Development and Evaluation of Haptics-based Rehabilitation System*

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***Abstract*—In this paper, we discuss the development and testing of a haptics-based stroke rehabilitation system. The system involves a 6-degrees of freedom haptic device and a virtual reality game designed to induce implicit learning in users. We present the preliminary usability/feasibility study of our system as a rehabilitation tool with 15 healthy subjects while using their non-dominant hand. The three-session study demonstrates improvements in all quantitative performance metrics of the learning tasks and the self-perceived workload levels of the subjects. We also studied the differences in performance arising due to three different assistance modes - no assistance, assist-as-needed, and continuous assistance. Comparing the differences in improvements of the performance metrics among the subject groups suggests that fewer sessions of assisted therapy may have the same effects as more sessions of unassisted therapy. We also observed that within the two assisted groups, the assist-as-needed strategy led to greater improvements than the continuously assisted group; which might be due to the lower mental/physical demand associated with the continuously assisted paradigm.**

***Index Terms*—stroke, robotic rehabilitation, tele-rehabilitation, assistive systems**

I. INTRODUCTION

About 2 million people in the United States suffer from stroke related motor impairments; making it the leading cause of disability in the US. An estimated 800,000 people suffer from stroke each year [1]. Nearly one-third of the stroke survivors have significant residual disability, with older individuals generally experiencing slower functional recovery [2]. Even mild motor impairments can manifest themselves as inhibitors to the patient's ability to carry out activities of daily living (ADL) such as using a fork and spoon, cutting food with a knife, writing, etc. To regain functional control via neuroplasticity, stroke patients participate in rehabilitation regimes.

Current stroke rehabilitation paradigms are primarily hospital-centric, involving an occupational therapist and a doctor working in close conjunction with the patient. As the therapy progresses, a transition in rehabilitation goals from gross motor skills to fine motor skills is observed [2]. Fine motor skills are fine movements that require the neural control of the muscle groups that effect hand and finger movements; making them crucial for conducting ADL tasks. Gross motor skills involve muscles in the arms, legs or torso resulting in their corresponding gross movements.

However, owing to the time-consuming and expensive nature of physical therapy aggravated by the disability of stroke patients to easily travel to the therapy center, patients are sent home after a few months to continue therapy on their own accord [3]. In such situations, home-based therapy presents itself as a viable alternative and is amiable to the rehabilitation of ADL skills. However, due to the lack of a human chaperone in home-based therapy, patients seldom practice therapy. Additionally, these home-based methods do not provide a reliable mechanism to monitor a patient's progress [4]. The therapist must rely on self-reporting by the patient and/or their family members about the nature and status of the therapy being practiced at home. Assuming these self-reports reflect the true nature of therapy, they still fail to provide a quantitative measure of the patient performance during these home-based sessions [5].

In order to address the above issues, recent years have seen the advent of haptics-based tele-rehabilitation systems [6]–[12]. These systems usually involve three key modules, viz, a patient side, a remote-therapist side and a server/cloud connecting these two. The patient side involves a haptic device and a simulation system. The patient is guided by the end-effector of the haptic device to carry out the rehabilitation tasks presented by the simulation system. The robot may assist or resist the patient's movements as per the therapy requirements. The therapist side consists of a similar setup that allows the therapist to observe the patient practicing therapy and provide any force feedback or modify system parameters (degree of assistance/resistance) as needed.

While such systems have demonstrated efficacy as a plausible means to deliver therapy [13], they are yet to be adopted as the status quo of home-based therapy [14]. The robots used in these regimes are expensive and usually have 2-degrees of freedom (DOF) [6]–[10], which restricts the therapeutic exercises to simple planar motions. Therapists have recommended the use of 3-DOF systems to better mimic real therapy

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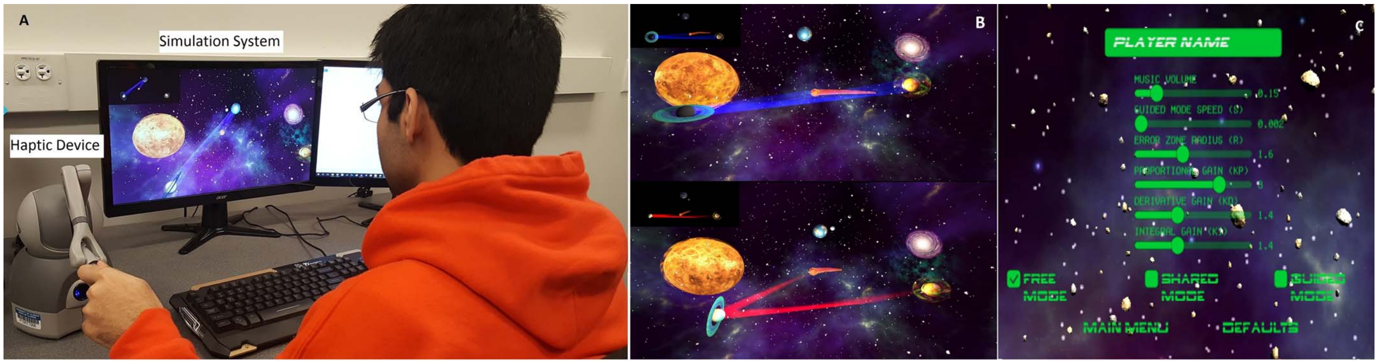

Fig. 1: (A) - Haptics-based rehabilitation system. (B) - A change of color from blue (B-Top) to red (B-Bottom) signifies a transition from the no-error zone to the error zone. (C) - Settings menu that is used to modify the system parameters.

scenarios [9].

In this paper, the results of a preliminary investigation of a new haptics-based rehabilitation system are presented. The system is being developed for home-based therapy and comprises of a 6-DOF low cost haptic device and a virtual reality game to administer and assist in rehabilitation of fine motor skills. Usability and efficacy studies in a controlled laboratory setting are conducted with 15 healthy subjects performing straight line tracking tasks. The system has been designed to imitate a massed practice therapy regime that benefits from the inherent advantages of implicit therapy. Implicit learning refers to skill acquisition without awareness or not directed at a conscious level [13]. For instance, in the current scenario, implicit learning is incorporated by programming the trajectory tracking task into a game. Studies have demonstrated the efficacy of implicit learning paradigms over explicit ones [15], [16]. A set of performance metrics [8], [9], [11] are used for evaluating the subject's progress across three training sessions.

The rest of the paper is organized as follows. The system components, control strategies and the performance metrics are described in section II, III, and IV, respectively. The usability study is presented in section V followed by the results in section VI.

II. SYSTEM DESCRIPTION

The system comprises of two main components - a haptic device, and a simulation system (Fig. 1-A). The haptic device used in this study is a 6-DOF Geomagic Touch[1] that can provide force feedback to the user. The device has 6 revolute joints which include 3 actuated joints and 3 passive joints. The actuated joints provide the force feedback to the user. This force feedback capability augmented by its small form factor, lower cost and three-dimensional work-space makes it a viable choice for home-based rehabilitation. The device operates at a sampling rate of 1000 Hz.

The simulation system comprises of a 3D trajectory following game called 'Space Explorer (SE)' (Fig. 1-B). The game has been designed for the rehabilitation of fine motor skills; crucial for performing ADL tasks. The game was developed using the Unity3D interface and C# programming. The end-effector of the robot acts as the game controller which is used by the subjects to follow a reference trajectory generated by the system.

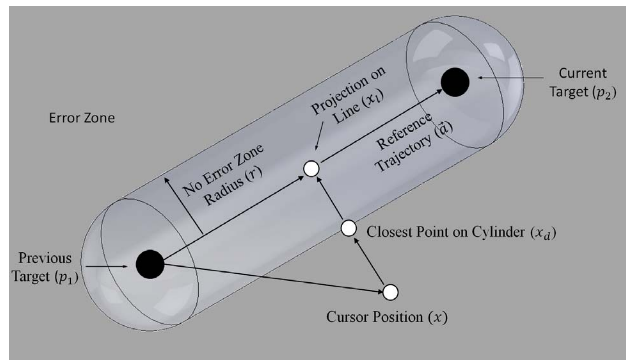

Fig. 2: Schematic representation of the virtual no-error zone cylinder.

SE involves three planets positioned in 3D space and the user is required to track straight line trajectories connecting them. The goal of the game is to minimize tracking error (distance from the straight line) and the task completion time (TCT). The subjects lap around the three planets for a predetermined number of times. The system imitates a massed practice therapy inducing implicit learning in user [13].

A virtual 'no-error zone' is constructed around the straight lines connecting consecutive planets. The no-error zone may be imagined as a cylinder with spherical ends having radius r and height equal to the length of the line connecting the planets (Fig. 2). While the end-effector is inside the cylinder, the tracking error is set to zero; otherwise the error is defined as the minimum distance from the subject's position (cursor position) to the surface of the cylinder. A change of color from blue to red indicates deviation from the no-error to the error zone and vice versa (Fig. 1-B). The radius of the cylinder can be changed depending on the patient performance and severity of impairment (Fig. 1-C). A mini-map on the top-left corner of the screen displays a top view of the game to enhance depth-perception.

[1] http://www.geomagic.com/en/products/phantom-omni/overview

The game operates in three modes - (1) *Free Mode* - the haptic device does not apply any assistive/resistive force; (2) *Shared Mode* - the haptic device assists the subjects by guiding them towards the desired trajectory in the events of deviations from the trajectory; and (3) *Guided Mode* - the haptic device assists the user by guiding them towards the desired trajectory as well as along it towards the next target. We discuss these modes in detail in Section III. The degree of assistance and the assistance modes can be adjusted as per the need in a settings menu available through the interface (Fig. 1-C).

Robot states and game data such as joint angles, cursor position, cursor velocity, position error, velocity error, and elapsed time are recorded at a sampling rate of 100 Hz and are used for off-line performance evaluation. The system comprises of two parallel processes; graphical rendering (sampling rate 100 Hz) and haptic rendering (sampling rate 1000 Hz). Since the higher sampling rate of 1000 Hz is not required for evaluation of the performance metrics, we log these states only during the graphical rendering process. These performance evaluations are discussed in Section IV

III. HAPTIC RENDERING

The haptic interaction with the simulation environment is called haptic rendering, and is modeled as a mass-spring-damper system. The robot provides an assistive force as the subject is playing the game. In other words, the robot assists the user as they guide the end-effector from one point to another. The assistive force command is generated based on the PID control law,

$$\mathbf{u}(t) = K_p\mathbf{e}(t) + K_i\int_0^t \mathbf{e}(\tau)d\tau - K_d\dot{\mathbf{x}}(t) \tag{1}$$

where, K_p, K_i and K_d[2] denote the proportional, integral and derivative gains respectively; $\mathbf{e}$ represents the difference between the desired position ($\mathbf{x}_d$) and the actual robot position ($\mathbf{x}$) at time t; and $\mathbf{u}$ is the control input provided to the robot to generate the haptic feedback. The gains determine the degree of robotic assistance and can be adjusted based on the subject's response to therapy. The definitions of the position error terms and the value of the gains change when switching modes. We now describe the different modes in finer detail.

A. Free Mode

Free mode refers to the unassisted paradigm in SE. In this mode, the robot applies no assistive/resistive force to the subject's hand motion and the subject is solely responsible for controlling the cursor motion. In this case, the gains of the control law given in (1), viz. K_p, K_i and K_d are set to zero. This mode serves to determine the baseline for evaluating the patient's progress and also as a training mode for expert subjects (subjects not requiring any assistance from the robot).

[2]The negative K_d term in (1) is obtained by setting the $\dot{\mathbf{x}}_d(t)$ term to zero in the derivative law $K_d(\dot{\mathbf{x}}_d(t) - \dot{\mathbf{x}}(t))$.

B. Shared Mode

This mode entails an assist-as-needed control paradigm, that turns on or off based on the subject's position error. As long as the subject remains inside the cylindrical no-error zone (see Fig. 2) with radius r, the robot offers no assistance. If the subject moves outside the no-error zone, the robot applies an assistive force towards the closest point, $\mathbf{x}_d(t)$, on the cylinder's surface. The closest point is calculated as,

$$\mathbf{x}_d(t) = \mathbf{x}_l(t) - r\hat{\mathbf{l}} \tag{2}$$

where,

$$\hat{\mathbf{a}} = (\mathbf{p}_2 - \mathbf{p}_1)/\left\|\mathbf{p}_2 - \mathbf{p}_1\right\|_2 \tag{3}$$

$$x_l(t) = \mathbf{p}_1(\mathbf{1} - \hat{\mathbf{a}}) + \mathbf{x}(t)\hat{\mathbf{a}} \tag{4}$$

$$\mathbf{l} = x_l(t)\hat{\mathbf{a}} - \mathbf{x}(t) \tag{5}$$

where, $\mathbf{p}_1$ and $\mathbf{p}_2$ are the known position vectors of the previous and current target (planet), respectively; $\hat{\mathbf{a}}$ is the unit vector along the line connecting the two targets; $x_l(t)$ refers to the projection of $(\mathbf{x}(t) - \mathbf{p}_1)$ on $\mathbf{a}$; and $\mathbf{x}_d(t)$ is the closest point on the surface of the imaginary cylinder. Remember that $\mathbf{x}_d(t)$ is the desired position in (1). Thus, control law to generate the assistive force for shared mode is,

$$\mathbf{u}(t) = \begin{cases} K_p\mathbf{e}(t) + K_i\int_0^t \mathbf{e}(\tau)d\tau - K_d\dot{\mathbf{x}}(t), & \text{if } d > r \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where, d is the euclidean distance between the current point $\mathbf{x}(t)$ and closest point on the line $\mathbf{x}_l(t)$.

C. Guided Mode

Guided mode refers to a continuously assisted mode in the SE game. In guided mode, the robot guides the subject along the trajectory from one planet to the next at a predefined constant speed (s). The mode has been developed to assist subjects with minimal motor abilities. Here,

$$\mathbf{x}_d(t) = \mathbf{x}_d(t-1) + s\hat{\mathbf{a}} \tag{7}$$

where, $\mathbf{x}_d(t-1)$ refers to the desired position at the previous epoch; and $\hat{\mathbf{a}}$ is the unit vector along the line connecting the two targets; $\mathbf{x}_d(t)$ serves as the desired position in (1). The derivative gain term (K_d) is set to a small positive value for the shared and guided mode to simulate the sensation of moving through a lightly viscous environment.

IV. PERFORMANCE METRICS

In order to evaluate the changes in performance of subjects while using our system, we define a set of five performance metrics [8], [9], [11]:

1) Task completion time (TCT) - refers to the time taken to complete a predetermined number of laps around the three planets and is measured in seconds.
2) Total error (TE)- refers to the area under the position error versus elapsed time curve.
3) Error instances ratio (EI) - refers to the ratio of number of epochs for which the cursor position was recorded in the error zone and the total number of epochs

(elapsed time) of the experiment. This metric does not penalize large error values which may arise due distractions/fatigue on the subject side such as subject dropping the end-effector and/or rest pauses.

4) Hand trajectory smoothness (HTS) - is given as the number of times a change in the cursor's motion direction is observed. A lower value signifies higher smoothness.
5) Error ratio (ER) - is defined as the ratio of the actual trajectory traversed by the subject and the desired trajectory (straight line connecting the two targets/planets).

V. USABILITY STUDY

In this section, we present a usability study conducted on our current framework. The goals of the study were to verify the efficacy of our system as a rehabilitation tool and to study the effects of using the different modes of the game on subject performance. The study was approved by university's Institutional Review Board (IRB).

A. Experimental Setup

Fifteen ($n = 15$) healthy subjects (8 males and 7 females; average age of 24.4 years; age range from 20 to 28) were recruited for the study. All subjects were right-handed and were students at the university campus. The subjects reported no history of any motor impairments. The subjects were randomly split up into three groups of five subjects each and were assigned to the control sets, FM (Free Mode), SM (Shared Mode) and GM (Guided Mode). The study comprised of three sessions spread over six days. The program included one day of practice followed by one day of rest.

Each session comprised of three tasks. The first task involved the subjects playing the SE game without any assistance from the robot. This was labeled as the baseline task. The second task involved the subjects playing the game with/without assistance, depending on the group they were assigned to. Groups SM and GM received assistance as per the control laws described in sections III-B and III-C, respectively. FM did not receive any assistance from the robot. The final task was also an unassisted task. The goal of this task was to measure any short-term improvements over the baseline within one session. For each task, the subjects played the game for three laps over the three targets using their non-dominant arm. The subjects were required to control all aspects of the interface on their own. Such as navigating through the menus, adjusting the music volume, switching between tasks, etc. The subjects were given a brief explanation of the interface and provided with a few minutes of practice in the unassisted and the assistance mode corresponding to their assigned group. For SM, the K_p, K_i and K_d gains were chosen as 0.8, 0.01 and 0.03, respectively. For GM, the respective gains were chosen to be 4.0, 0.01 and 0.01, and the constant speed s was set to 0.002. For all three modes, the error zone radius r was fixed at 1.50.

After each task, the subjects reported their self-perceived workload through the NASA-TLX form [17]. NASA-TLX scores are evaluated on a scale of 5 to 100 with 100 being

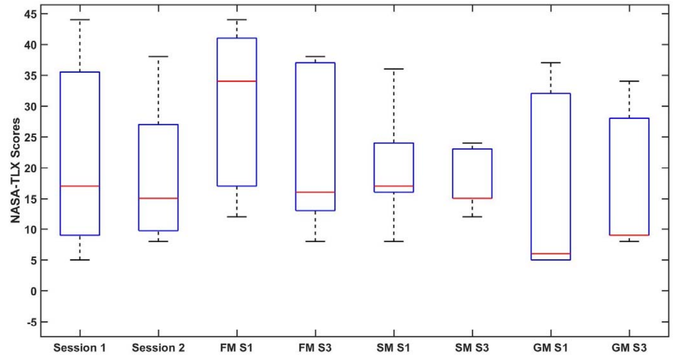

Fig. 3: Variation of NASA-TLX across the three sessions. Plots titled 'Session 1' and 'Session 2' refer to the variation across all 15 subjects. The rest are for individual groups. (Key: S1 - Session 1; S2 - Session 2)

the highest. The subjects also filled out a modified version[3] of the System Usability Scale (SUS) [18] at the end of the first session. SUS is a highly robust and versatile tool that enables quick and easy collection and evaluation of a user's subjective rating of a product's usability [19]. The subjects were encouraged to give verbal feedback (if any) regarding their general experience with the system.

VI. RESULTS AND DISCUSSIONS

In this section, the qualitative and quantitative results of the above experiments are discussed. We also discuss some critical issues highlighted by the subjects regarding the general usability and design of the game.

A. System Usability Scale

The system scored a mean score of 85.16 (range between 72.5 and 97.5; standard deviation of 7.58) on the SUS across the 15 subjects. This score is widely interpreted as 'Excellent' [19], highlighting the intuitiveness and usability of the system. The subjects found the system to be engaging and reported that it would be safe and easy to use in the home setting without the presence of a technician.

6 out of the 15 subjects reported that the depth perception aid (mini-map at the top left of the screen) was not intuitive enough and led to some confusion while performing the task. However, these subjects also mentioned that they could overcome the issue with practice.

B. NASA-TLX Load Index

We evaluate the NASA-TLX scores as the change in self-perceived workload between the first task of the first session and the third (last) task of the third (last) session. An average reduction in the NASA-TLX scores (perceived workload) of 21.86 (range between 1 and 55; standard deviation of 14.94) across the fifteen subjects was reported. These reductions were also compared across the three groups (FM, SM and GM). A

[3]We replaced the first question in the standard SUS with "I found the system to be relaxing."

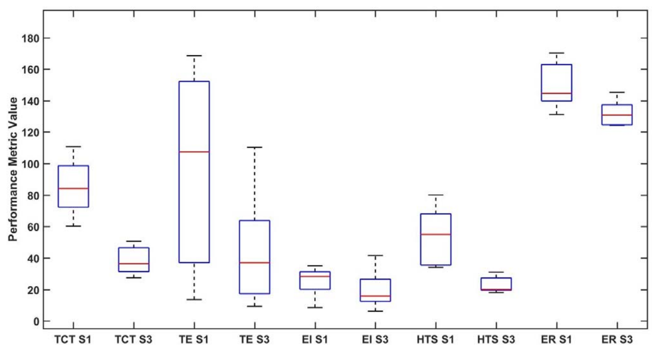

Fig. 4: Long term effects of proposed haptic therapy. (Key: TCT - Task completion time; TE - Total Error; EI - Error instances ratio; HTS - Hand trajectory smoothness; ER - Error Ratio; S1 - Session 1; S3 - Session 3).

mean reduction of 25.6, 23.8 and 16.2 was observed across the FM, SM and GM groups, respectively (Fig. 3). These reductions between groups do not demonstrate any significant differences at a significance level of 5%.

C. Quantitative Assessment

We now evaluate the changes in the quantitative performance metrics (Section IV) across the three sessions and within each session.

1) Long-term effects: Long-term effects are defined as the differences in performance metrics between the first task (baseline) of the first session and the last task of the last session. A reduction in all the five metrics was observed, suggesting the feasibility of the system as a rehabilitation tool. These differences are expressed as percentage changes w.r.t. the baseline recordings. Fig. 4 represents these observations graphically[4]. For TCT, a mean reduction of 43.03% across all the subjects was observed; with the FM, SM and GM groups demonstrating a mean reduction of 53.79%, 41.92% and 33.39%, respectively[5]. TE demonstrated a mean reduction of 35.35% across all subjects with individual group reductions at 22.45%, 37.54% and 46.05%. EI reduced by 32.68% across all subjects and by 17.02%, 41.81% and 39.21% across the groups. HTS exhibited a mean reduction of 52.73% across the subjects and 54.85%, 49.67% and 53.68% across individual groups. ER demonstrated an across subject reduction of 10.70% and within group reductions of 11.15%, 10.68% and 10.29%. These evaluations were conducted over the five subjects within each of the three groups.

None of the metrics demonstrated any significant differences across the groups at a 5% significance level. This suggests that fewer sessions of assisted therapy (SM, GM groups) can have the same effect as more sessions of unassisted/passive therapy (FM Group). Note that SM and GM groups received assistance only once per session, whereas FM group performed the unassisted therapy three times during each session.

2) Short-term effects: We define short-term effects as changes in performance metrics observed across the same session i.e. the differences between the first and the last task during each session. As with the long-term effect case, a reduction in all five performance metrics was observed. No significant differences were observed within groups for the first and the last session. However, TCT ($p = 0.015$) and HTS ($p = 0.018$) demonstrated significant differences at a 5% significance level between the FM and SM groups for the second session. In both cases, the SM group demonstrated higher reductions at 31.89% for TCT and 42.80% for HTS; as opposed to FM that demonstrated mean reductions of 9.56% and 15.86%, respectively. Comparing the SM and GM groups, a significant difference for the TCT case with p-value as 0.028 was reported. Once again the SM group exhibited a higher mean reduction at 31.89% when compared to the GM group reduction of 14.68% (Fig. 5).

These results may indicate the superiority of the assist-as-needed strategy implemented for the SM group. We attribute the lower performance of the GM group to the lack of mental engagement arising due to the autonomous operation of the haptic device. The GM group control law enables the robot to essentially complete the task on its own. During the experiments, we observed a tendency among the subjects to loosen their grip on the end effector and even lower their gaze from the computer screen. While this causation is speculative, we are currently studying the effects of the above modes on mental engagement using a non-invasive brain-computer-interface (BCI) to verify the above claim.

VII. CONCLUSION AND FUTURE DIRECTIONS

In this paper, a haptics-based rehabilitation framework that takes advantage of repetitive massed practice and implicit therapy was demonstrated. We described the implementation and testing of a straight line following game - 'Space Explorer'. The game has been designed to motivate subjects to perform seemingly mundane and repetitive therapy tasks. The preliminary usability study evaluated the usability and feasibility of the system as a rehabilitation tool. Improvement was observed in all five performance metrics used for the evaluation and the self-reported perceived workload levels measured using the NASA-TLX form. Differences in performance arising due to the type of assistance being provided to the subjects was also studied. No significant differences across the assisted and unassisted groups were observed, suggesting that haptic assistance with fewer therapy rounds might have the same effects as unassisted tasks with more therapy rounds.

Finally, intermittent assist-as-needed (SM group) strategy is observed to perform better than the continuously assisted paradigm (GM group). This is attributed to the relatively lower engagement levels arising due to the autonomous operation of the robot in the GM group. However, this hypothesis is yet to be tested and we are currently conducting a non-invasive BCI-based study to verify the same. At its current implementation,

[4]We scale EI and ER values by 1000 and 100, respectively for the sake of easier visualization.

[5]For the sake of convenience, from this point forward, we follow the same order within groups without explicitly stating them; i.e. free mode (FM), shared mode (SM) and guided mode (GM).

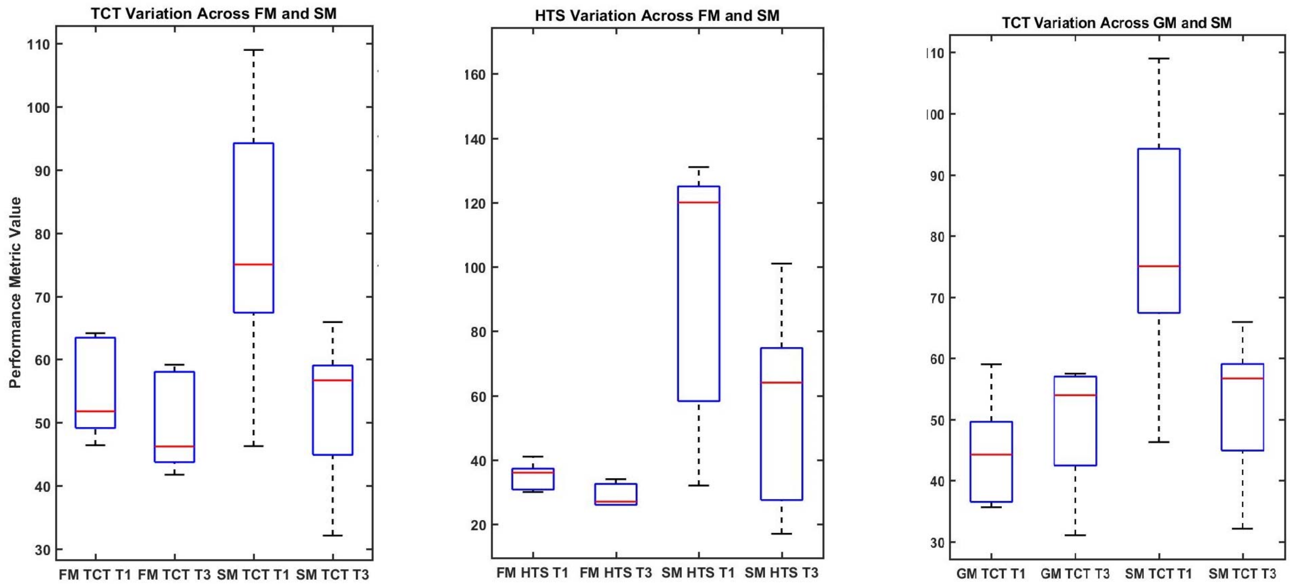

Fig. 5: Performance metrics that demonstrated significant differences over the short-term analysis. (Key: T1 - Task 1; T3 - Task 3).

the system lacks networking capabilities; limiting its feasibility as a home-based rehabilitation system. We are currently working towards the realization of such a remote therapy system. Additionally, we propose the use of BCI to study the real time cognitive states of the subject and adjust the system parameters (gains, error zone size, etc.) accordingly. The system was tested with healthy subjects, but will be studied with stroke patients to obtain a true measure of efficacy and usability. A key criterion to measure the efficacy of any learning paradigm is the transfer of learning to perform daily activities. It is important to study how the patients use the skills gained from this system in actual practice; as this transfer of learning is the goal of any therapy regime.

References

[1] "Stroke," http://www.cdc.gov/stroke/, accessed: 2017-09-30.

[2] P. Langhorne, J. Bernhardt, and G. Kwakkel, "Stroke rehabilitation," *The Lancet*, vol. 377, pp. 1693–1702, 2011.

[3] S. Rosewilliam, C. A. Roskell, and A. D. Pandyan, "A systematic review and synthesis of the quantitative and qualitative evidence behind patient-centred goal setting in stroke rehabilitation." *Clinical rehabilitation*, vol. 25, pp. 501–514, 2011.

[4] E. Haeuber, M. Shaughnessy, L. W. Forrester, K. L. Coleman, and R. F. Macko, "Accelerometer monitoring of home-and community-based ambulatory activity after stroke," *Archives of physical medicine and rehabilitation*, vol. 85, no. 12, pp. 1997–2001, 2004.

[5] H. Zheng, N. D. Black, and N. D. Harris, "Position-sensing technologies for movement analysis in stroke rehabilitation," *Medical and biological engineering and computing*, vol. 43, no. 4, pp. 413–420, 2005.

[6] N. Hogan, H. I. Krebs, J. Charnnarong, P. Srikrishna, and A. Sharon, "Mit-manus: a workstation for manual therapy and training. i," in *Robot and Human Communication, 1992. Proceedings., IEEE International Workshop on*. IEEE, 1992, pp. 161–165.

[7] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 10, no. 2, pp. 102–108, 2002.

[8] H. Sugarman, E. Dayan, A. Weisel-Eichler, and J. Tiran, "The jerusalem telerehabilitation system, a new low-cost, haptic rehabilitation approach," *Cyberpsychology & behavior*, vol. 9, no. 2, pp. 178–182, 2006.

[9] R. Huq, E. Lu, R. Wang, and A. Mihailidis, "Development of a portable robot and graphical user interface for haptic rehabilitation exercise," in *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*. IEEE, 2012, pp. 1451–1457.

[10] P. Lam, D. Hebert, J. Boger, H. Lacheray, D. Gardner, J. Apkarian, and A. Mihailidis, "A haptic-robotic platform for upper-limb reaching stroke therapy: Preliminary design and evaluation results," *Journal of NeuroEngineering and Rehabilitation*, vol. 5, no. 1, p. 1, 2008.

[11] J. Broeren, A. Bjorkdahl, L. Claesson, D. Goude, A. Lundgren-Nilsson, H. Samuelsson, C. Blomstrand, K. S. Sunnerhagen, and M. Rydmark, "Virtual rehabilitation after stroke." *Studies in health technology and informatics*, vol. 136, p. 77, 2008.

[12] A. Alamri, M. Eid, R. Iglesias, S. Shirmohammadi, and A. El Saddik, "Haptic virtual rehabilitation exercises for poststroke diagnosis," *Instrumentation and Measurement, IEEE Transactions on*, vol. 57, no. 9, pp. 1876–1884, 2008.

[13] B. R. Brewer, S. K. McDowell, and L. C. Worthen-Chaudhari, "Post-stroke upper extremity rehabilitation: a review of robotic systems and clinical results," *Topics in stroke rehabilitation*, vol. 14, no. 6, pp. 22–44, 2007.

[14] E. T. Esfahani, S. Pareek, P. Chembrammel, M. Ghobadi, and T. Kesavadas, "Adaptation of rehabilitation system based on user's mental engagement," in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2015, pp. V003T14A017–V003T14A017.

[15] P. S. Pohl, J. McDowd, D. Filion, L. Richards, and W. Stiers, "Implicit learning of a motor skill after mild and moderate stroke," *Clinical rehabilitation*, vol. 20, no. 3, pp. 246–253, 2006.

[16] J. L. Patton and F. A. Mussa-Ivaldi, "Robot-assisted adaptive training: custom force fields for teaching movement patterns," *IEEE Transactions on Biomedical Engineering*, vol. 51, no. 4, pp. 636–646, 2004.

[17] S. G. Hart and L. E. Staveland, "Development of nasa-tlx (task load index): Results of empirical and theoretical research," *Advances in psychology*, vol. 52, pp. 139–183, 1988.

[18] J. Brooke *et al.*, "Sus-a quick and dirty usability scale," *Usability evaluation in industry*, vol. 189, no. 194, pp. 4–7, 1996.

[19] A. Bangor, P. Kortum, and J. Miller, "Determining what individual sus scores mean: Adding an adjective rating scale," *Journal of usability studies*, vol. 4, no. 3, pp. 114–123, 2009.