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Design of Adaptive Haptic-enabled Virtual Reality based System for Upper Limb Movement Disorders: A Usability Study

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Abstract— **Neurological disorders are major cause of global disease burden. They often impair hand function, a critical element of our day-to-day activities of daily living. Conventional rehabilitation techniques aim to improve one's ability to use affected limbs which are tailored to individual capabilities (performance and stress level) by clinicians based on the patient's health and progress in skill. However, in developing countries, like India with increasing healthcare costs for availing specialized services, patients are often discharged sooner than required from healthcare units following stroke. Additionally, the situation becomes critical with limited availability of trained healthcare resources. Thus design of intelligent home-based technology-assisted individualized rehabilitation platform with real-time feedback with monitored skill progress is essential. In our present research, we have designed a Virtual Reality (VR) based haptic-enabled Physiologically Aided (PA) Rehabilitation System for patients with upper limb movement disorders. Additionally, we have made a comparative analysis of our PA system with Performance Sensitive (PS) system while offering tasks of varying difficulty levels along with audio-visual feedback. We have designed a Usability Study as proof-of-concept application where we have focused on the patient's shoulder abduction and adduction exercise. The preliminary results of our study are promising. This shows that our system can be a step towards designing a VR-based technology-assisted rehabilitation platform for stroke patients with a potential to address at least some of the issues associated with upper limb movement disorders.**

Keywords— Stroke; Virtual Reality; Stress; Electrodermal Activity, Haptic

I. INTRODUCTION

Global estimates show that about 15 million people are affected by stroke annually and among these ⅔rd of stroke incidence occurs in low-and-middle-income countries like India [1] where the prevalence rate of stroke is 84-262/100,000 in rural and 334-424/100,000 in urban areas [2]. It is also predicted that by 2050, 80% of stroke events will occur in low- to middle-income countries [3]. In India, incidence of stroke is not only restricted to elderly population (12-20/1000 in the 75-84 year age group), but also among younger adults (0.1-0.3/1000 in the <45 year age group) [3], causing a burden on the society. Stroke often leads to disability, such as hemiparesis, loss of limb coordination, balance, postural and gait disturbances etc. leading to difficulty in performing activities of daily living. Recent evidence indicates that intensive massed practice may be necessary to modify neural organization and effect recovery of motor skills in patients following stroke [4]. Physical therapy that requires one to practice different physical activities related to specific daily living tasks has been shown to address these problems by promoting mobility among motor-impaired patients [5]. Trained physiotherapists prescribe physical therapy to patients that are individualized to their capabilities and stress level, at specialized healthcare outlets. However, countries like India are often adversely affected with limited availability of skilled clinicians, limited access to healthcare centers in rural areas, and high cost of availing specialized services.

Thus, it is critical to have a technology-assisted stress-sensitive home-based rehabilitation platform for post-stroke patients. Different investigators have been exploring technology-assisted rehabilitation platforms, e.g., robot-based, human-computer based platforms. Robot-assisted techniques (e.g., ARMin [6]) are often costly and heavy to handle increasing financial burden on the patient. Researchers such as, Broeren et al. [7] have explored computer-based techniques in which they developed 3D games to promote motor learning skills in patients suffering from left arm paresis. Sucar et al. [8] presented the VR-based Gesture Therapy platform for upper limb rehabilitation. Recently, Ballester et al. [9] showed the efficacy of Virtual Reality (VR) based intervention in enhancing the motor skills of the paretic limb in hemiparetic stroke patients. Researchers have often used VR in conjunction with external peripherals, e.g., Wii (Nintendo) [10], Kinect Sensor (Microsoft) [11], Eye toy, Move (Sony) [12] and haptic devices [8] that adds to the sense of presence and movement. Among the different technology-assisted rehabilitation platforms, we used VR to design an interactive 3D computer-generated environment coupled with peripherals where users can see through realistic imagery, hear and even feel objects in the created environment through tactile feedback. Use of VR-based platforms has shown great potential in post-stroke rehabilitation because of their capability to provide repetitive task-oriented training while encouraging the patient to stay

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motivated in the task by providing context-specific imagery [13]. Also, VR provides a designer the flexibility to manipulate the rehabilitation paradigm, along with qualitative and quantitative feedback to the therapist and also the patient. Additionally, with technological progress, VR-based platforms can be designed in a cost-effective manner.

The pioneering contributions of VR-based studies have been instrumental in showing the applicability of VR-based rehabilitation platforms to contribute to different skills, such as motor retraining, improvement of dexterity and range of motion [8, 14]. These systems mostly offered VR-based exercises for upper limb for stroke patients based only on one's performance. Stress, defined as a state of threatened homeostasis [15] is a growing problem in day-to-day lives which often adversely affects one's performance and efficiency. Stroke patients are often stressed while performing rehabilitation exercises. In homeostasis, the body muscles contract and relax utilizing autonomic adaptive techniques while making physiological and behavioral responses to external stimuli whereas in stress condition, the muscles become stiffer. Salmon has indicated that people who are less susceptible to stress might be more ready to take up training exercises [16]. Excessive stress often adversely affects an individual's concentration, increases the risk of heart disease, atrial fibrillation, atheroma, aneurisms and stroke [17]. Thus, given the importance of monitoring one's stress level during a task, in order to make the therapy effective, it is critical to understand the patient's stress level that expert therapists can infer by using observation-based techniques. However, these are often subjective in nature. Physiology related biomarkers can serve as an avenue to provide quantitative estimates of one's stress level while doing exercise. Further the physiological signals can be readily available and easily interpreted by the computing environment. Literature review indicates that various physiological signals e.g., Electromyogram, Cardiovascular, Electrodermal Activity (EDA) etc. are often affected by one's stress level during a task. Evidence from literature shows that one's EDA increases with stress [18-20]. Presently, for our preliminary study we have chosen one's EDA signal as an indicator of stress.

Thus in our present work we have designed a usability study as a proof-of-concept application of a novel VR-based haptic-enabled rehabilitation platform that is adaptive to both the user's performance and stress level predicted from the user's physiological signal named as Physiologically Aided (PA) system. Additionally, we have compared the performance of such a PA exercise platform with a performance-sensitive (PS) platform that is adaptive to only one's performance, namely, task completion time and performance errors while doing a VR-based task. Presently, we have considered VR-based exercise tasks that are based on one's shoulder abduction and adduction capability often required to independently perform activities of daily living.

The objectives of this paper are three fold: (a) develop VR-based exercise platform equipped with force feedback (b) make this exercise platform sensitive to one's individualized stress level and (c) carry out a comparative analysis of our observations made using PS and PA systems. This paper is organized as follows. Section II describes system design. Section III presents experimental setup and the methodology used. Section IV discusses the results obtained in our usability study. Finally, Section V summarizes our research findings, discusses the limitations of current study as well as the direction of our future research.

II. System Design

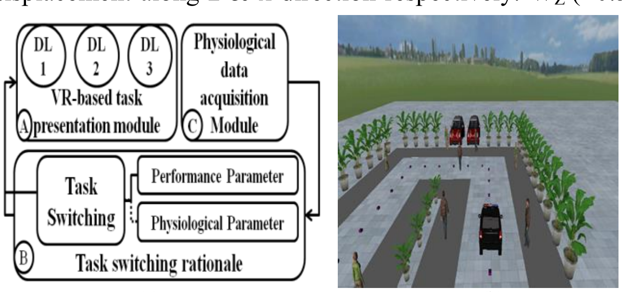
Our VR-based system comprises of three sub-modules, (A) VR-based task presentation module (B) Task switching module and (C) Physiological data collection module. Fig. 1(a) shows a block schematic of the system.

A. VR-based Task Presentation Module

In our present study we used desktop VR due to its ease of accessibility and comparatively less cost. We designed co-ordination tasks in VR using python-based Vizard software toolkit (commercially available from Worldviz Inc.) and Google sketch-up. The VR-based tasks consisted of a repository of 72 templates (24 templates in each difficulty level) randomly presented to the participant to avoid monotony for approximately 30 minutes. The VR environment was augmented with tactile feedback by using 'Phantom Omni' haptic device (from Geomagic Inc.). The haptic device includes a pen type stylus that can be held using one's hand and the stylus can be moved in three directions (*x, y and z*). In our present study, we used two translational movements, namely *x* and *z*, to translate the VR object towards left/right and front/back to trigger the horizontal abduction and adduction of one's shoulder joint. For our preliminary study we used eq. (1) and did not use the turret like movement of the haptic stylus since we did not focus on the roll capability of one's wrist joint.

$$\Delta Z_{DIST} = W_Z*(z+z_{OFFSET}),\ \Delta X_{DIST} = W_X*(x+x_{OFFSET}) \quad (1)$$

where, ΔZ_{DIST} , ΔX_{DIST} represents the distance the car traverses in the VR environment corresponding to a displacement along z & x direction respectively. W_Z (=0.5),



(a) (b)

Fig.1 (a) System design (b) Snapshot of a typical VR-based task

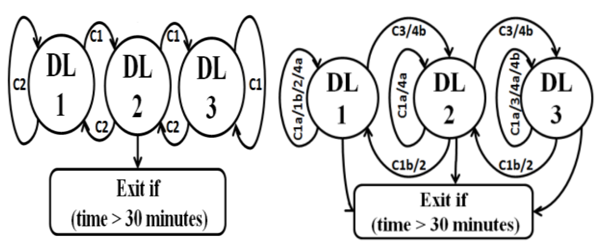
W_X (=4.5) are the weight factor used in our study to render a smoother and controlled maneuver of the virtual car along the track. z_{OFFSET} (=0.5) is the offset used for getting the virtual car coordinates on a 0 to 1 scale whereas x_{OFFSET}(=0) in our case. These weight factors and offset values were chosen as an initial approximation as per physiotherapist in our team and these can be changed in future. In our study, we programmed our haptic device to give a force feedback upto 1.6 N upon colliding with an obstacle (static or dynamic) in the VR environment as guided by physiotherapist. Also, the patient was provided with a hand-support platform (made in-house) so as to give support to the affected hand that a stroke patient was asked to use to interact with the VR-based tasks. The hand-support prevented the patient's hand from falling off while holding haptic stylus.

A.1 Design of VR-based Tasks

We designed VR-based car maneuvering tasks of three difficulty levels (DL1-DL3) based on the shape of tracks. Participant was asked to move the car in VR environment following track trajectory using a haptic device. The tasks required the participant to make shoulder abduction and adduction moves while holding the haptic stylus and making physical displacements of 0x70, 60x70, 120x70 mm for DL1, DL2 and DL3 tasks respectively. For example, DL1 task was kept fairly easy with a straight track. Tracks were curved for increased difficulty, e.g., DL2 had semi-circular track and DL3 had semi-square-track. Fig. 1 (b) shows a typical example. The VR-based tasks were made more challenging and realistic with dynamic obstacles in the form of pedestrians. If one's car collided with pedestrian or side wall of track in VR environment, then our system registered that as an error. Additionally, at the end of each task trial we provided audio-visual feedback to the participant based on his performance in terms of motivational messages (e.g., 'Good job!' for adequate performance) along with the score.

B. Task Switching Module

Our system was programmed to offer tasks of varying challenges to the participants (a) based only on the task performance (Performance-sensitive (PS) system henceforth) and (b) based on the composite effect of performance and stress level predicted from physiological index e.g., mean tonic activity ($Tonic_{MEAN}$) extracted from EDA signal (Physiology aided (PA) system henceforth) using a state machine representation [21]. The PS system offered a task of higher difficulty if participant's task performance was 'Adequate', i.e., performance ≥ 70% (condition C1 in Fig. 2 (a)) and vice-versa for 'Inadequate'



(a) (b)

Fig.2. State Machine Task Switching Module for (a) PS and (b) PA system
Note: C1- Adequate Performance, C2- Inadequate Performance

performance (condition C2 in Fig. 2(a)). The task switching rationale for PA system is represented by state machine representation (Fig. 2(b)) and Table I. The Predicted Stress (from $Tonic_{MEAN}$ derived from EDA signal) can be 'High'/'Low' and Performance can be 'Adequate'/'Inadequate'. If $\Delta Tonic_{MEAN} = Tonic_{MEAN\_Present} - Tonic_{MEAN\_Previous}$ is ≥0, then Stress is 'High' else, 'Low'.

TABLE I
TASK SWITCHING CRITERIA

Condition	Predicted Stress	Performance	Action
C1a/b	High	Adequate	→/↓
C2	High	Inadequate	↓
C3	Low	Adequate	↑
C4a/b	Low	Inadequate	→/↑

B.1 Computation of Task Performance

Performance (PF) was evaluated from time (T) taken by a participant to complete a given task and the number of collision errors (E) made by participant while performing the task. We calculated time fraction (TF) and error fraction (EF) from the time (T) and error (E) information. From our previous pilot study with 6 age-matched healthy participants (Mean (SD) = 48(18.23) y), we decided threshold values T_{TH} and E_{TH} for a given task. The TF is defined by eqs. (2-4).

If $T \le T_{TH}$, then TF=1 (2)

If $T_{TH} < T \le 2*T_{TH}$, then $TF = \frac{2*T_{TH} - T}{T_{TH}}$ (3)

If $T > 2*T_{TH}$, then TF=0 (4)

Likewise will be the case for EF.

Based on the prior pilot study, we chose, T_{TH}=50, 80, 110 for DL1-DL3 and E_{TH}=5 for DL1-DL3 respectively. As a first approximation, based on physiotherapist's advice, we have considered a weight distribution of 60% for EF and 40% for TF (eq. 5) since performing a task accurately with less number of errors is important from the viewpoint of rehabilitation.

$$PF = 100 * ((0.6 * EF) + (0.4 * TF)) \quad (5)$$

C. Real-time physiological data acquisition

While our participants interacted with VR-based tasks, our system acquired the participant's EDA signal using BioPac MP150 (from Biopac Systems Inc.). Here we computed the $Tonic_{MEAN}$ over the length of each task from the participant's EDA signal and used it as an indicator of stress level. BioPac MP150 with Acknowledge 4.3 software allows data acquisition in standalone mode. In our present work, we acquired EDA signal at 1000 samples/sec using BioPac MP150. From the EDA signal, we extracted $Tonic_{MEAN}$ and mapped it to the Predicted Stress level, thereby closing the loop to adaptively present tasks of varying challenges to the participant. For this we designed hardware interface comprising of microcontroller (ATMEGA328), 12-bit Analog-to-digital converter and RS232 serial port for communicating the EDA signal acquired by MP150(Fig. 3(a)) to the Task Computer (Fig. 3 (b)) executing the VR-based tasks.

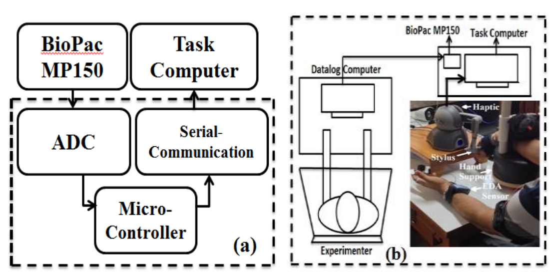


Fig. 3 (a) Hardware Interface of data acquisition module and (b) Experimental Setup

III. METHODS

In our present work, we designed a usability study in which 3 patients with hemiplegia participated. These patients were recruited through referral from a local Government Hospital. The participants' characteristics are shown in Table II. The study had ethics approval. Patients provided informed consent before participation.

TABLE II
PARTICIPANT CHARACTERISTICS

	Age (yrs)	Affected Hand	Post-stroke Period (yrs)	ROM (Ab-Ad)	Observations from MRI Report
P1(m)	48	R	2 years	100^o-10^o	Right frontal white matter lacunar infarct
P2(m)	19	R	2years	80^o-10^o	Subacute non-hemorrhagic infarct
P3(m)	52	R	8years	100^o-5^o	Not Available

Note: m: Male, R: Right; Ab: Abduction; Ad: Adduction (Shoulder Joint); ROM: Range of Motion.

A Inclusion and Exclusion Criteria

Patients presenting stroke (aged 18 - 75 years and having post-stroke period > 3 months) were included in the study. Patients were also screened by physiotherapist through Range of Motion (RoM) of horizontal abduction and adduction measures of their shoulder joint on the first day to see whether it was less than the corresponding values for healthy adults as reported in literature [22, 23]. Patients with a history of recent surgery (<3 months), having musculoskeletal injury, metal implants or pace makers, or cognitive impairment that prevented them from providing informed consent were excluded.

B. Experiment Setup and Procedure

The experimental setup (Fig. 3(b)) comprised of a chair placed in the front of a Task Computer mounted on a table along with a haptic device. The participant was asked to sit on the chair which was placed at a distance of approximately 60 cm from the 2D computer monitor. A haptic device, connected to Task Computer, was placed in front of the participant at a distance of about 30 cm. Biopac MP150 (wireless mode) was used to measure the participant's EDA signal with the sensor attached to the index and ring fingers of the non-playing hand. We invited participants for a minimum of 10 exposures in total for both the PS and PA systems. One participant was exposed to PS-followed by-PA and the remaining two participants had exposure in reverse order to consider ordering effects. Our study required an involvement of approximately one hour on the first day and about 30 minutes on remaining days. After the participant arrived, he was asked to sit down on a chair and relax for 5 minutes. Next, the experimenter explained the experimental setup to the participant. The physiological sensors were then attached to the participant's body and the experimenter checked to see whether the data logger computer connected to the Biopac was recording the physiological signals properly. Also, the experimenter informed the participant that he was free to quit the study at any point he felt uncomfortable while interacting with the system. After taking the baseline measurements, the participant was asked to interact with the VR-based tasks with the help of the haptic device using his affected hand.

IV. RESULTS AND DISCUSSION

We carried out a preliminary usability study with three stroke participants. Our objective was to understand (1) the implication of our PA system on participants' performance and physiological indices and (2) carry out a comparative study with the PS system.

A. Participants' group performance and physiology.

Rehabilitation exercises are designed to improve a participant's task performance. In our study each participant was exposed to each of the PS and PA systems for duration of 5 days on an average. Here we present implication of PA and PS systems on one's task performance in terms of (i) change in performance score between the first (F_DAY) and last (L_DAY) days, (ii) increase in time efficiency during task performance, and (iii) reduction in errors committed. We also studied implication on group $Tonic_{MEAN}$.

A.1 Change in performance score between F_DAY and L_DAY

One's normalized performance score ($Perf_{NORM}$) for participants' interaction with different numbers of tasks (N_{DL1}-N_{DL3}) belonging to varying difficulty and getting various % average performance scores (P_{DL1}- P_{DL3}), is,

$$Perf_{NORM} = \frac{P_{DL1}*N_{DL1}+P_{DL2}*N_{DL2}+P_{DL3}*N_{DL3}}{100*(N_{DL1}+N_{DL2}+N_{DL3})} \quad (6)$$

Please note that here, we have not considered weights for tasks of different difficulty levels while computing the ($Perf_{NORM}$) and instead we considered the number of exposures i.e. task trails played by the participants. The reason behind this is that we have designed our system as a proof-of-concept application for a rehabilitation platform that mainly aims for increased task practice (more task trials) by patients with the hope of achieving improved performance. It can be seen from Fig. 4(a) that increase in group $Perf_{NORM}$ from F_DAY to L_DAY (Δ=16.27%) for PA system was higher than that for PS system (Δ=7.60%). In other words, the PA system contributed to greater improvement in performance compared to the PS system.

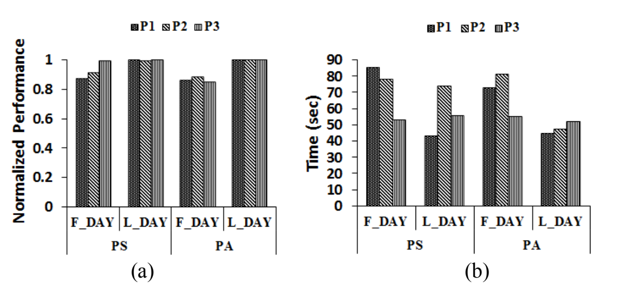


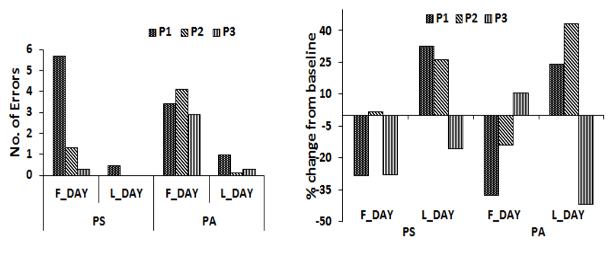
Fig. 4 (a) Avg. normalized performance and (b) Avg. Time Taken.

A.2 Increase in Time efficiency in terms of Group Average Time Taken

From Fig. 4(b), we observe that the decrease in the group average time taken to complete the tasks from the F_DAY to L_DAY was higher for PA (Δ=30.99%) than that for PS (Δ=20.12%) system. Thus, from the preliminary results we can say PA system has potential to contribute to improved performance and also to time efficiency.

A.3 Reduction in Group Average Number of Errors

For effective rehabilitation, one needs to attain improved performance score with capability to execute the tasks faster. But that should not come at the expense of increased number of errors. From Fig. 5(a), we observe that for PA there had been decrease in the number of group average errors from the F_DAY to L_DAY (Δ=86.49%), but it is comparable to and PS (Δ=92.92%). This might indicate that with practice, the PS system has potential to contribute to the PA system as far as the number of errors is concerned. However, reduced number of errors, though vital, is only one of the aspects of improved performance which if comes with adverse effects on the other aspects (e.g., for PS) is not acceptable.



(a) (b)

Fig. 5 (a) Average number of errors and (b) % change of $Tonic_{MEAN}$ from baseline.

A.4 Implication on Group Average Variation in Tonic mean

To nullify the effect of day variability for $Tonic_{MEAN}$, we considered %change (%Δ) with respect to (w.r.t) baseline measure. While the participants interacted with our VR-based tasks, we acquired their EDA signal in real-time and in a synchronized manner along with task propagation. We extracted the $Tonic_{MEAN}$ from the EDA signal as a biomarker of one's stress level [18]. From Fig. 5(b) we can see that the reduction in $Tonic_{MEAN}$ on the F_DAY from baseline ($\Delta Tonic_{MEANwrtBaseline}$) was greater than that on L_DAY from baseline for PS (Δ=49.89%) compared to that for PA (Δ=7.24%) system. Thus the PS system, with repeated exposure (i.e., practice) to tasks, is accompanied with greater fluctuation in stress level from F_DAY to L_DAY with $\Delta Tonic_{MEANwrtBaseline}$ being greater on L_DAY compared to F_DAY which might also infer greater excitement [24] to perform better. However, for PA system, on the other hand, even with repeated exposure, lesser fluctuation of stress level was seen on the F_DAY compared to the L_DAY. This might imply that our intelligent PA system was able to maintain a controlled stress level along with improved performance (Section IV.A).

B. Implication on Individual Performance

So far we have seen the different measures of group performance. Here we present performance-related measures for an individual participant, e.g., P2.

B.1 Implication on Individual Task Progression

The Fig. 6 shows the task progression of P2 while performing the VR-based tasks. For PA system, the task switching between different difficulty levels was more frequent compared to the PS system. In fact, since the PA system was adjusting its task presentation based on the stress level, it manifested itself with more frequent task switching and in turn facilitating P2 to continue in DL3 before exiting the interaction on L_DAY for PA system compared to DL2

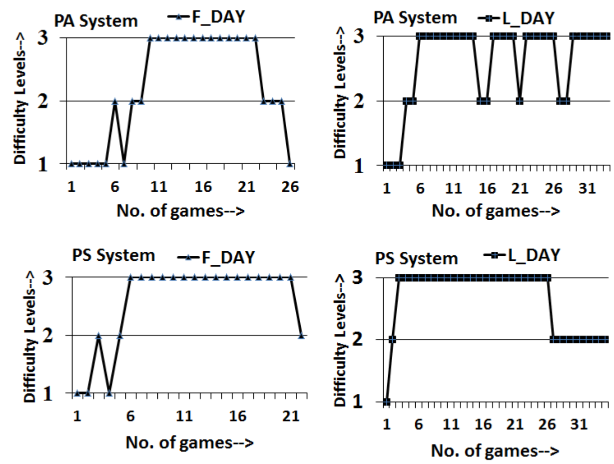
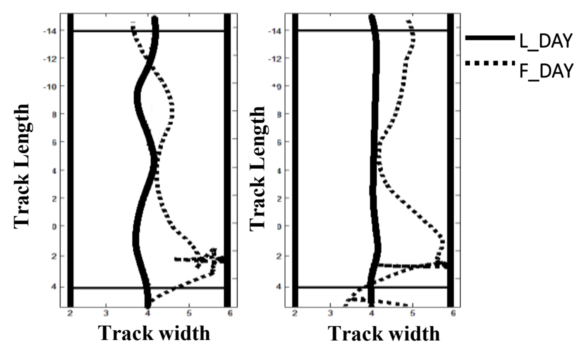


Fig. 6 Task progression for P2 participant of (a) PA and (b) PS system.

for PS system.

B.2 Implication on Car Trajectory

While P2 was maneuvering the virtual car along different



(a) (b)

Fig. 7 Car trajectory for (a) PS and (b) PA system of P2

tracks in the VR environment with the help of the haptic device, we recorded the trajectory of the car. The participants were asked to stay close to the central dotted line in each track. The Figures 7 (a) and (b) show a comparative representation of car trajectory between F_DAY and L_DAY for PA and PS systems for P2. From this we can see that the trajectory was closer to the middle of the straight track on the L_DAY than the F_DAY for both the PA and PS systems indicating improved stylus movement. Again, please note that the trajectory on the L_DAY was closer to the middle of the track with lesser deviation from the middle for the PA system as compared to that for the PS system which might infer controlled object maneuvering capability.

V. Conclusion

In our present research, we have designed a usability study as a proof-of-concept application while using VR-based haptic-enabled exercise platform to facilitate abduction and adduction exercises for shoulder joint for individuals with upper limb movement disorder. In our preliminary study, 3 stroke patients participated. The tasks were designed to be performance-sensitive (PS) and physiologically aided (PA). The PA system was adaptive to both the predicted stress level and performance. The preliminary study revealed that with the PA system we could achieve improved normalized performance, time efficiency and increased association with the exercise tasks (i.e., number of trials) as compared to the PS system. However, with respect to the number of errors committed, though the PS system had lesser errors (from F_DAY to L_DAY) than the PA system, yet this was comparable. Additionally, the stress-adaptive feature of PA system might be responsible for contributing to improved smoothness of one's hand movement on the L_DAY than that on the F_DAY. From the post-study survey, we understood that all the 3 participants liked interacting with our VR-based systems. While the results of the preliminary usability study are promising, our study has a few limitations that need to be borne in mind.

Since our study was a proof-of-concept application, we tried our systems with few participants. However, we admit that one of the limitations was the limited sample size. In future, we plan to test our system with greater number of participants and over a longer duration, (more exposures / sessions). In our present study, the VR-based task was to maneuver the virtual car on a straight track (DL1) along south to north, on an arc shaped path (DL2) in counterclockwise direction and semi square track (DL3) from south-to-north followed by east-to-west and followed by north-to-south. Thus, unicycle direction of hand movement was considered as far as the car maneuvering task was concerned. In future, we plan to expose our participants to car maneuvering task in different directions other than unicycle.

Our overall plan is to develop an individualized adaptive rehabilitation system which is interactive and can be used by the individuals at their home. Also, we hope that this will serve as a complementary tool in the hands of the physiotherapist. We hope that our system is a step towards developing an affordable home-based, individualized rehabilitation platform for individuals having upper limb movement disorders, thereby bringing in a paradigm shift in healthcare.

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