8-12-2014

Therapeutic Potential of Haptic TheraDrive: An Affordable Robot/Computer System for Motivating Stroke Rehabilitation

Andrew Theriualt
Marquette University

Mark L. Nagurka
Marquette University, mark.nagurka@marquette.edu

Michelle J. Johnson
Marquette University, michelle.j.johnson@marquette.edu

Accepted version. Published as a part of *5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, (August 12-15, 2014). DOI. © 2014 IEEE. Used with permission.

5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechanics, (2014). DOI.

Therapeutic Potential of Haptic TheraDrive: An Affordable Robot/computer System for Motivating Stroke Rehabilitation

Andrew Theriualt
Department of Mechanical Engineering, Marquette University, Milwaukee, WI
Mark Nagurka
Department of Mechanical Engineering, Marquette University, Milwaukee, WI
Michelle J. Johnson
Department of Physical Medicine and Rehabilitation and Department of Bioengineering, University of Pennsylvania, Philadelphia, PA

Abstract:

There is a need for increased opportunities for effective neurorehabilitation services for stroke survivors outside the hospital environment. Efforts to develop low-cost robot/computer therapy solutions able to be deployed in home and community rehabilitation settings have been growing. Our long-term goal is to develop a very low-cost system for stroke rehabilitation that can use commercial gaming technology and support rehabilitation with stroke survivors at all functioning levels. This paper reports the results of experiments comparing the old and new TheraDrive systems in terms of ability to assist/resist subjects and the root-mean-square (RMS) trajectory tracking error. Data demonstrate that the new system, in comparison to the original TheraDrive, produces a larger change in normalized trajectory tracking error when assistance/resistance is added to exercises and has the potential to support stroke survivors at all functioning levels.

SECTION I. Introduction

After acute care, stroke survivors still need additional rehabilitation. The Framingham Heart Study documented that after discharge, 50% of stroke survivors, 6 months post-stroke and post-rehabilitation, had some paralysis of the upper and lower limb, 30% were unable to walk without some assistance, and 26% were dependent in activities of daily living.[1] Community-based stroke rehabilitation programs offer a solution by providing stroke survivors access to rehabilitation services at reduced costs and the opportunity to improve functional independence after discharge; however, they do so with limited therapy resources.[2] Stroke survivors, once discharged from a nursing home or sub-acute care, are able to continue therapy in this setting. A study by Rijken and Dekker 1998 indicated that stroke patients were the most common chronically ill patients treated by occupational therapists in non-institutional care (246 per 1000).[3] Efforts to develop low-cost robot/computer therapy solutions that are able to be deployed in home and community rehabilitation settings have been growing. A major part of making a robot therapy environment effective is creating appropriate force feedback and controllers to maintain motor training and motivation. The element of maintaining motivation and compliance is even more important when the device is expected to be used in under-supervised environments. Early research efforts demonstrated the feasibility of affordable stroke rehabilitation.[4,5] Examples of commercial efforts to create low-cost rehabilitation devices using game therapy are Hand-of-Hope (Rehab-Robotics, Ltd), Diego (Tyromotion), and Bi-Manu-track (Reha-Stim). These systems are making inroads, but are still relatively expensive, use custom-games, and are not always strong enough for the most severe stroke survivor. Our long-term goal is to develop a very low-cost system for stroke rehabilitation that can use commercial gaming technology and support rehabilitation with stroke survivors at all functioning levels.

Our first efforts in this area initially revolved around Driver's SEAT,[6] a split steering wheeled device that used bilateral force measurement to promote impaired arm use after a stroke. More recently, we developed TheraDrive, a low-cost robotic system for post-stroke upper extremity rehabilitation using commercial games.[7–8,9,10,11] A new low-cost, high-force haptic robot with a single degree-of-freedom has been developed to address these concerns.[12,13] A pilot study assessed the viability of the new haptic robot, Haptic Theradrive, which improves upon the original TheraDrive system by increasing the torque output and adding an adaptive controller. It was hypothesized that these improvements would make the haptic robot suitedbetter to support low-functioning subjects, and these improvements would be apparent through improvements in quantitative measures of subject performance, such as RMS trajectory tracking error. In this paper we compare the old and new TheraDrive systems in terms of effectiveness to assist/resist subjects and the RMS trajectory tracking error for each exercise.

SECTION II. Methods

A. Theradrive Systems

Figure 1 shows both systems (devices are described in details in[9,13]). The **original Theradrive** uses off-the-shelf computer gaming Logitech wheels with force feedback to help reduce motor impairment and improve function in the arms of stroke survivors.[7–8,9,10,11] There was force feedback and the force-feedback control modes consisted of no-control (no force) and spring control for light assistance or resistance at the wheel during tracking tasks. However, there were a few shortcomings. The maximum torque that could be applied was 1.5 N-m. Preliminary results showed that the TheraDrive system lacked a robust mechanical linkage that can withstand the forces exerted by patients, lacked a patient-specific adaptive controller to deliver personalized therapy, and was not capable of delivering effective therapy to severely low-functioning patients.

The **new Haptic TheraDrive** device consists of an actuated hand crank with a compliant transmission.[12,13] Actuation is provided by a brushed DC motor, geared to output up to 223 N (50 lbf) at the end effector. To enable safe human-machine interaction, a special mechanical element was developed that provides compliance and also functions as a fail-safe torque limiter. A custom load cell was used to determine the human-machine interaction forces for use by the robot's new impedance-based controller. The impedance controller creates a virtual spring that attracts or repels the end effector from a moving target that the human must track during therapy exercises.

As exercises are performed, an adaptive controller monitors patient performance and adjusts the spring stiffness to ensure that exercises are difficult but doable, which is important for maintaining patient motivation. In the zero-impedance mode, the crank arm appears to rotate freely, though it will be actuated and no assistive/resistive forces are applied. In static control mode, the crank provides assistive/resistive forces at a level set prior to each exercise.

Figure 1: Old theradrive and the haptic theradrive systems.

The plain adaptive controller adjusts the assistance/-resistance based on the RMS performance error over 3rad and provides more force assistance if the subject appears to have errors greater than a desired error (0.25 rad) corresponding to the width of the target. If errors drop consistently below the target, the force resistance increases to make tracking incrementally more difficult. The position-based adaptive control mode adjusts the assistance/resistance based on the position of the crank arm (in seventeen regions evenly spaced about the crank circle) and provides more assistance where the subject appears to have greater difficulty.

B. Experiment

A total of six human subjects were tested using the two TheraDrive robots: two normal subjects and four stroke subjects (Table 1). After arrival, subjects reviewed and signed a consent form with study personnel. Stroke subjects were evaluated by a therapist to determine their level of impairment. The Upper Extremity Fugl-Meyer test was used to quantify the degree of impairment in the stroke subjects.[14] Low-functioning subjects were defined as subjects with a score of 30 or lower; medium-functioning subjects had scores ranging from 31 to 50; and high-functioning subjects had scores of 51 or greater.

During experiment sessions, subjects performed mock therapy exercises consisting of sinusoidal trajectory tracking using each Theradrive system. Each exercise consisted of tracking the given trajectory for 90 seconds. Tracking exercises presented different trajectory-following tasks. Trajectories consisted of a sum of four sinusoids, centered about the vertical crank position, of amplitude 0.5 rad and frequencies of 0.5, 1.0, 1.5, and 2.0 rad/s. The relative phases of the sinusoids were randomized for each exercise to reduce learning effects while still preserving the range of motion and frequency content. In the trajectory-following exercises the patient was presented with a cursor that follows the robot end effector and a target that moves along a path. The objective of the exercise is to keep the cursor on the target for the duration of the exercise.

Four exercises were performed for each operating mode of each robot, for a total of 24 exercises per subject. The first robot presented to the subject was chosen randomly. The old Theradrive with no spring assistance/resistance was compared to the new Haptic Theradrive in zero-impedance, static assistance/resistance, and adaptive control. It was hypothesized that the change in performance after assistance/resistance was added would be greater for the new robot versus the old robot. It was also hypothesized that this change in performance would only be significant for low-functioning subjects who required more assistance than the commercial Logitech wheel could provide.

Following exercises with each robot, subjects were asked to complete a series of surveys to express their opinions of each robot. A motivation survey presented subjects with a list of 25 statements such as “I believe doing this activity could be beneficial to me,” and “I think I am good at this activity,” and asked them to rate their agreement with these statements on a scale of 1 (strongly disagree) to 7 (strongly agree). Each of these statements was assigned to a certain category of motivation, and responses to the questions added points to the respective categories. A post-activity survey asked subjects about their level of exertion and overall opinion of each robot and included space for subjects to leave general comments. After completion of exercises with both robots, subjects were given a final survey in which they indicated a preference of robot along with the strength of this preference and the reason for this preference.

C. Data Analysis

Haptic Feedback Utility: To determine the utility of the haptic force-feedback upgrade from the old to new Theradrive systems in terms of ability to assist/resist subjects, the root-mean-square trajectory tracking error was computed for each exercise. The RMS tracking error between the measured and commanded trajectories is calculated as follows:

$$\Delta x_{RMS} = \sqrt{\frac{1}{T}\sum_{t=1}^{\frac{T}{\Delta t}} \left(x_a(i) - x_d(i)\right)^2 \Delta t}$$

where Δt is the sample period and T is the duration of the exercise. The tracking error without assistance/resistance was defined as the baseline performance for each robot, and data from each subject was normalized by the baseline performance for the appropriate robot. Normalization was performed so that the relative change in performance after the addition of assistance/resistance could be compared for each robot.

To compare subject performance changes with assistance/resistance by different robots, data needed to be normalized by baseline performance with the robot used to cancel any other factors that would influence subject performance, such as robot dynamics. Data from the old and new TheraDrive robots was normalized with respect to baseline performance with each robot by the following equation, where x is the parameter of interest and $\bar{x}$ bass is the baseline value of the parameter as in Equation 2,

$$x_{norm} = \pm \frac{x_{row} - \bar{x}_{bass}}{\bar{x}_{bass}}$$

The sign of the normalized value is reversed for subjects requiring assistance, allowing the absolute value of the change in performance to be compared across all subjects in one group. Data points were categorized by subject, robot mode, and trial number.

The absolute normalized change in RMS tracking error after the addition of assistance/resistance was used as the primary measure to compare the efficacy of the assistive/resistive force provided by the TheraDrive and the haptic robot. Although the RMS trajectory tracking error is calculated by the same method for each robot, the tracking error must be normalized in order to compare data across the two systems since the subjects' baseline performances with each system were not necessarily equal. The sign reversal on the performance change for stroke subjects gave the magnitude of the change in performance after the addition of assistance/resistance. To examine the utility of the adaptive controllers, data from the exercises performed by subjects with the new Haptic TheraDrive system was analyzed. The RMS trajectory tracking error in non-adaptive mode was taken as a baseline for each subject.

D. Surveys

The surveys covered topics such as motivation, comfort, perceived safety, and degree of effort. For motivation, subjects rated their agreement with the following statements on a scale of 1 (strongly disagree) to 7 (strongly agree). These responses were categorized according to seven scales: value/usefulness, interest/enjoyment, perceived competence, effort/importance, pressure/tension, relatedness and perceived choice. Responses in each category were averaged to produce a set of motivation scores for each subject.[15] This motivation scale has been used to evaluate preferences with other rehabilitation robots.[16] Post survey questions addressed ease of use, perceived utility, perceived safety, confidence during use of robot, robot preference and strength of that preference. These results were reported as subjective data.

E. Statistics

A p-value of less than 0.05 was considered significant for all statistical tests performed. An ANOVA test was performed with the null hypothesis that measures of performance do not vary with respect to any of the three categories. In the event that the null hypothesis of the ANOVA test was rejected for any category, a t-test would be performed comparing the means within the category, with the null hypothesis that the means are equal. A t-test then compared absolute normalized change in RMS tracking errors across the two Theradrive systems to quantify impact of the non-adaptive controllers on performance.

SECTION III. Results and Discussion

A tabular description of the t-test performed can be found in Table 3, and aggregated raw data is shown in Table 2. Figures 2 and 3 show the tracking results.

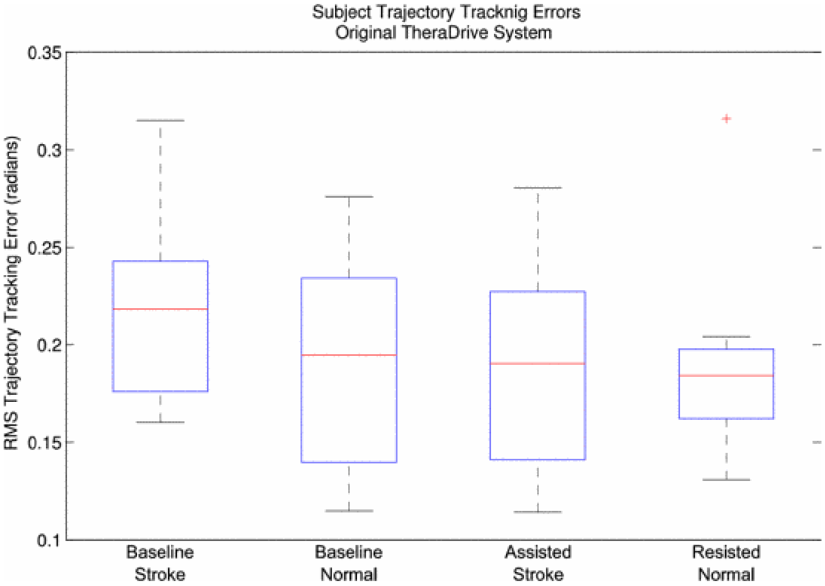


Figure 2: Quartile boxplots of raw rms tracking error of subjects with the old theradrive system. Outliers are shown as crosses.

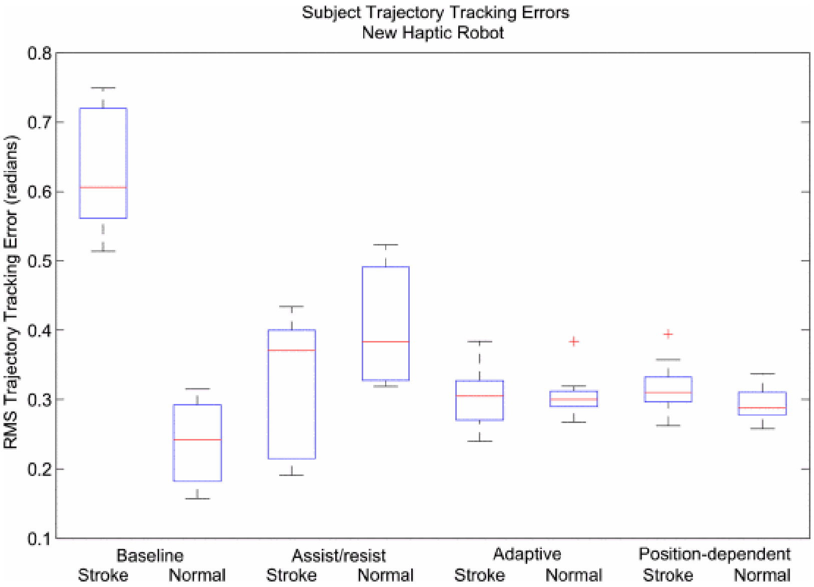


Figure 3: Rms tracking errors in haptic theradrive

A. Old Versus New Theradrive

Results of the ANOVA test confirm the null hypotheses that the *normalized* data do not vary significantly by subject (p=0.28) and that the data do not vary significantly across different trials of the same exercise (p=0.62). The first of these two results indicates that normalization was effective in removing the influence of overall subject performance, and the second result indicates that the experiment is repeatable. The ANOVA test rejects the null hypothesis that data does not vary with respect to robot mode (p<0.0001), suggesting that performance in exercises with assistance/resistance could vary between the two robots. Using a one-tailed Student's t-test, the changes in subject performance with the addition of assistance/resistance for each robot were compared, with a null hypothesis that the means were equal. The null hypothesis was rejected with a p-value of less than 0.0001, meaning that the addition of assistance/resistance with the new haptic robot causes a larger change in subject performance than the addition of assistance/resistance with the old system for all subjects in general.

B. Adaptive Control Comparison

Figure 3 shows the lowest-functioning stroke subject (05, with a Fugl-Meyer score of 29) tracking trajectories in the four operating modes of the new robot. Since the ANOVA test performed previously showed that subject performance varied between robot operating mode, t-tests could be used to compare subject performance with plain adaptive and position-dependent adaptive control to performance with non-adaptive control in exercises with the new haptic robot. A t-test showed that the RMS tracking error was significantly lower-and closer to the desired RMS error of 0.25 rad-for exercises using the plain adaptive controller versus the non-adaptive controller (p=0.026). However, t-tests did not show any significant difference (p=0.398) in performance when comparing the position-dependent adaptive controller to the plain adaptive controller. The plain adaptive controller is able to set appropriate gains for a subject more accurately, shown by the results of the first t-test in Table 3.

C. Motivation Results

Data from stroke subjects' motivation surveys is graphed in Figure 4. Motivation data collected from normal subjects was collected but not analyzed because it was deemed irrelevant in the context of motivating rehabilitation for stroke patients. For the two robots, no significant difference in motivation scores was observed, as each score for the haptic robot is within less than one standard deviation of the corresponding score for TheraDrive. Subjects performed the same tasks with each robot and viewed very similar displays, so most of the motivating features were identical across the two systems, with the exception of exercise difficulty, and scores from the motivation surveys reflected this. Additionally, the set of data was too small to produce significant results in any but the most extreme cases. When explicitly asked about their preference of robot in the final post-activity survey, all stroke subjects chose the new robot over the original TheraDrive system, despite the lack of difference in motivation scores between the two systems. Subjects commented that they liked the increased assistance and increased range of motion of the new robot. One subject liked the fact that the robot had a similar feel to an arm bike used in physical therapy. Healthy subjects did not receive the new system as well as stroke subjects. Because of the high resistive force output, healthy subjects had difficulty controlling the robot, especially when changing the direction of motion. These high forces also raised concerns about safety and caused more fatigue than was desired.

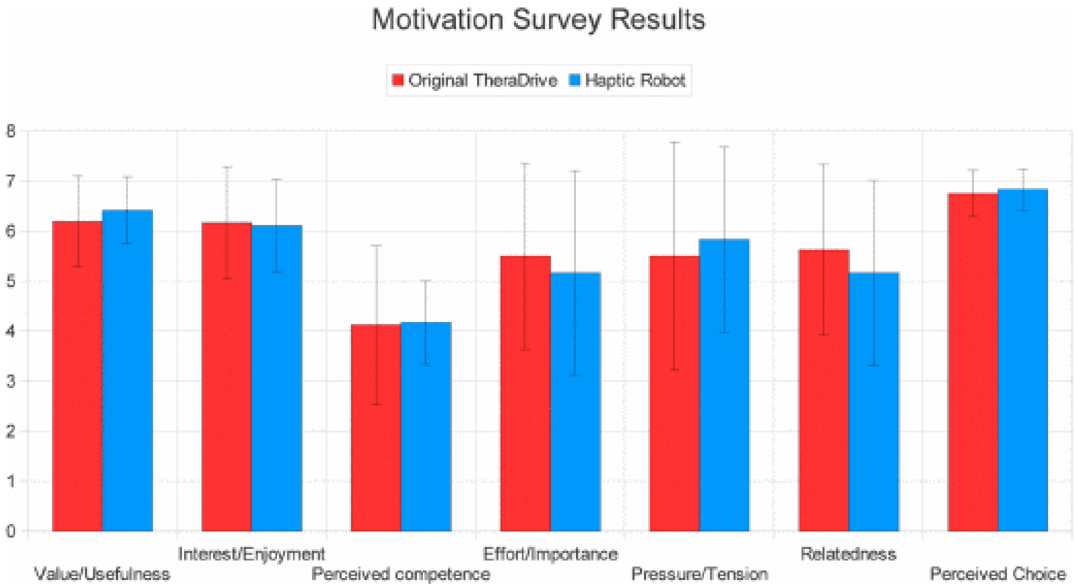


Figure 4: Motivation survey results for stroke subjects, plotted by category for each robot. Motivation is rated on a scale of 1 to 7. Standard deviation is shown by error bars.

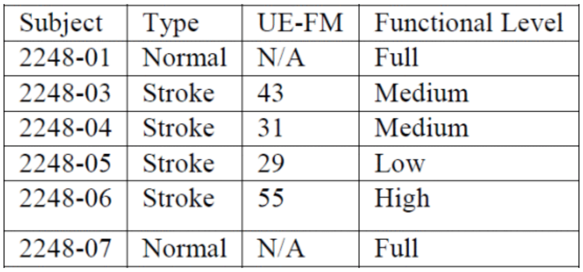
SECTION IV. Discussion and Conclusions

The assistance/resistance of the haptic robot produced a significantly larger change in performance than that of the wheel. This result was expected, as the haptic robot is able to exert 30 times the torque of the wheel, so it would follow that the haptic robot can provide more assistance or resistance. The mechanical linkage of the haptic robot provides more support to subjects-enough for low-functioning subjects to be able to complete exercises. In the baseline zero-impedance mode, the haptic robot is much more difficult for stroke-impaired subjects to move than the Logitech wheel. This can be seen when comparing the non-normalized RMS tracking error, shown in the leftmost boxes in Figures 2 and 3. The likely cause of this increase in difficulty is the larger workspace of the haptic robot, which has a crank arm radius approximately double that of the Logitech wheel. All of the stroke subjects had a reduced range of arm motion, which caused them difficulty in moving the haptic robot's crank through its full range of motion. This difference in baseline difficulty between the two robots may have influenced the results of the statistical comparison.

An adaptive controller monitors patient performance and adjusts the spring stiffness. A rationale for using the adaptive gain is the tuning process. For the non-adaptive control modes, the process of trial and error was used to determine the assistive gain for relevant exercises. This process was not an accurate way to find an appropriate controller gain, and it can be time-consuming, taking up to ten minutes. Experiments show the adaptive controller's ability to maintain difficulty of exercises after a period of initial calibration. Data showed that subject performance with the adaptive controlled robot to be closer to a desired level. Motivation surveys showed no significant difference in subject motivation between the two systems.

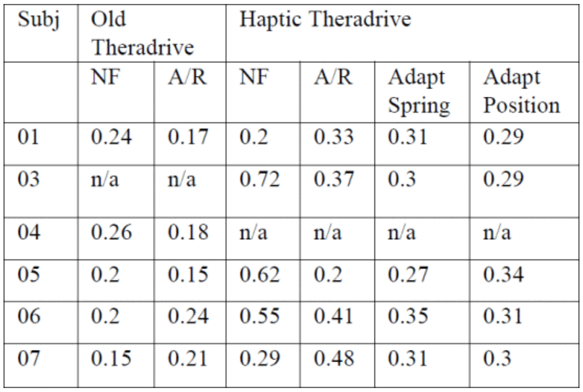
A significant source of error in the experiments performed was the small sample size. The data collected is insufficient to prove that the haptic robot is an effective therapy tool, but the successes of these preliminary experiments are enough to merit larger trials with the system, especially with lower functioning patients. In fact, the new haptic robot is a viable replacement for the commercial Logitech wheel in the TheraDrive system, for stroke subjects who require assistance to complete tasks. Stroke-impaired subjects were able to perform tasks effectively with the robot, and they showed favorable opinions of it, unanimously indicating the new haptic robot to be preferred over the original TheraDrive system. Furthermore, Experimental data show the ability of the adaptive controller to tailor the difficulty of exercises to the ability level of subjects.

Table 1: Listing of subjects with fugl-meyer scores



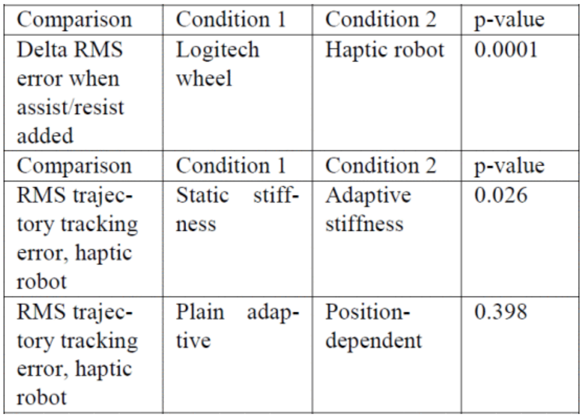
Subject	Type	UE-FM	Functional Level
2248-01	Normal	N/A	Full
2248-03	Stroke	43	Medium
2248-04	Stroke	31	Medium
2248-05	Stroke	29	Low
2248-06	Stroke	55	High
2248-07	Normal	N/A	Full

Table 2: Average RMS tracking error for subjects, sorted by robot model



Subj	Old Theradrive		Haptic Theradrive			
	NF	A/R	NF	A/R	Adapt Spring	Adapt Position
01	0.24	0.17	0.2	0.33	0.31	0.29
03	n/a	n/a	0.72	0.37	0.3	0.29
04	0.26	0.18	n/a	n/a	n/a	n/a
05	0.2	0.15	0.62	0.2	0.27	0.34
06	0.2	0.24	0.55	0.41	0.35	0.31
07	0.15	0.21	0.29	0.48	0.31	0.3

Table 3: List oft-test parameters and result



Comparison	Condition 1	Condition 2	p-value
Delta RMS error when assist/resist added	Logitech wheel	Haptic robot	0.0001
Comparison	Condition 1	Condition 2	p-value
RMS trajectory tracking error, haptic robot	Static stiffness	Adaptive stiffness	0.026
RMS trajectory tracking error, haptic robot	Plain adaptive	Position-dependent	0.398

ACKNOWLEDGMENT

We acknowledge the Clement J Zablocki Veterans Administration for supporting the Rehabilitation Robotics Research and Design Lab and the Marquette University mechatronics lab.

References

1. Heart Disease and Stroke Statistics-2012 Update: A Report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee, Circulation 2012; 125: e2-e220. doi: 10. 1161/ CIR. 0b013e31823ac046

2. Duncan PW, Zorowitz R, Bates B, Choi JY, Glasberg JJ, Graham GG, Katz RC, Lamberty K and Reker D, Management of adult stroke rehabilitation care: A clinical practice guideline. Stroke. 2005; 36; e100-e143.

3. Rijken PM and Dekker J. Clinical Experience of Rehabilitation therapists with chronic diseases: A quantitative approach. Clinical Rehabilitation 1998; 12: 143-150

4. Wood SR, Murillo N, Bach y Rita P, Leder RS, Marks JT, and Page SJ, "Motivating, game-based stroke rehabilitation: A brief report, " Topics in Stroke Rehabilitation, vol. 10, pp. 134-140, October 2003.

5. Reinkensmeyer DJ, Pang CT, Nessler J, and Painter CC, "Web-based telerehabilitation for the upper extremity after stroke, " IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 10, no. 2, pp. 102-108, 2002.

6. Masia L, Casadio M, Giannoni P, Sandini G, and Morasso P, "Performance adaptive training control strategy for recovering wrist movements in stroke patients: A preliminary, feasibility study, " Journal of Neuroengineering and Rehabilitation, vol. 6, p. 44, December 2009.

7. Johnson MJ, Van der Loos HFM, Burgar CG, Shor P, and Leifer LJ, "Experimental results using force-feedback cueing in robot-assisted stroke therapy, " IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 13, pp. 335-348, September 2005.

8. Johnson MJ, Feng X, Johnson LM, Winters JM, Potential of a suite of robot/computer-assisted motivating systems for personalized, home-Based, stroke rehabilitation J NeuroEng Rehabil 2007; 4(6) (Mar 1 open access) doi: 10. 1186/1743-0003-4-6

9. Ruparel R, Johnson MJ, Strachota E, McGuire J, and Tchekanov G, "Evaluation of the theradrive system for robot/computer assisted motivating rehabilitation after stroke, " in 31st Annual International IEEE EMBS Conference, pp. 811-814, April 2009.

10. Johnson MJ, Shakya Y, Strachota E, Ahamed SI. Low-cost monitoring of patients during unsupervised robot/computer assisted motivating stroke rehabilitation, Biomed Tech (Berl). 2011; 56(1): 5-9.

11. Feng X and Winters JM, "A pilot study evaluating use of a computerassisted neurorehabilitation platform for upper-extremity stroke assessment, " Journal of NeuroEngineering and Rehabilitation, May 2009.

12. Theriault, AR, Nagurka, ML, Johnson, MJ, "A robust wheel interface with a novel adaptive controller for computer/robot-assisted motivating rehabilitation, " in ASME International Symposium on Flexible Automation, June 2012.

13. Theriault, AR, Nagurka, ML, Johnson, MJ. Design and Development of an Affordable Haptic Robot with Force-Feedback and Compliant Actuation to Improve Therapy for Patients with Severe Hemiparesis. Transactions on Haptics. IEEE Computer Society In Press. 2014

14. Fugl-Meyer AR, The post-stroke hemiplegic patient. A method for evaluation of physical performance, Scand J Rehabilitation Med, 1975; 7: 1.

15. Birch D, Veroff J. Motivation: A Study of Action. Belmont (CA): Brooks/Cole; 1966.

16. Johnson MJ, Loureiro RV, Harwin WS, Collaborative telerehabilitation and robot-meditated therapy for home rehabilitation at home or clinic, Intel Services Robotics 2008; 1(2): 1861-2776

Citations

1. Dayo O. Adewole, Michelle J. Johnson, "A computer model of the human arm: Predictive biomechanics for the theradrive rehabilitation system", *Rehabilitation Robotics (ICORR) 2015 IEEE International Conference on*, pp. 798-803, 2015.

2. Michael Minge, Ekaterina Ivanova, Katharina Lorenz, Gesche Joost, Manfred Thüring, Jörg Krüger, "BeMobil: Developing a user-friendly and motivating telerehabilitation system for motor relearning after stroke", *Rehabilitation Robotics (ICORR) 2017 International Conference on*, pp. 870-875, 2017.

3. Ekaterina Ivanova, Jörg Krüger, Robert Steingräber, Simone Schmid, Henning Schmidt, Stefan Hesse, "Design and concept of a haptic robotic telerehabilitation system for upper limb movement training after stroke", *Rehabilitation Robotics (ICORR) 2015 IEEE International Conference on*, pp. 666-671, 2015.