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Cognitive fatigue effect on rehabilitation task performance in a haptic virtual environment system

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Abstract

Introduction: This paper presents a study on an affordable rehabilitation approach to post-stroke patients. In this approach, a patient performs a task on a haptic virtual environment system and a physician examines the patient's task remotely based on the performing data.

Objectives: The objective of this study is to test a hypothesis that an elevated cognitive fatigue state may significantly affect the patient's task performance so as to disturb judgment by physicians.

Methods: The study included the development of a test-bed for the experiment and an experimental study for the hypothesis. The study took the wrist coordination function of the upper limb as an example.

Result: The study showed that the cognitive fatigue state has a significant influence on the patient's task performance; in other words, there is a noise (75% discrepancy from the true performance information) in the performance data.

Conclusion: The study provides great potential for accurate assessment of the functional state from true patient task performance. The future work needs to focus on the removal of the noise. The limitation of this study is that the experiment was carried out on healthy subjects, although post-stroke patients are more susceptible to an elevated cognitive fatigue state from a common sense.

Keywords

Stroke patient, mind state, task performance, wrist coordination

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Introduction

Stroke is one of the leading neurological diseases that cause the death and disability in Canada.[1] Stroke often causes the loss of the functional ability on one side of body. In 30% to 60% of stroke patients, the affected upper limb remains dysfunctional for about six months after an acute stroke; only 5% to 20% of stroke patients demonstrate a complete recovery.[2] Therefore, there is a need of rehabilitation on a continuing basis after the occurrence of an acute stroke to regain the desired functional state for the affected upper limb. Ideally, such a rehabilitation process can be taken at home, while the patient's task performance data are transmitted to the hospital or major medical center over the Internet. This approach to rehabilitation will dramatically reduce the cost of rehabilitation because both the expensive physical rehabilitation equipment and physical therapists are saved along with the cost incurred from the hospital visiting by patients.

The main problem with the home-based rehabilitation approach is that the patient's task performance data may not truly represent the patient's functional state due to patient's non-compliances to a standard procedure (including an elevated cognitive fatigue

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state), when they perform the prescribed task. The study presented in this paper concerned whether the elevated cognitive fatigue (or fatigue for short) state of a patient may significantly disturb or influence the patient's task performance.

It is noted that the need of this study on the cognitive fatigue is also supported by literature in some relevant areas. Colle et al.[3] reported that (cognitive) fatigue is a common complaint after stroke and occurs in 39–72% of the stroke survivors. Johansson et al.[4] pointed out that the mental or cognitive fatigue is a common symptom after a brain injury or a neurological disease. Severijns et al.[5] presented a study to show that the fatigue negatively affects the patient's participation in training for multiple sclerosis diseases. Another note is that understanding whether the mental state (including the emotional state) in general and the cognitive fatigue state in particular may significantly affect the patient's task performing may lead to some new protocols in rehabilitation – that is incorporating a proper mental state (e.g. a good mood or emotion) of the patient into the rehabilitation protocol for a better treatment outcome. Finally, how the cognitive fatigue state significantly affects the user task performance has been studied in other applications area, e.g. vehicle driving,[6] surgery,[7] but the issue is not often discussed in the context of stroke patient rehabilitation.

This study first built a test-bed (i.e. the Internet-based haptic virtual environment (HVE) system) and then conducted an experiment on the test-bed. The *hypothesis* of the experiment was: *an elevated cognitive fatigue state may significantly affect the task performance of post-stroke patients in a haptic virtual environment rehabilitation (HVER) system.* A particular function of upper limb (i.e. wrist coordination) was taken as an example, and a particular rehabilitation task (i.e. manipulating a virtual ball to follow a circular path), which corresponds to the loss of the wrist coordination, was taken in this study.

It is to be noted that the experiment was performed on the healthy subject in this study based on the assumption that post-stroke patients or patients are more susceptible to an elevated cognitive fatigue than healthy patients from a common sense. This assumption is likely valid, as post-stroke patients need to put more mental effort to control their body due to the functional loss on motors, and thus, the task performance of post-stroke patients is more susceptible to an elevated fatigue state than healthy people. Nevertheless, this assumption needs to be further studied.

The next section provides an overview of the literature regarding the HVE rehabilitation system for stroke patients or more generally neurological disease patients. Then an outline of the test-bed development and a statistical design of the experiment are presented. Results with discussion then follow, leading to a couple of conclusions in the last section.

Literature review

A virtual environment refers to the interactive simulation for humans to interact with virtual objects that appear sound and have similarities to real world objects[8] and in which the users experience tele-presence.[9] The term 'presence' refers to the sensation of 'being there' in a mediated environment.[10] The term 'haptic' refers to a sense of touch, by which the users get reaction forces when interacting with a real or virtual object. An HVE system consists of a human user, a haptic device, and a virtual environment.[11] The HVE system thus gives the users a tactile feeling when they interact with objects in a virtual environment or computer. With the HVE, patients have opportunities to perform tasks similar to daily activities such as eating and cooking, which require them to reach and stretch with physical workloads by force.

One of the most important advantages with the HVE along with the Internet technology (readily available today) is that patients can perform rehabilitation at home while physicians can monitor a patient's task performance over the Internet. It is herein noted that the patient's task performance generates two categories of data: (1) the task performing process (i.e. how the patient performs a task) and (2) the task performing product (i.e. the result of the patient's task performing). This study considered that only the second category of data is available to physicians.

Previous work in Bardorfer's group showed labyrinths games which were created in a virtual environment and conceived a new upper limb analysis test on the functional assessment test by using PHANTOM Premium haptic device.[12] In their system, with the information of the position of a stylus and the force on a stylus in a virtual environment, the clinician was able to characterize the motor behavior of patients with neurological diseases. Broeren et al.[13] proposed an assessment device for stroke patients incorporating both the virtual environment and haptic device (PHANTOM Omni). In the virtual environment, several parameters (including time, speed, and movement of the upper limb) were extracted as the patient's task performance data and evaluated. Their study presented the functional assessment for motor skills of the upper limb. Their result showed that the performance in the patient group appeared to be significantly different from the reference group. The study therefore demonstrated that the HVE enables individuals to perform tasks with the sensory feedback (e.g. capability to grasp). Other examples of the HVEs for rehabilitation are Cyber Force[14] and Cyber Glove.[15] These systems

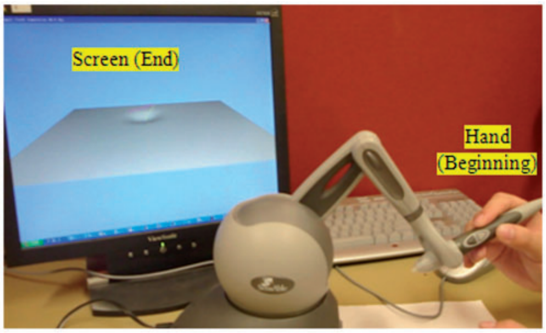

Figure 1. System set-up of the haptic virtual environment (HVE).

were proposed for haptic-based exercises for finger movements and strength improvements. However, no system as mentioned above discussed how the elevated mental states such as cognitive fatigue state may affect the task performance of post-stroke patients, which may thus compromise the accuracy of the functional assessment of the upper limb based on the patient's task performance data.

Development of the test-bed

In this study, an HVE system was built, which consisted of a computer and haptic device (PHANTOM Omni) manufactured by the SensAble Technology. The computer provides a virtual environment, and it has a workspace of 160 (width) ×120 (height) ×70 (depth) mm. Figure 1 illustrates the system setting of the HVE, where the haptic device plays a role as the position input and force feedback from the virtual environment. At the beginning, users are supposed to move the haptic stick. At the end, they could see the virtual ball pointer moving in the screen and feel the sense of touching when the virtual ball interacts with other three-dimensional objects (soft plane) in the virtual environment.

In this study, we took a particular function of the upper limb, the wrist coordination function, as an example without the loss of generality. A task designed for patients followed the assessment protocol of Brunnstrom[16] and Fugl-Meyer Assessment (FMA).[17] In Brunnstrom theory,[16] the recovery process is classified into six stages in the hemiplegic arm and leg, and in FMA theory,[17] there is an evaluative measurement system for the motor impairment and the test items with the procedure in FMA are specific to the function loss based on the Brunnstrom's six-stage theory. The task of the wrist coordination considered in this study was at Stage 6 based on the Brunnstrom theory. To examine the wrist coordination, a task called 'following a circle' was designed in accordance with the test item 'wrist circumduction' in FMA. Figure 2 further illustrates the 'following a circle' task. In the 'following a

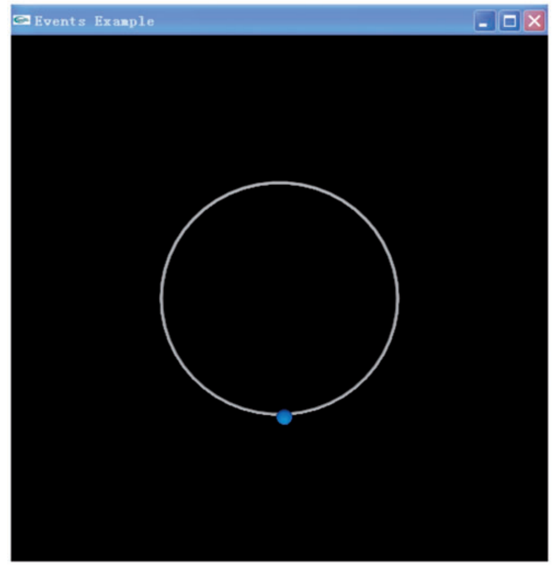

Figure 2. Task for wrist coordination in the virtual environment.

circle' task, the patient is supposed to follow a circle by moving his or her wrist a round. This wrist movement represents the wrist coordination. There is one issue in the implementation regarding the haptic device, that is, patients need to hold the haptic stick when they perform the tasks on the HVE system. In this study, it was assumed that the subjects are able to hold the haptic stick, which is usually the case for post-stroke patients at Stage 6.

Statistic design of the experiment

Human subjects

This research was approved by the Ethics Committee of the University of Saskatchewan. All subjects have been informed and agreed the consent to participate in this research project. A total of eight healthy subjects (four men, four women) were randomly selected from the students recruited from the website of the University of Saskatchewan in the experiment. The age of the subjects was from 22 to 27 years old, and their ethnic identification was equal with 50% Caucasian and 50% non-Caucasians. All the healthy subjects were qualified to participate in the experiment; in particular, they were capable of responding to simple mathematical questions and had no previous deficits on upper limb based on questionnaire.

Factor and response

There were two factors and one response in this experiment. One factor was the fatigue state and it had two levels: Level 1: no-fatigue (used as control treatment or reference) and Level 2: significant-fatigue. Due to possible inconsistent interpretations across individuals, this experiment defined the fatigue factor as a within-subjects factor. The other factor was the day when the rehabilitation task was performed and it had two levels that corresponded to different time spans of days for performing the rehabilitation task. The response was the rehabilitation task performance.

Elicitation of fatigue

The experiment required stimuli that can elicit the fatigue state – particularly for the two levels of fatigue (no-fatigue state, significant-fatigue state). The no-fatigue state was taken as a control treatment or reference. The significant-fatigue state was elicited by the test which produces a cyclic cognitive workload in mental effort, called Paced Auditory Serial Addition Test (PASAT).[18]

The PASAT can be performed on the web http://cognitivefun.net/test/25. The PASAT contains a simple but repetitive task, e.g. adding two numbers (Figure 3), and the numbers sounded continuously. Figure 3(a) shows two numbers '2' (past) and '7' (current), and the sum is '9' (which should be answered by the user). Figure 3(b) shows two numbers '7' (past) and '9' (current), and the sum is '16' (which should be answered by the user). The PASAT required the participants to attend auditory information and to retrieve it from their working memory system, which thus gives a bit cognitive challenge. Particularly, in this experiment, for the no-fatigue state, the subject did the PASAT task for one trial with 3 min; for the significant-fatigue state, the subject did the task in five 3-minute on-trials, followed by 1-minute off-trials. In this study, it was assumed that the subjects were in a no-fatigue state prior to the experiment.

Test procedure

For each subject, the experiment was carried out in two days (Day 1, Day 2), the time span of which was seven days, eliminating the confounding factor with the familiarity. On each day, the subject performed eight times for the no-fatigue state and eight times for the significant-fatigue state, respectively. The task performing process followed the PASAT elicitation right away. It is noted that details regarding the evaluation of the effectiveness of HVE and the validation of fatigue elicitation are referred to the unpublished master thesis of the first author.[18]

Before the subject performed the task, the starting position was set such that the wrist and fingers kept relaxed. The patient's forearm was held in such a way that the palm faced down, while the elbow was kept in flexion to 90°. To keep the elbow in flexion at 90°, the patient may need a support device on elbow, which was further fastened on the widget (Figure 4). The constraints on elbow or arm ensured that the operation was taken only with the wrist. However, details of the design of the widgets were out of the scope of the present study. The screen shot of the required starting position is shown in Figure 4. During the assessment, the patient was required to move the hand round with the wrist to follow a circle trajectory displayed in the virtual environment (i.e. the computer screen). Figure 5 illustrates the wrist movement in the wrist coordination task.

It is noted that the device described above was proven to be effective to the assessment of the wrist coordination on the experiment conducted by us,

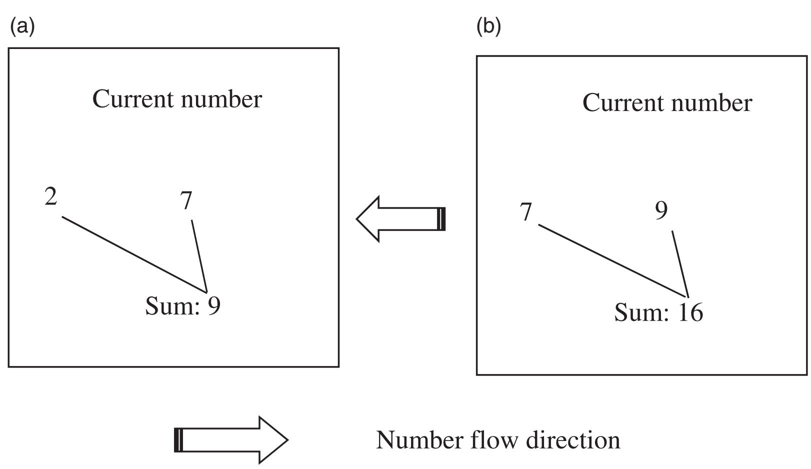

Figure 3. An example of PASAT – adding two numbers continuously. (a) PASAT task a. (b) PASAT task b.

reported elsewhere in details.[18,19] A similar device and task were used by other researchers; see literature[12] among others.

Measurement of the rehabilitation task performance

In the 'following a circle' task, the error between the actual trajectory of the ball and the desired trajectory is the performance measure, denoted by R. To compute R, the following parameters are measured: (1) position of the ball with respect to the starting point (x, y, z) measured in inches; (2) time of the task performing (T) sampled in ms; and (3) perimeter of the circle (L) measured in inches. Based on the foregoing parameters, the trajectory (s) generated by the patient can be found by

$$s = \int_0^T \dot{s}\,dt = \int_0^T \sqrt{x^2 + y^2 + \dot{z}^2}dt \quad (1)$$

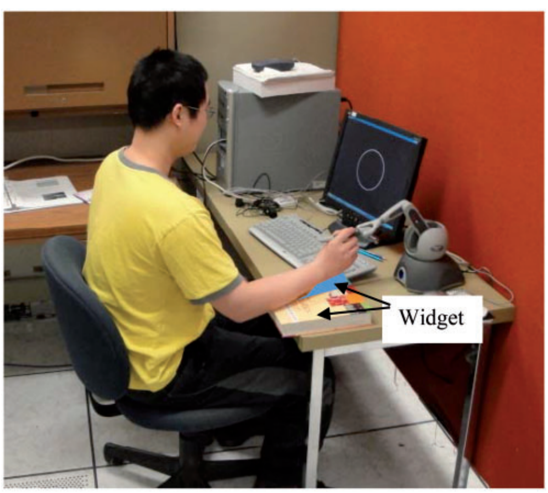

Figure 4. Required position before the experiment.

R is then calculated by

$$R = \left| \frac{\int_0^T \dot{s}\,dt}{L} - 1 \right| \quad (2)$$

The parameter R is further normalized by

$$\frac{\text{Original (R)}}{\text{Baseline (R)}} \quad (3)$$

where the original R represents the raw performance data and the baseline R represents the average R when the subjects are in a no-fatigue state. The normalized performance represents a degree of the change in task performance from the no-fatigue state to the significant-fatigue state. It is noted that the units of the above parameters are defined in the coordinate system of the computer monitor. The true units of the parameter are not important to the rehabilitation approach discussed in this paper. It is further noted that only the error between the actual trajectory and desired trajectory, which was calculated from the actual position of the ball with respect to the prescribed circle, was considered in this study, as this error is in align with the clinic practice (after consulting with the physician of physical medicine and rehabilitation).

Data analysis

The significant level α is equal to 0.05 for the experiments conducted in this study.[a] The randomly selected two-way ANOVA F-test was employed for data analysis because there were two factors (day and fatigue state) and one response (rehabilitation task performance) with randomly selected subjects.

Results and discussion

Table 1 shows the rehabilitation task performance of the eight subjects, which are a combination of the two

Figure 5. Wrist movement in the wrist coordination task.

Table 1. Rehabilitation task performance in the two-way ANOVA test.

Subject \ Fatigue and day	No-fatigue and Day 1	Sig.-fatigue and Day 1	No-fatigue and Day 2	Sig.-fatigue and Day 2
1	0.35	1.32	0.67	1.31
2	0.85	1.00	0.77	1.46
3	0.64	2.18	0.82	1.09
4	1.20	1.20	1.10	1.00
5	1.14	1.57	0.86	0.57
6	0.45	1.09	1.18	1.27
7	1.38	1.75	0.38	3.00
8	0.50	2.50	0.33	2.33

factors (i.e. fatigue and day). Before examining the data, the assumption for ANOVA test was confirmed as valid such that the subjects were independent with each other. The adequacy of the sample size was confirmed next. To calculate the statistical power, descriptive statistics were employed to get the average, standard deviation, and sample size. Table 2 shows the descriptive statistics of the rehabilitation performance data in terms of fatigue.

In Table 2, N denotes the number of samples, M stands for the population mean of the normalized rehabilitation performance calculated from equations (1) to (3), and σ is the standard deviation. From the descriptive statistics, the statistical power was calculated according to Rosner[20] by

$$\text{Power} = \phi\left[-z_{(1-\alpha)/2} + \frac{|\mu_1 - \mu_2|}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}\right] \tag{4}$$

where σ_1 and σ_2 represent the standard deviation for the two populations, α stands for the significant level, μ_1 and μ_2 are the means of the two population groups (respectively), n_1 and n_2 are the sample sizes of the two groups (respectively), and z represents the normal distribution. In this study, $n_1 = n_2 = 16$, $|\mu_1 - \mu_2| = 0.69$, $\sigma_1 = 0.41$, $\sigma_2 = 0.67$, $\alpha = 0.05$. From equation (4), we obtain

$$\text{Power} = \phi\left[-z_{(.975)} + \frac{0.69}{\sqrt{\frac{0.41^2}{16} + \frac{0.67^2}{16}}}\right] = \phi\left[-1.96 + \frac{0.69}{0.196}\right] = \phi(1.560) = 0.941$$

Table 2. Descriptive statistics of rehabilitation task performance.

	N	Mean (M)	Std. deviation (σ)
No-fatigue	16	0.92	0.41
Significant-fatigue	16	1.61	0.67
Valid (list wise)	16		

Table 3. F-test statistics for the effect of fatigue on the rehabilitation performance.

Test of between-subjects effects				
Dependent variable: performance over baseline				
Source		Df	F	Sig.
Day	Hypothesis	1	1.327	0.287
	Error	7		
Fatigue	Hypothesis	1	7.219	0.031
	Error	7		
Subject	Hypothesis	7	0.842	0.619
	Error	2.966		
Day×fatigue	Hypothesis	1	0.023	0.884
	Error	7		
Day×subject	Hypothesis	7	0.588	0.75
	Error	7		
Fatigue×subject	Hypothesis	7	1.814	0.225
	Error	7		

Thus, the statistic power in this experiment is 94.1%. Cohen[21] pointed out that the statistical power of the experiment in human behavior should be higher than 80%. Therefore, the statistical power in this experiment is strong enough to carry out the statistical analysis.

Further, from the means of the task performance for the fatigue state and that for the no-fatigue state in Table 2, we can calculate the noise (i.e. the error in terms of task performance assessment) is

$$\frac{M_{fatigue} - M_{no-fatigue}}{M_{no-fatigue}} = \frac{1.61 - 0.92}{0.92} = 75\%$$

Table 3 shows the result of the F-test statistics and corresponding p-value. According to this table, F-test statistics is as follows: (1) for the day variable, $F(1, 7) = 1.327$, corresponding to p-value $= 0.28$; (2) for fatigue variable, $F(1, 7) = 7.219$, corresponding to p-value $= 0.031$; (3) for the randomly selected subject, $F(1, 7) = 0.842$, corresponding to p-value $= 0.619$. From Table 3, a couple of points were noted. First, at the significance level $\alpha = 0.05$, there is no evidence to conclude that measurements in different days and different

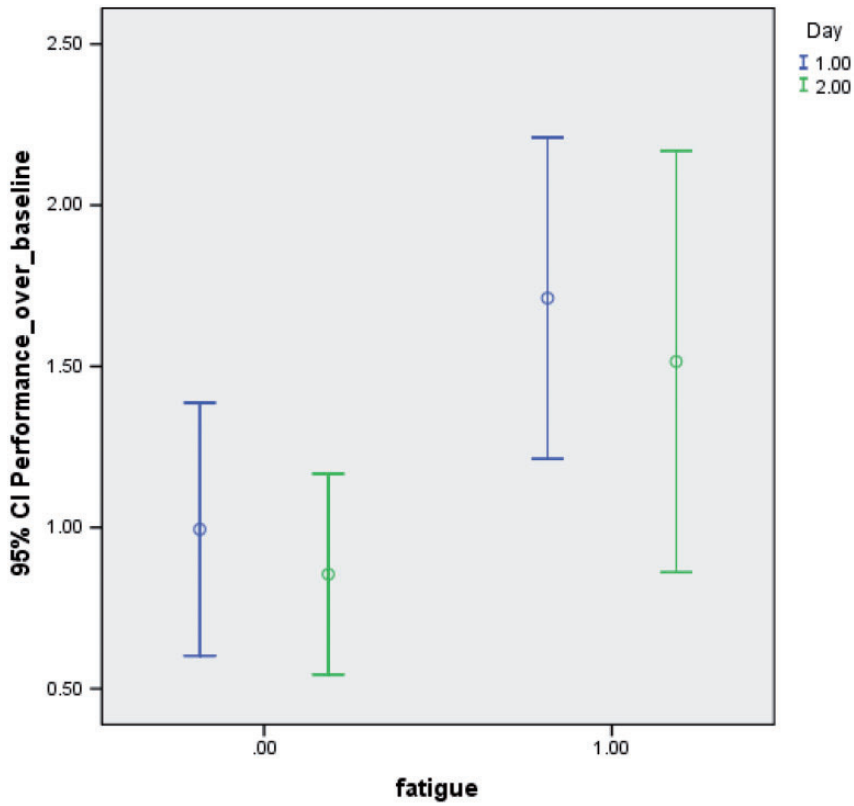

Figure 6. Estimated average error (R) of the task performance between no-fatigue (left) and significant-fatigue (right).

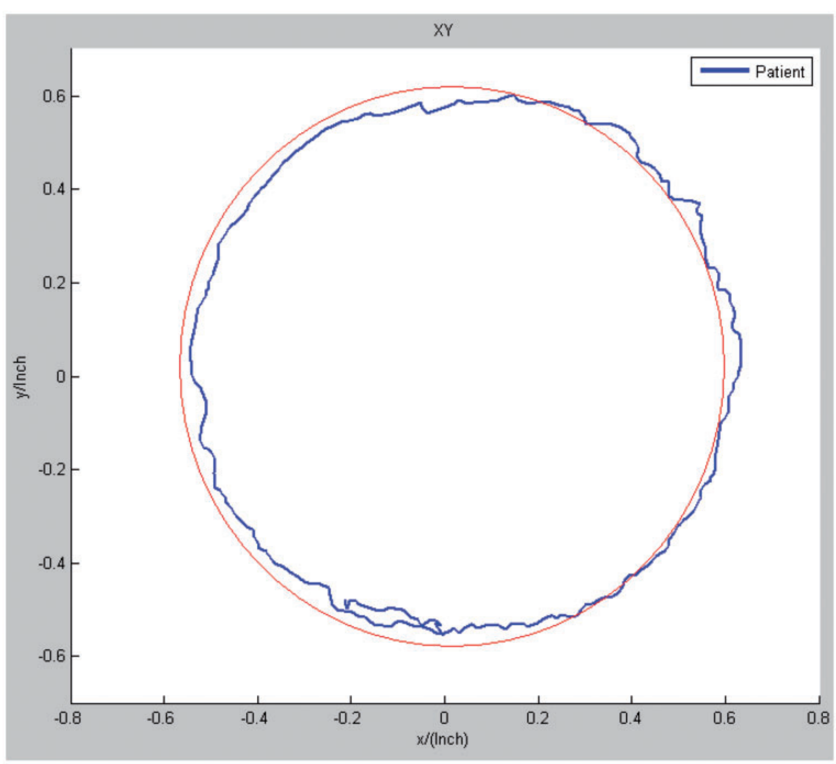

Figure 7. Trajectory of a patient in HVE.

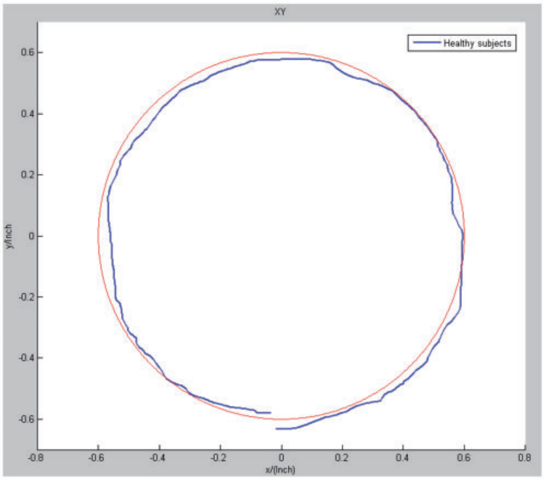

Figure 8. Trajectory of a healthy subject in the HVE.

subjects may affect the rehabilitation task performance in the subjects with $F(1, 7) = 1.327$ and 0.842, corresponding to p-value = 0.287 and 0.619 > 0.05, respectively. Second, there is evidence to conclude that there is significant difference in the rehabilitation task performance for the assessment of the wrist coordination between the non-fatigue state and the significant-fatigue state in the subjects with $F(1, 7) = 7.219$, corresponding to p-value = 0.031 (<0.05).

Figure 6 shows the estimated average error (R), with respect to the baseline performance, between the significant-fatigue and no-fatigue states. From Figure 6, it can be seen that the fatigue affects the performance in the wrist coordination function significantly. In addition, at the significant-fatigue state, the error can increase up to two times as high as the error at the no-fatigue state. This clearly suggests that if the functional assessment of the wrist coordination based on the task performance data is conducted in the event that the patient is in an elevated fatigued state, the assessment result is prone to error.

The performance difference between the patient subject and healthy subject was also examined in this study in order to give evidence that the task designed in this experiment is sensitive to the wrist coordination. In particular, we compared the trajectory of the virtual ball in HVE with one by a patient subject and one by a healthy subject. Figure 7 shows the patient's task performance (i.e. the trajectory along the circle in the haptic system), which shows that there is a saw-toothed trajectory representing jerk motions in the movement. Figure 8 shows the trajectory produced by the healthy subject, which is much smoother than the one by the patient. Nevertheless, a more rigorous experiment on patients along with data analysis for the legitimacy of the test as designed in this study for the wrist coordination is warranted in the future.

Conclusion

This study examined the fatigue effect on the rehabilitation task performance in an HVE system for the functional assessment of the upper limb – in particular the wrist coordination. It can be concluded from the result that an elevated fatigue state significantly affects the wrist coordination task performance in rehabilitation. Although this conclusion is derived from the experiment on healthy subjects, it is quite likely that the conclusion is valid for patients. The knowledge about the fatigue effect on the rehabilitation task performance can be extended to the knowledge for other mental states such as anxiety and frustrating, which will be part of our future work. A work to eliminate the mental state effect on the task performance data is also under way, which will improve the accuracy and reliability of the assessment of the functional loss of the stroke patient. In future, the similar experiment is expected to perform on the stroke patient. Further, two other emotional states such as anxiety and frustrating will be studied in future.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Research ethics and patient consent

This study has been approved by the Behavioral Research Ethics Board in the University of Saskatchewan with approval number BEH#11-61.

Guarantor

WJZ.

Contributorship

WJZ and CY researched the literature and conceived the study. CY was involved in protocol development, gaining ethical approval, subject recruitment, and data analysis. CY wrote the first draft of the manuscript. All the authors reviewed and edited the manuscript and approved the final version of the manuscript.

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Note

a. This choice is in accordance with a general consensus in human factors research.

References

1. Canadian Institute for Health Information (CIHR). The burden of neurological diseases, disorders and injuries in Canada, http://www.cpa.ca/cpasite/UserFiles/Documents/Practice_Page/Burden_neuro_diseases_en.pdf (2007).
2. Kwakkel G, Kollen B, Prevo AJ, et al. Probability of regaining dexterity in the flaccid upper limb. *Stroke* 2003; 34: 2181–2186.
3. Colle F, Bonan I, Leman MC, et al. Fatigue after stroke. *Ann Réadapt Méd Phys* 2006; 49: 361–364.
4. Johansson B, Starmark A, Berglund P, et al. A self-assessment questionnaire for mental fatigue and related symptoms after neurological disorders and injuries. *Brain Inj* 2010; 24: 2–12.
5. Severijns D, Octavia JR, Kerkhofs L, et al. Investigation of fatigability during repetitive robot-mediated arm training in people with multiple sclerosis. *PLoS One* 2015; 10: e0133729.
6. Yang G, Lin Y and Bhattacharya P. A driver fatigue recognition model based on information fusion and dynamic Bayesian network. *Inf Sci* 2010; 180: 1942–1954.
7. Kahol K, Leyba MJ, Deka M, et al. Effect of fatigue on psychomotor and cognitive skills. *Am J Surg* 2008; 195: 195–204.
8. Schultheis MT and Rizzo AA. The application of virtual reality technology in rehabilitation. *Rehabil Psychol* 2001; 46: 296–311.
9. Steuer J. Defining virtual reality: dimensions determining telepresence. *J Commun* 1992; 42: 73–93.
10. Slater M and Usoh M. Representations systems, perceptual position, and presence in immersive virtual environments. *Presence* 1993; 2: 221–233.
11. Srinivasan MA and Basdogan C. Haptics in virtual environments: taxonomy, research status, and challenges. *Comput Graph* 1997; 21: 393–404.
12. Bardorfer A, Munih M, Zupan A, et al. Linear and circular tracking exercises in haptic virtual environment for hand control assessment. In: *IEEE international conference on rehabilitation robotic*, 2005, pp.1–5. USA: IEEE.
13. Broeren J, Björkdahl A, Pascher R, et al. Virtual reality and haptics as an assessment device in the postacute phase after stroke. *Cyberpsychol Behav* 2002; 5: 207–211.
14. Kayyali R, Shirmohammadi S, Saddik A, et al. Daily-life exercises for haptic motor rehabilitation. In: *IEEE international workshop on Haptic, Audio and Visual Environments and Games, HAVE 2007*, October 2007, pp.118–123. USA: IEEE.
15. Adamovich SV, Merians AS, Boian R, et al. A virtual reality-based exercise system for hand rehabilitation post-stroke. *Presence* 2005; 14: 161–174.
16. Brunnstrom S. *Movement therapy in hemiplegia: a neurophysiologic approach*. New York, USA: Harper and Row Inc., 1970, pp.357–375.
17. Fugl-Meyer AR, Jaasko L, Leyman I, et al. The post-stroke hemiplegic patient: a method for evaluation of physical performance. *Scand J Rehabil Med* 1975; 7: 13–31.
18. Cook DB, Connor PJ, Lange G, et al. Function neuroimaging correlates of mental fatigue induced by cognition among chronic fatigue syndrome patients and controls. *NeuroImage* 2007; 36: 108–122.
19. Yang C. *Fatigue effect on task performance in haptic virtual environment for home-based rehabilitation*. MSc Thesis, University of Saskatchewan, Canada, 2011.
20. Rosner B. *Fundamentals of biostatistics*, 7th ed. Duxbury: Thomson Brooks/Cole, 2010, p.303 (see Equation 8.28).
21. Cohen J. *Statistical power analysis for the behaviour sciences*. Hillsdale, New Jersey, USA: Lawrence Erlbaum Associates Inc., 1988, pp.17–20.