating that the measure may have a low resolution using the defined protocol in which no restrictions were placed on speed. The purpose of excluding a speed constraint was to ensure task performance assessment is relatable to the natural movements of the participants. This is evident when we compare each direction with control subjects corresponding directions; significant differences in peak velocity was observed for both participants.

Like the case of peak velocity, the time to peak velocity measure demonstrated no significant difference across directions for control participants. However unlike peak velocity, it had a lower degree of variability. The stroke participants demonstrated greater variability in time to peak velocity than the control participants, however no significant difference was observed. In contrast, when comparing each stroke participant to the control subjects for each corresponding direction, only Patient 1 demonstrated significant differences. For Patient 2 the only significantly different direction was 0°. This result might be an indication that time to peak velocity has relatively less sensitivity for the defined protocol compared to smoothness measure as it tends to show less significant differences between participants.

However, independently all of these parameters have significance as SAL relates to ability to coordinate between the limbs and peak velocity relates to the ability of participants to perform the task in timely and active manner. It is important to realize that subjects were instructed to move at natural pace as the interest was more on relating the measure to natural task performance. We might observe a more significant difference between control and stroke-affected participants if the subjects were instructed to complete the task at the maximum speed possible, but this could affect smoothness of task performance and might not relate directly to functional ability.

Overall, the results of the study are promising and indicate the potential to use the proposed approach for workspace assessment and in particular the proposed measures. Some of the limitations of this study include the age difference between the control and stroke populations. We plan to collect data from healthy elderly participants in order to remove variability due to differences in age groups. Additionally, the number of stroke participants is very limited since the study is ongoing. In future studies we plan to present more detailed concepts and analyses. Finally, due to the limited number of participants, the correlation of these measures with clinical scales is not presented. This analysis is required for building a detailed understanding of these measures. All of these factors can be addressed in greater detail in future studies.

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