Potential of a Suite of Robot/Computer-Assisted Motivating Systems for Personalized, Home-Based, Stroke Rehabilitation

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Abstract

Background: There is a need to improve semi-autonomous stroke therapy in home environments which are characterized by the low supervision by clinical experts and low extrinsic motivation. Our distributed device approach to this problem consists of an integrated suite of low-cost robotic/computer-assistive technologies driven by a novel universal access software framework called UniTherapy. Our strategy for providing extrinsic motivation, personalizing the therapy and ensuring adequate assessment is presented and evaluated.

Methods: Three experiments evaluated the potential of the suite. Conventional force-reflecting joystick, a modified joystick therapy platform (TheraJoy) and steering wheel platform (TheraDrive) were tested separately with the UniTherapy software. Stroke subjects with hemiparesis and able-bodied subjects completed tracking activities with the devices in different positions. Metrics assessed motor performance in terms of accuracy across subject groups and across device platforms and muscle activation across device position and configuration.

Results: Trends in the assessment metrics were consistent across devices with able-bodied and high functioning strokes subjects being significantly more accurate in their motor performance than low functioning subjects. Able-bodied subjects showed no significant differences in tracking metrics on different joystick devices for the same tasks but notable differences in muscle activation patterns for shoulder and elbow across different device configurations.

Conclusions: We confirm the importance of personalizing the device interface and the need for using the appropriate metrics. The results suggest that the concept of the distributed suite of systems has great potential for stroke rehabilitation. All the

devices combined would create a versatile and flexible framework for therapy. Subjects enjoyed using the devices and interacting with the software and third party games. A larger longitudinal study is still needed to evaluate these systems in the home or under-supervised environment.

Background

Stroke-induced impairments and disabilities, especially those affecting the upper extremity, often disrupt a person's ability to function independently in his or her chosen living environment [1]. Rehabilitation training of the impaired upper extremity focuses on reducing impairment and improving independent function on various daily activities (ADLs) salient to patients' real-life environments [1-4]. It is considered effective and successful if patients are able to transfer motor and functional gains seen during supervised therapy to their living environments, i.e., they are able to use their impaired arm away from therapist supervision [2-4].

Most stroke therapy environments for the upper arm, including robot-assisted ones, are not able to consistently demonstrate carryover of motor gains during upper extremity training to increased functional use of the impaired arm in under-supervised environments [5, 6]. Robotic-assisted therapy devices provide autonomous training where patients can engage in repeated and intense practice of goal-directed tasks leading to improvements in motor function [7-10]. Results of clinical trials using these systems are positive, and motor gains seen and captured by sensitive kinematic variables such as movement smoothness and movement time correlate well to clinical motor impairment scales such as the Fugl-Meyer [11] but not as well to functional ones [5].

While encouraged by the success by these approaches, there is also a need to improve the cost-to-benefit ratio of robot-assisted therapy strategies and their effectiveness in extending motor gains to ADLs and increasing the functional use of the impaired arm. These goals are challenging when considered in the context of providing autonomous stroke therapy for environments characterized by the low supervision by clinical experts, less intensive training, low extrinsic motivation, subjective assessment of outcomes, etc [4,12]. In addition, semi-autonomous training emphasizes the issues of timely monitoring and of the usability and accessibility of the system [13].

The vision of the combined Falk Neurorehabilitation Engineering Research Lab and the Rehabilitation Robotics Research and Design Lab (RRRD) for meeting these needs combines robotic therapy and tele-rehabilitation technologies with motivating rehabilitation strategies. We created an upper arm stroke therapy suite consisting of several affordable hardware platforms and a novel and customizable universal software platform. The hardware platforms include commercial force-reflecting joysticks and wheels with the custom-made platforms are UniTherapy [14], TheraDrive [15], and TheraJoy [16]. The hardware and software platforms are reconfigurable and can promote unilateral or bilateral arm movements. We use a distributed framework supports remote interactions with therapists and game-based activities for therapy and assessment. These combined systems are our low-cost, robotic and computer-assisted motivating rehabilitation (Robot/CAMR) suite.

This paper will outline our design approach as well as evidence for its potential effectiveness in stroke therapy. First, we discuss our *design strategy* for sustaining *motivation* to engage in therapy, for *personalizing* the therapy interface, and for providing objective *assessment* tools for training-induced gains. Second, we discuss example results from three experiments that were conducted to evaluate the potential of our strategies for stroke rehabilitation, in terms of the ability to distinguish across persons at different functioning levels (with a task), across devices in the suite and across device located at different positions. Our conclusions support the potential benefit of the Robot/CAMR suite for stroke rehabilitation and that the device was enjoyable to use. We confirm the importance of personalizing the device interface and configuration and of choosing the most appropriate assessment metric. RMSE differentiated between subjects on different functional levels but was limited in differentiating across devices. In contrast, upper arm muscle activations levels were able to differentiate across devices and locations. A larger study is still needed to evaluate these systems in the home or under-supervised environment.

A. Design Strategy for Sustaining Motivation

Wolf, Taub and others showed that stroke survivors often have diminished spontaneous use of their impaired arm in real world tasks and a learned bias for use of their less-affected arm [17, 18]. A brief review of the literature indicates that non use of the impaired arm may occur because of one or more scenarios (Table 1) [1-4, 17-20].

<< *INSERT TABLE 1 HERE*>>

These behaviours clearly indicate that, after stroke rehabilitation, the use of the impaired arm away from the clinic cannot be assumed. The literature offers some suggestions on how to overcome tendencies to not use the impaired arm. For example, Trombly and Ma [4, 21] discuss sustaining motivation to use the impaired arm through the use of game-based and purposeful activities (real or virtual) that tap into patients' life roles. Wolf, Taub and colleagues [22] have use of bindings on the less-affected arm combined with intense one-on-one supervision of task practice of ADLs in their forced-use and constraint-induced (CI) therapies. Lum and colleagues via an automated CI environment (AutoCITE) used real tasks and positive feedback [23] to motivate compliance in the under-supervised environment. Bach-y-Rita et al [24] and Reinkensmeyer [25] used games and simple or commercial hardware to assess and motivate arm use.

Our approach also uses commercially available, game-based activities and custom assessment activities along with tele-supported clinical interactions to create an enjoyable therapy. We attempt to tap the competitive desire to win at the games presented and by doing so, we hope to motivate them to become immersed in the game, work harder and use the arm longer. In combination, we use a familiar battery of off-the-shelf technologies for affordability, and modify them so that they can be used within a therapy environment. By doing so, we make the therapy approachable and more like everyday play. While we do not explicitly analyze the effect of this strategy we briefly discuss feedback from our users.

B. Design Strategy for Personalizing Interfaces and Protocols

Each potential patient or client has different abilities, functional needs and interests. This suggests that personalization of a prescribed therapeutic program makes sense. An emphasis on more autonomous use of robotic therapy systems makes personalization of the human-technology interface very important. There are two key components of personalized interfaces: the physical interface (e.g., location and range of operation of a handle relative to the user’s torso, and its physical capabilities) and the communication interface (e.g., software and monitor, including software support for possible alternative interface features). Each is briefly discussed.

The physical interface for most existing robotic applications consists of a single handle (or wrist cuff) that is coupled to a multi-link manipulator, in some cases with a form of passive antigravity support. Such a manipulator facilitates use of the handle/cuff within different regions of the workspace, ideally spanning a threedimensional (3D) space [5-10]. Our alternative strategy is to offer a suite of 1- and 2-degrees of freedom (DOF) low-cost physical interfaces, with each additionally able to be mounted in different parts of the arm workspace. A natural thought is that these simple devices would limit the options for therapy. However, inspection of the tasks employed by the high-end robotic systems [6] indicates that they tend not to take full advantage of the complex capabilities of these advanced robotic systems, but rather focus on using a limited subset of the arm workspace. In addition, the mechanical limitations of similar systems may be outweighed by cost reduction.

Perhaps the greater research challenge relates to what and how to personalize. In conventional therapy, therapists routinely customize and adjust the focus of therapeutic intervention, especially as a client demonstrates improvement. This suggests the importance of a training protocol that is easily (and often purposefully) varied, both in terms of use of the full “ability” workspace (including force assistance to gently expand this ability space) and of the types of tasks performed within the workspace.

There has been limited focus in stroke rehabilitation on the accessibility and personalizing of the communication interface. This may have been due to the heavy assumptions that the stroke therapy interface is not controlled by the impaired user. The literature from mobile, wheelchair and workstation rehabilitation robotics can help inform this process [26-29]. In these examples, the interface is customized for the user’s expertise level (e.g., novel, expert, and engineer), for their disability level (e.g., voice control if speech is difficult), and for the task execution level (e.g, autonomous or semi-autonomous).

In our approach, the UniTherapy platform [30] was designed to permit the personalization of the therapy via its task, device, and tele-support of the relationships between patient, therapy provider and the rehabilitation technology (shown in Fig. 1). The following outlines these relationships.

- >>***Patient*** to ***Therapy Provider Interface***: By integrating tele-conference capabilities, therapy providers can observe the patient performance remotely and interact with patients by audio, video, and text messages and thus a therapy provider can adjust the intervention protocols based on observation with the hypothesis that more frequent and timely assessments will optimize the intervention outcome.
- >>***Rehabilitation System*** to ***Therapy Provider Interface***: Therapy providers can design "tailored" goal-directed tasks for their patient based on their capability and can later update the tasks based on the progress Design templates allow the therapy provider to design individual tasks. A utility called "task design wizard" provides questions to aid in the design of simple tasks. This allows the therapy provider to participate in the rehabilitation process more actively.
- >>***Patient*** to ***Rehabilitation System Interface***: UniTherapy supports therapeutic devices ranging from standard force-feedback joystick, or driving wheels to customized third-party devices such as TheraDrive and TheraJoy discussed in subsequent sections, with the goal-directed task being able to be mapped between a subject's capability space and device workspace so that most tasks can be guaranteed to be accomplished. Compliant with ANSI INCITS 389-393 standard [31], it allows user to interact with the system by personal assistance device (e.g. PocketPC) with user interfaces to be generated automatically based on user preferences and capabilities [32].

<< *INSERT FIGURE1 HERE*>>

C. Design Strategy for Assessing Functional Outcomes

Assessment is a critical component which is important both for the evaluation of human performance so as to support an optimized therapeutic process, and as a key motivational tool. The provision of these assessment tools is fundamental to most robot-assisted stroke therapy systems [8, 9, 33]. The ability to provide an objective assessment of therapeutic outcomes is a feature that therapists require from these systems [34, 35]. Assessment metrics have also been used as an online measure to provide performance feedback during or immediately following a task trial. These types of feedback are especially important in semi-autonomous or autonomous training, because they serve as extrinsic motivators for performance. For example, Lum and colleagues [23] display performance means and provide verbal encouragement such as “Wow!” via AutoCITE.

Goal-directed tasks with the affected limb in stroke subjects are typically characterized by decreased range of motion (ROM), movement speed, smoothness and coordination, and abnormal pattern of muscle activation [36]. This suggests that the form of assessment tasks should be varied and be able to be customized to target the individual subject’s motor deficit. Our approach via UniTherapy implements four toolboxes consisting of customizable assessment tasks to evaluate different aspects of motor performance and commercial games as fun therapy tools to provide encouragement and feedback:

- The *ROM toolbox* can be used to assess the user’s initial and final capability ROM when using an input device and optionally used to map between the input device workspace range and the user's capability range by a 2D transformation algorithm [14].

- The *tracking toolbox* implements discrete tracking and continuous tracking. Discrete tracking requires the subject to move a cursor into a target window as quick as they can and stabilize before the target jumps. Continuous tracking instructs subjects to follow the continuously moving target and minimize the tracking error as much as possible.
- The users' stable motor performance is also evaluated using the *System Identification toolbox*. Predefined force perturbations are applied to the subject under a certain instruction (e.g., "hold," "relax"). The force data and experimenter's instruction are recorded as input while subject's movement data is recorded as output.
- The *Fun toolbox* contains third-party computer game programs that can be integrated into the framework with the system collecting input device signals without affecting the game performance at the front end. A collection of simple arcade games (e.g. several card and poker games, driving games, Pong, Pac-man) are current examples of fun therapy tools being used.

By reviewing literatures and developing specific metrics for assessment toolbox and fun therapy tools in UniTherapy, a number of performance metrics examining accuracy [36, 37, 38], smoothness [33], quickness [33, 36], stability, motivation [40], strength [39], and so on have been developed (see Table 2) with the goal being to assess treatment changes due to the devices and subjects and monitor training intensity and motivation.

<< *INSERT TABLE 2 HERE* >>

Methods

In this section, we describe the set-up and protocols used in three separate experiments, which evaluated the Robot/CAMR Suite concept for different sets of hardware systems with the UniTherapy software customized to accommodate 1-dimensional (wheel) and 2-dimensional (joystick) systems.

A. UniTherapy Software

We utilize UniTherapy in three separate experiments with Joystick (SideWinder from Microsoft) and wheel force-reflecting technology (Logitech) along with two custom-made therapy platforms, TheraJoy (adapted joystick) and TheraDrive (steering wheel). UniTherapy applied none or varying levels of force-feedback to these devices, depending on the settings and the task; these were programmed for a series of passive force effects such as a virtual spring and damper, or active force perturbations such as sinusoid or random. These effects were experienced as assistance or resistance during tasks. Position and force data were collected at 33Hz.

The toolboxes were also customized for each device. The joystick systems used mainly the tracking tasks in rectangular coordinates with both x- and y-direction under the user control. The fun therapy toolbox consisted of third-party games such as solitaire and Pac-man. The wheel systems used both polar and rectangular coordinates for the tracking tasks. The angle of movement and only the x-direction was under user control. The fun toolbox here consisted of two off-the-shelf driving games, SmartDriver and Trackmania.

B. Robot/CAMR Hardware Suite

Commercial Joysticks and TheraJoy: Joystick systems consisted of the TheraJoy and conventional force-feedback joysticks with the UniTherapy software. Figure 2a-c shows the current version of the TheraJoy System along with the conventional joystick.

<< *INSERT FIGURE 2 HERE*>>

The TheraJoy system expands the length of a conventional joystick (Microsoft) shaft to nearly one meter with a resting position near the waist of the user. This system incorporates a larger range of motion that can be scaled and modified depending on the anthropometrics and abilities of the user. Pneumatic springs were added to the system to add passive resistance and to compensate for an inverse pendulum effect. A linkage system was added to the extended shaft to incorporate vertical planar motions that are more common to activities of daily living; the system allows vertical movement of the arm expressed as horizontal translation of the joystick. The linkage connects to the shaft of the joystick with a ball and socket joint, and at the sliding shaft with a combination sliding and pin joint. An additional horizontally placed support spring compensates for the effects of gravity, inertia, and joint friction inherent in the system. The system is accessible to wheelchairs, and patients with varying levels of arm range of motion and hand function.

Commercial Driving wheels via TheraDrive: Experiments were conducted using the TheraDrive interfaced with the UniTherapy software. Figure 3 shows the TheraDrive System in two steering configurations.

<< *INSERT FIGURE 3 HERE*>>

TheraDrive is a custom steering environment. One or two force-reflecting wheels (Logitech) can be mounted on the front or side rails of a height-adjustable platform and tilted from 0 to 90 degrees. The platform accommodates wheelchairs and supports front and side unilateral driving and bilateral front steering at any wheel angle. The tilt angle and optional mounting is facilitated by special mounts that uses pin joints to rotate the wheel and tubular clamps to mount wheels to the front or side rails. A special gripper (Mobility Systems) is mounted onto the wheel to ensure the consistent transfer of tangential forces during steering movement. All subjects had to steer while holding onto the gripper. The gripper can be sensorized to measure grip forces and tangential forces during movement.

C. Hypotheses

Three experimental protocols (EP1-EP3) were implemented. We examined three hypotheses: **hypothesis 1)** Performance metrics derived tracking activities with a device are sensitive to the functional level of subjects (EP1 and EP2), **hypothesis 2)** Device settings influence the performance of human subjects in goal-directed tasks (EP1 and EP2), **hypothesis 3)** Device position and configuration influence the muscle activation patterns of subjects for shoulder and arm and therefore potentially, therapeutic prescription and benefits (EP3).

D. Procedures

Experimental protocols EP1 and EP3 involved evaluating UniTherapy system customized for the conventional joystick and TheraJoy system. These studies were approved by the Institutional Review Board at Marquette University. Experimental protocol EP2 involved evaluating UniTherapy system customized for force-feedback steering wheel and the TheraDrive system. This study was approved by the Institutional Review Boards at the Clement J. Zablocki VA and Marquette University.

Stroke subjects with hemiplegia and able-bodied (Control) subjects participated in these protocols and gave informed consent. Table 3 summarizes the subjects used in each experiment. All stroke survivors were at least six months post-stroke and had been discharged from all forms of physical rehabilitation. All experiments included at least the upper extremity motor control portion of the Fugl-Meyer (UE F-M) assessment test as a tool to assess level of motor impairment of stroke survivors. This test is used to partition stroke survivors into a high and low functioning level. All subjects gave informed on consent.

<<*INSERT TABLE 3 HERE*>

Joysticks' Experimental Procedure #1 (EP1) – Assessment of Performance:

This experiment aimed to evaluate the usability of the conventional joysticks and the TheraJoy system with UniTherapy. The experimental protocol consisted of two sessions focusing first on training the individual on using each device (conventional joystick (CJS) and TheraJoy in horizontal (HJS) and vertical (VJS) configurations), then on collecting performance and EMG data on a suite of goal-directed assessment tasks.

First session: All joysticks were placed in the position of greatest comfort for the subject, including altered handle position and interface to allow for maximum comfort. Stroke subjects were then evaluated using the ROM toolbox. A test was completed with each of the devices. All subjects then completed several tasks from the Tracking and System Identification toolbox with the conventional joystick. Some tasks were completed under various force filed only for conventional joystick. Some tasks were then repeated with the horizontal and then vertical TheraJoy. All tasks were repeated with both arms. After, they completed a game of Solitaire from the Fun Therapy Toolbox using only the conventional joystick. To complete the first day of testing, the subject was introduced to tele-health technology using IP videoconferencing as a part of the UniTherapy software (not discussed here).

Second session: In the second day of testing the tasks were repeated but this time both video and EMG data were also collected. Video data was collected using the Mobile Usability Lab (MU-Lab) [42] and EMG data was collected on eight shoulder and arm muscles (Motion Lab Systems, Inc). Usability Surveys were given at the end of the second session to determine the prospective use of the system in the subject's home and their impression of the UniTherapy software and TheraJoy hardware.

Wheels' Experimental Procedure #2 (EP2) – Assessment of Performance:

The experimental protocol also consisted of two sessions as in EP1, with Day 1 focused on training and Day 2 on collecting a variety of tracking tasks. This study was conducted to evaluate the usability of the TheraDrive system with UniTherapy.

To complete the tracking tasks in both Day 1 and Day 2, the wheel was either attached to the front or to the side of the hardware frame and the height was positioned to be comfortable. The wheel was used at a tilt angle of 20 degrees (for normal drive) and 90 degrees (for bus driver mode) (see fig. 4). Subjects held onto the gripper to complete a variety of tracking tasks. The tasks were also completed with or without force feedback and with either the impaired arm, unimpaired arm, or both. At the end of both days, subjects played the third-party driving games. Surveys were given at the beginning and end of the sessions to determine the prospective use of the system in the subject's home and their impression of the driving games. Position and video data was collected on both days while EMG data on seven upper arm muscles were only collected only for day 2. Again as in EP1, the EMG and video data is not analyzed here and only representative tracking data are analyzed in the results section.

Representative Tracking Tasks Analyzed in EP1 and EP2: The EP1 and EP2 protocols were purposely designed to overlap in a subset of tracking tasks so that human subject performance on various therapeutic interfaces. The representative results from continuous pseudo-random sinusoidal tracking will be presented here. It is important to note that the joystick tasks required the users to control the motion in TWO directions (both x and y) while the steering wheel task required the subject to control the task in only ONE direction (x) with the y-direction position of the subject automatically set to the y-direction position of the target.

Continuous Pseudo-Random Sinusoidal Tracking: Subjects in both protocols were asked to complete continuous pseudo-random tracking (which is generated by overlapping three various frequency (1HZ, 2HZ and 3HZ) sinusoid curve) where they were asked to move the wheel or joystick to keep pace with the square box as it moves in a x-direction in a pseudo-random sine pattern; the overlapped sinusoidal curve were shown to human subject as a preview. Figure 4 shows this task along with a representative look at the x-direction motion for the wheel. For the joystick tasks, while human subjects were instructed to control the joystick in both directions to get into the target window, the program only counts x-direction data as success criteria.

<< INSERT FIGURE 4 HERE>>

Experimental Procedure #3 (EP3) – Assessment of Postural Effects: Each device was anthropometrically positioned in 3-5 locations throughout the arm workspace (i.e. close to the body, far from the body, neutral to the shoulder, neutral to the sternum, etc.). The study was conducted to evaluate the EMG activity of key shoulder and arm muscles and movement paths while using a conventional joystick and the TheraJoy in both the horizontal and vertical configurations, each within multiple areas of the arm workspace.

For a given device position, two discrete tracking tasks were designed to encompass each device workspace by having the subject track eight points on a rectangle and on a circular starburst (center target in a circle of targets at every 45 deg angle), three times in each direction. Subjects were asked to complete the tasks as quickly and accurately as possible. Data collected included tracking data via the joystick port, EMG activity (Motion Lab Systems, Inc.) of eight muscle groups (anterior deltoid, posterior deltoid, latissimus dorsi, pectoralis major, biceps, triceps, and forearm flexor and extensor groups), and three views of video using the MU-Lab system.

E. Data and Statistical Analysis

The data was analyzed across subjects within the same experiments. For analysis, stroke survivors were partitioned according to their motor impairment levels, High (FM > 57) and Low (FM <= 57).

EP1 and EP2 tasks data and statistical analysis: The pseudo-random sinusoidal tracking was analyzed across subjects within joystick and wheel tasks using the Percentage Time on Target (PTT) and RMSE metric (Table 2). The data have been analyzed with the special attention paid to validate hypothesis 1 and 2. Mean and standard deviation value are calculated and presented in graph for control (n=8), high function (n=5) and low function group (n=4) in joystick settings and high function (n=4) and low function group (n=3) in wheel settings. Non-parametric statistical tests including Mann-Whitney test (equivalent to t-test to compare 2 sample groups) and Kruskal Wallis test (equivalent to one-way ANOVA to compare multiple groups) have been used. A significance threshold level of $p < 0.05$ was used for interpretation.

EMG Processing and Analysis: While a wide variety of data were collected during the TheraJoy positioning study, the focus of analysis here is on EMG. Each EMG file passed through standard signal processing techniques including a filter to remove the average signal value and remove any signal offset, a high pass filter Butterworth filter with a corner frequency of 60 Hz to remove noise in the signal due to cardiac muscle, and an RMS low-pass filter (window length=.15, window overlap=.075). Upon completion of all tasks for a given subject the overall maximum RMS value was used to scale each EMG. All RMS data was then passed through a threshold filter and binned in one of 8 bins according to a proportion of the greatest value observed for each subject and each muscle (cutoffs 85%, 70%, 55%, 40%, 25%, 10%, 5%). The data have been analyzed with the special attention paid to validate **hypothesis 3.** Trends are described.

Results

A. Hypothesis 1 and 2: Sensitivity of Metrics across Subjects and Devices

Figure 5 shows Percentage Time on Target (PTT) for the joysticks and wheel across the EP1 and EP2 groups for the continuous tracking tasks. The results on the PTT show that controls and high functioning stroke subjects had a tendency to be more accurate and stable than low functioning subjects. There was a significant difference between control and low function group in joystick settings (p=0.0283) and a strong trend indicated difference between high function and low function group in wheel settings (p = 0.114: low function group has lower PTT in both cases.

<< *INSERT FIG. 5 HERE*>>

Figure 6 shows the normalized root mean square errors (RMSE) for the joysticks and wheel across the EP1 and EP2 groups for the continuous tracking tasks. The results on the RMSE show that controls and high functioning stroke subjects had a tendency to be more accurate than low functioning subjects. There was a significant difference both among control, high function and low function group (p = 0.008) in joystick setting and between high function and low function group in wheel settings (p = 0.11): low function group has higher RMSE in both cases. There was a trend observed that low function group subjects using conventional joystick had a bigger RMSE than low function group using driving wheel. In addition the results suggest a possible sensitivity to device complexity. Having to control 1-D versus 2-D may have made a difference in tracking performance in the low functioning subjects in that low stroke in EP1 were lower functioning than in EP2.

<< *INSERT FIG. 6 HERE*>>

Figure 7 shows the normalized RMS errors across joysticks types for the EP1 control group for the continuous tracking task. For this task, there was no statistical difference on the RMSE among using three various joysticks when control subjects performing pseudo-sinusoidal tracking task (p = 0.677). No significant differences were found across these three devices for the control subjects. This suggests that the RMS error was not sensitive to the differences in the joystick devices.

<< INSERT FIG. 7 HERE>>

A. Hypothesis 3: Effects of Device and Device Location on EMGs for EP3

Overall EMG results show that not only does each device target different muscle groups, but also that changing the position of the device relative to the shoulder also alters control strategies. A general tendency was for all muscles to display increased average activity from the conventional joystick to the horizontal TheraJoy and then again to the vertical TheraJoy. For the horizontal TheraJoy, Figure 8 (A) displays a representation of the muscle activity observed during both clockwise and counter clockwise rotations of the rectangle tracking pattern. This is a representation of average muscle activity across all positions. The anterior deltoid and pectoralis major act synergistically as prime agonists for clockwise movements in the left region and counterclockwise movements of the right region of rectangular movements, suggesting that these muscles are *direction* dependent within certain *regions* of the workspace, being an agonist for certain movement directions and a passive antagonist for the opposite direction.

<< INSERT FIG. 8 HERE>>

Muscle adjustments to the figure above occur when the device is positioned in different parts of the arm workshop. For instance, when positioned close to the body and neutral to the shoulder, the latissimus dorsi is used as an agonist to internally rotate the arm to complete movements. When the device is closer to the body, the posterior deltoid has increased activity to complete movements by extending the shoulder. When positioned further from the body, the triceps takes over and is able to extend the elbow.

The vertical TheraJoy shows overall increased muscle activity, especially in the anterior deltoid, latissimus dorsi and biceps. Figure 12 below displays a representation of the muscle activity observed during both clockwise and counterclockwise rotations of the rectangle tracking pattern for the vertical TheraJoy In evaluating movements in opposite directions within the same workspace, it is clear that anterior deltoid is especially necessary to hold positions where the arm is elevated at or above the shoulder height, specifically when the device is positioned across the body with a neutral position in line with the sternum. During movements in this workspace subjects spent at least 17% of each movement with medium levels of EMG activity. In contrast, during activities in the lower region of the workspace, the anterior deltoid is off during at least 49% of each movement.

The latissimus dorsi is very important to use of this device, particularly during use in the neutral position. This muscle shows a considerable spread of activity during movements with the highest activity, suggesting considerable use for both initiating and correcting ongoing movements. Activity is highest during motions that are above shoulder height regardless of direction, probably related to this muscle working as a stabilizer in conjunction with other muscles of the shoulder complex. Activity is the lowest during movements that release the arm back to a resting position, again regardless of direction, and the position of the arm here is such that to complete such movements, the shoulder horizontally flexes, thus the importance of the pectoralis major.

These results suggest that each device uses different muscle control strategies even for the same screen task, including both the use of different muscle groups and different magnitudes of each muscle. This affects exercise prescription. For instance, to promote agonist anterior deltoid activity, the horizontal and/or vertical TheraJoy would be recommended, assuming that the client is able to move for a reasonable range of motion within these workspaces.

Discussion

Our results support the potential benefit of the Robot/CAMR suite for stroke rehabilitation. Despite a small data sets across the experiments analyzed, we were able to confirm the importance of personalizing the device interface and configuration and the usefulness of assessment metric and muscle activation levels in distinguishing between subjects on different functional levels.

Three experiments evaluated the potential of the suite using the toolboxes and strategies outlined. We hypothesized that assessment metrics can distinguish between motor performances of subjects with different functional levels (on the same task). We found that our PTT and normalized RSME metric could detect differences in accuracy across low and control/high functioning subjects on a continuous tracking task. Low-medium functioning stroke subjects performed significantly worse than able-bodied and high functioning stroke survivors for joysticks and close to significantly different on the wheel (Fig. 5 and Fig. 6). Trends in this assessment metric were consistent across devices (Fig. 7).These results were consistent with the other published data [36, 37], were for this type of tracking task, RMS error were found to sensitive to the functional level of persons with brain injury and stroke. Although not presented here, we tested the sensitivity of other metrics (e.g.

smoothness (Peak Speed Number), curvature (Deviation), quickness (Movement Time)) in our battery (see table 2) and showed that these metrics were also able to detect differences in functional levels. Low functioning subjects moved slower and less smooth than higher functioning subjects. These results agreed with other published data [33, 36-39, 41].

We hypothesized that assessment metrics can distinguish between motor performances of the same subjects using different devices. We tested the three joysticks (CJS, VJS, and HJS in EP1) with controls. Control subjects showed no difference in tracking metrics on different joystick devices for the same tasks. We expected these differences because each device required different postures for use. CJS was a desktop device and mainly used the forearm while VJS and HJS required larger ROMs than CJS and movements on different planes (horizontal versus vertical). The results from experiment EP3 also suggest that there should have been a difference. It showed that across VJS and HJS for tracking on a similar task, there were large differences in muscle activation patterns and strategies for shoulder and elbow configurations. The lack of difference could be due to the fact that the RMSE metric was not sensitive enough to the differences or that the mapping of the ROMs for the device to the task diminished the effect of the differences on motor performance. The first reason may be more likely when considered against the published results from Johnson and colleagues [16], which showed that movement time was significantly different for each device. Further investigations would be needed to exclude the second reason. This suggests that it is important that the most appropriate metric be chosen for analyzing motor performance across the workspace.

Finally, we hypothesized that device position and device configuration influence muscle activation patterns and control strategies for shoulder and elbow.

The results from EP3 showed that different devices (VJS and HJS) utilized different muscle combinations and control strategies during tracking tasks and for a given location. Within these devices, the direction of the movement was also important with movements toward the lateral edge of the workspace increasing muscle activity. As an example, neutral positions of HJS are lead to higher posterior deltoid activity, occurring in medial regions of the workspace. The position of the device was also important. Muscles such as pectoralis major, latissimus dorsi, and biceps were sensitive to device position. The CJS, for example, could best be used in regions other than the neutral location (i.e. close to the body, far from the body, or across the body). These results from EP 3 indicate that device type and its relative location within the arm workspace plays a significant key role in the muscle-level control strategies and will affect the effectiveness of therapy with the Robot/CAMR device suite.

Although not explicitly analyzed, our surveys indicated that most participants with stroke-induced impairment found the devices very enjoyable to use, and commented to investigators that although they did not frequently use a computer, if given the opportunity to use these devices their level of use may increase. The subjects enjoyed using the third party software such as Pacman (EP1) and SmartDriver (EP2) and were motivated to play to increase their game score. All were satisfied with the technology, operability and comfort of the system. Most responded positively to the questions asking if they would use the system frequently and if they would use the system in their home.

In summary, the results suggest the different tracking tasks, different location and different devices are needed to create therapeutic flexibility and a stroke therapy environment that is flexible. The challenge here is in identifying the optimum combination for subjects and creating a seamless mapping between these settings and the user disability and therapeutic needs. Further research is needed.

The main limitations of our study were in the small sample size and that our subject population across devices weren’t always the same. We believe that our results were adequately supported by other published work and suggest that the concept of the distributed suite of systems has great potential for stroke rehabilitation. All the devices combined would create a versatile and flexible framework for therapy. A larger longitudinal study is still needed to evaluate these systems in the home or under-supervised environment.

Conclusions

There is a need to improve the cost-to-benefit ratio of robot-assisted therapy strategies and their effectiveness for stroke therapy in home environments characterized by the low supervision by clinical experts and low extrinsic motivation. Our distributed device approach to this problem consisted of an integrated suite of low-cost robotic/computer-assistive technologies driven by a novel software framework. Our strategy for sustaining motivation, personalizing the therapy and ensuring adequate assessment was presented. We validated the potential of the concept via three experiments. The results support the fact that the choice of a task, metric, the device and its placement in the workspace with respect to the user must be wisely chosen and personalized to fit the therapeutic needs of the individual. It also supports the usability of using the low-cost mass-marketed devices in goal-directed performance assessment: the result which shows significant difference between low function and control/high function subjects agreed with the published data and demonstrated the usefulness of our platform. Although not explicitly analyzed, these results apply to the steering wheel and conventional joysticks and suggest that their placement for task practice should be carefully considered. More research is needed here to characterize the devices in the suite in terms of locations that may optimize the use of muscles such as the triceps that are typically weaker after stroke. Our survey results indicated the receptivity of stroke subjects and therapists to the systems. They had fun using it.

An IRB study has been proposed and submitted to Marquette University with the aim of investigating the influence of personalized interface and protocol on the outcome of performance assessment and therapeutic intervention. Our hypothesis is that personalized rehabilitation, same as other form of personalized medicine, will optimize the rehab process and thus benefit the patient. A larger longitudinal study is still needed to evaluate these systems in the home or under-supervised environment and to determine how well these results can be generalized.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

LMJ, and XF were involved in all stages of subject recruitment and data acquisition. MJJ and XF were the primary composers of the manuscript with major contributions LMJ and JM. JM generated the initial concept for TheraJoy studies and oversaw their progress while MJJ generated the initial concepts for TheraDrive studies and oversaw their progress. LMJ and JM designed and built the TheraJoy hardware. MJJ designed and built the TheraDrive hardware with the assistance of colleagues at the Clement J. Zablocki VA. XF and JM designed and built the software robotic devices used for training with assessment metrics with some input LMJ, and MJJ. All authors contributed significantly to the intellectual content of the manuscript and have given final approval of the version to be published.

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Figures

Figure 1 - Therapy Interactions

Use Cases of Rehabilitation System under Motivation Therapy context: Rehabilitation system provides goal-directed assessment and therapeutic intervention to patient; therapy providers interacted with patients and observe their performance; based on the observation, therapy providers optimize their therapy plan with the assistance by rehabilitation system.

Figure 2 – Joystick Systems

Conventional Joystick (a) and TheraJoy version 3: Horizontal (bt) and Vertical (c)
The vertical linkage system attaches to the horizontal joystick with a ball and socket joint, and a fixed vertical post with a pin and sliding joint

Figure 3 - TheraDrive System for home-based rehabilitation.

This figure shows the driving wheels mounted in front and side configurations with the subject holding onto a v-gripper.

Figure 4 – Representative continuous tracking task

The screen shot shows the pseudo-random sinusoid task that the subject tried to complete and the average of three trials of a subject from EP2 study when he performed the pseudo-random tracking task and the desired movement.

Figure 5 –Percentage Time on Target (PTT) for continuous tracking for CJS and TheraDrive wheel

This figure shows PTT for continuous tracking on the conventional joystick (a) and wheel (b) for control, high function and low function groups. For joystick settings, control group PTT = 48.89 +/- 9.60, high function group PTT = 35.45 +/- 18.02, low function group PTT = 25.83 +/-18.25; for wheel settings, high function group PTT = 25.83 +/- 18.25, low function group PTT = 19.72 +/- 8.04.

Figure 6 –RMSE for continuous tracking for CJS and TheraDrive wheel

This figure shows RMSE for continuous tracking on the conventional joystick (a) and wheel (b) for control, high function and low function groups. The RMSE is normalized to percentage of the workspace. For joystick settings, control group RMSE = 3.99 +/- 0.67, high function group RMSE = 6.05 +/- 1.80, low function group RMSE = 19.05 +/-18.12; for wheel settings, high function group RMSE = 5.81 +/- 1.64, low function group RMSE = 11.31 +/- 3.86.

Figure 7 –RMSE for continuous tracking across joystick devices

This figure shows RMSE for continuous tracking for the control subjects in EP 1 across the conventional joystick (CJS), the horizontal joystick (HJS) and the vertical joystick (VJS). Note: CJS: Conventional Joystick RMSE= 3.99 +/- 0.67; HJS: Horizontal Joystick RMSE = 4.21 +/- 0.44; VJS: Vertical Joystick RMSE = 4.32 +/- 0.81.

Figure 8 – Muscle control strategy shifts for rectangle task for HJS and VJS

A: shows a representation of control strategy shifts throughout the rectangle task, for horizontal TheraJoy. Solid arrows indicate agonist or high activity, dashed lines indicate antagonist or notably low activity relative to typical levels. Muscles of interest here include anterior deltoid (AD), posterior deltoid (PD), pectoralis major (PM), latissimus dorsi (LD), biceps (BIC), and triceps (TRI).

B: shows a representation of control strategy shifts throughout the rectangle task, for vertical TheraJoy. Solid arrows indicate agonist or high activity, dashed lines indicate antagonist or notably low activity relative to typical levels. Muscles of interest here include anterior deltoid (AD), posterior deltoid (PD), pectoralis major (PM), and latissimus dorsi (LD).

Tables

Table 1 - Summary of common scenarios leading to decreased impaired arm involvement during real life

	GENERAL CASES	SCENARIOS
1	The immediate rewards of engaging in compensatory behaviors are more apparent and achievable than for engaging restorative behaviors	Patient becomes confused and feels encouraged to engage in both compensatory activities and restorative behaviors. Patient becomes satisfied with the level of independence attained either through caregivers (proxy control) or through the compensatory strategies.
2	The effort (or cost) to engage in restorative behaviors is beyond their ability.	Patient stops using the impaired arm due to the frustration encountered during attempts to use the arm. The effort to engage in restorative behavior is prohibitive and therefore achieving bilateral arm use is perceived as an unrealistic goal. Patient perceives that the activities are too challenging and therefore impossible to achieve or too easy and therefore irrelevant. Patient loses range of motion, muscle strength, dexterity and other motor abilities due to factors such as abnormal muscle activation and force generation. Patient loses sensory feedback in the impaired limb. Patient has a frontal lobe lesion and diminished motivation.
3	The effort to engage in restorative behaviors is not seen as resulting in getting their perceived needs met.	Patient perceives that continuing in rehabilitation is unproductive because it will not help in regaining previous roles in life.
4	The reasons (or incentives) given to encourage them to engage in restorative behaviors are not sufficient.	Patient believes their discharge from the hospital signals the end of recovery and believes the standard predictions that there is minimal to no recovery after 6 months. Patient loses the ability to focus on treatment activities because of neurological deficits and must be reminded to do it.

Table 2 - Summary of selected performance metrics used in assessment tasks and fun therapy tool [41]

Assessment Category	**Metric Name**	**Definition**	**Remark**
Range of Motion (ROM)	ROM Area Ratio	The ratio of the area size of user capability space to the input device work space.	Reflects the user's ***Movement Range*** in the range [0, 1]; ideally this value should be close to 1.
Discrete Tracking	Reaction Time	The time from the jump of the target to the first significant movement by subject.	Reflects the human machine system response Capability (***Reaction quickness***).
	Movement Time	The time between the end of the reaction time to the time after the human subject stayed within the target stably.	Reflects the ***Movement Quickness***.
	Movement Speed	Derived from the movement time movement speed is the average speed within the movement time window.	Reflects the ***Movement Quickness*** in the movement time window.
	Error	The average error from the target position to the subject position.	Reflects overall performance ***Accuracy***.
	Deviation	The average deviation error from the straight target path.	Reflects ***Movement Curvature***. This metric is for Joystick only.
	Peak Speed Number	The number of peak speed in the speed profile within the movement time window.	Fewer *PN* represent fewer periods of acceleration and deceleration, making a more ***Smoothness*** movement.
	Dwelling Percentage Time in Target	Defined as the percentage of time subject staying in the target during the dwell window period.	The metric is in the range [0, 1]; ideally this value should be close to 1.The higher value indicates a better ***Stability*** performance.
Continuous Tracking	Percentage Time on Target	The percentage time the human subject staying within the target	Reflects overall performance ***Accuracy*** and ***Stability***.
	Root Mean Square Error	The squared root of the mean-squared error	Reflects movement ***Accuracy***.
	Average Deviation	The average deviation error from the straight target path.	Reflects ***Movement Curvature***. This metric is for Joystick only.
System Identification	Perturbation Range	The movement range of the human subject in the perturbation direction.	Depends on the instruction to human subject. In case "holding" instruction, the bigger value indicates weak ***Strength***; in case "relax" instruction, the bigger value indicates less ***Muscle Stiffness***.
	Perturbation Standard Deviation	The standard deviation value of the human subject position in the perturbation direction.	
Fun Therapy	ROM Intensity Image	The human subject ROM movement image with the high intensity indicates intensive human movement area.	Reflects ***Movement Range and Intensity*** without overwhelming with movement data when task context is unknown.
	Motivation Score	used as a multidimensional assessment tool to evaluate subjects' subjective experience related to a target activity in laboratory experiments	Reflects ***Motivation***

Table 3 – Subjects for EP1, EP2 and EP3

Protocol	Subjects Group	Male	Female	Age	UE FM
EP1 (Joysticks)	Able-Bodied	4	4	21-43	N/A
	Stroke-Induced Arm Impairment	3	6	33-76	Low (22-57): 4 High (58-66): 5
EP2 (TheraDrive)	Stroke-Induced Arm Impairment	5	2	55-62	Low (24-56): 3 High (58-66): 4
EP3 (Posture Study)	Able-Bodied	6	6	22-62	N/A

UE FM—Upper Extremity Fugl-Meyer.

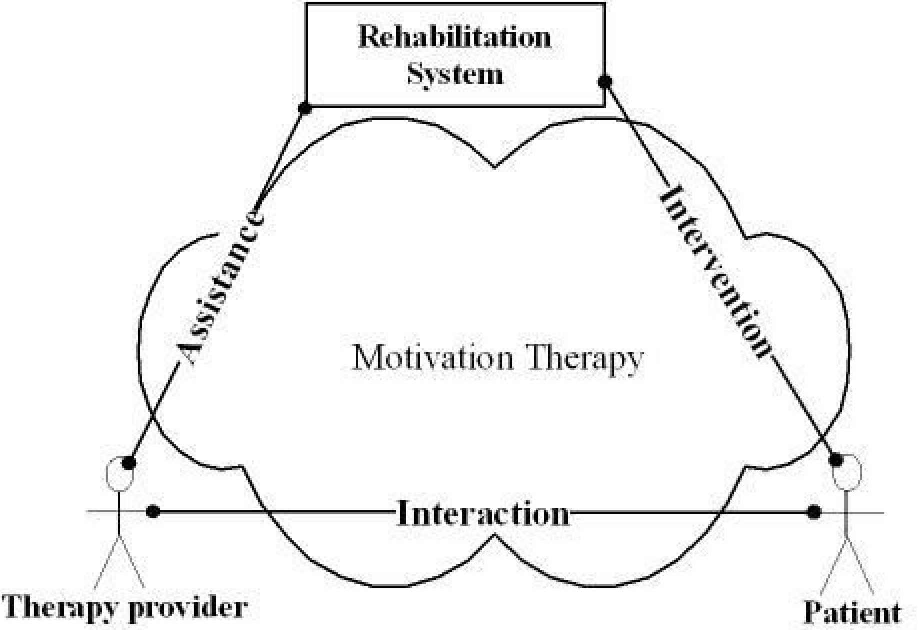

Rehabilitation System
Assistance
Intervention
Motivation Therapy
Interaction
Therapy provider
Patient

Figure 1

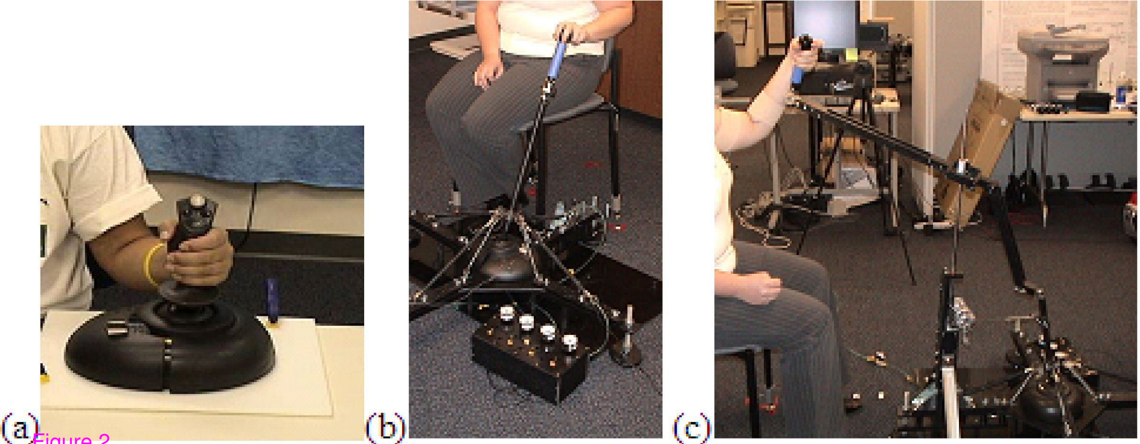


Figure 2


Wheel mounted for Side Drive
Wheel mounted for Front Drive
V-Grip
Display
Steering wheel

Figure 3

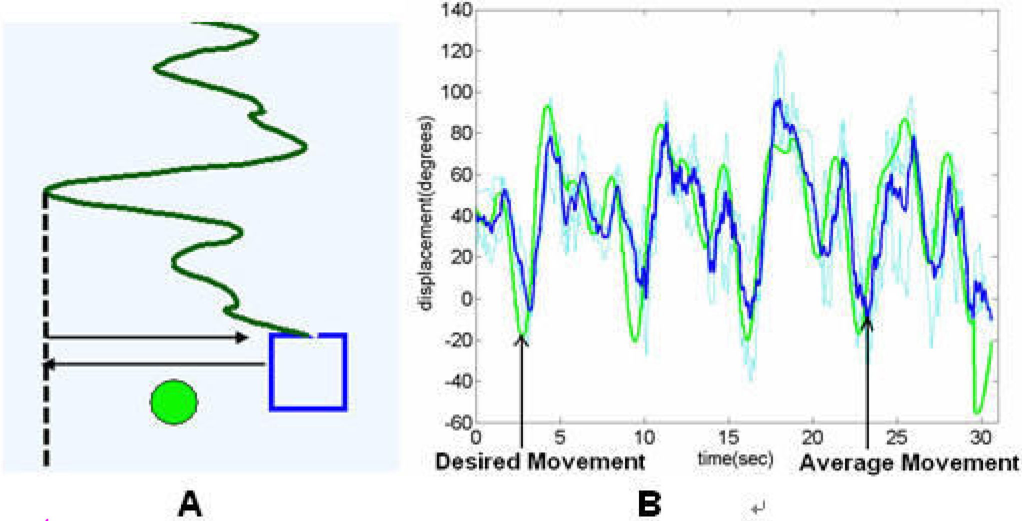
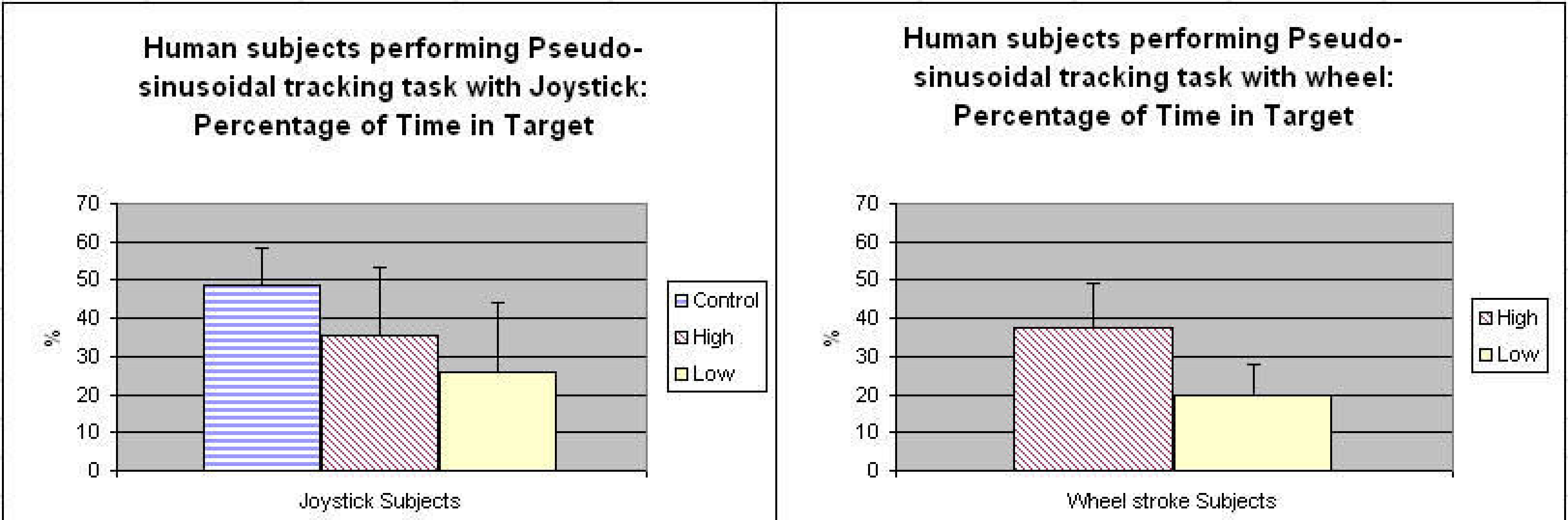

A
B
140
120
100
80
60
40
20
0
-20
-40
-60
displacement(degrees)
0
5
10
15
20
25
30
time(sec)
Desired Movement
Average Movement

Figure 4



Human subjects performing Pseudo-sinusoidal tracking task with Joystick: Percentage of Time in Target

Human subjects performing Pseudo-sinusoidal tracking task with wheel: Percentage of Time in Target

Figure 5

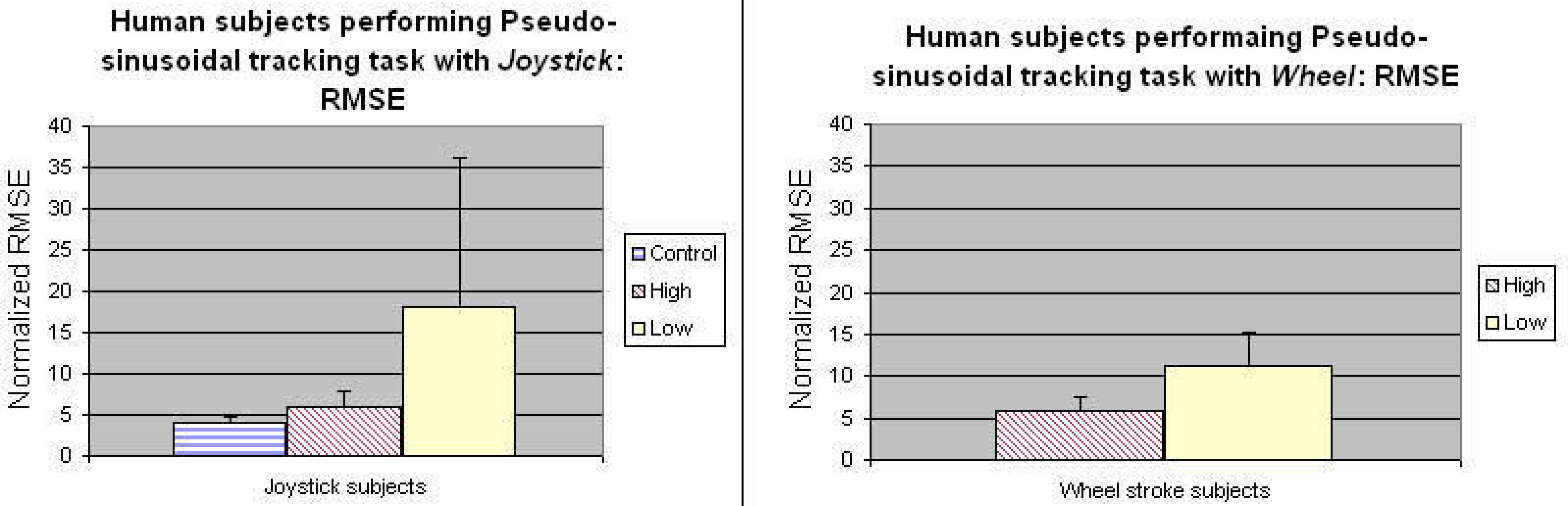

Human subjects performing Pseudo-sinusoidal tracking task with Joystick: RMSE
Normalized RMSE
0
5
10
15
20
25
30
35
40
Control
High
Low
Joystick subjects
Human subjects performaing Pseudo-sinusoidal tracking task with Wheel: RMSE
Normalized RMSE
0
5
10
15
20
25
30
35
40
High
Low
Wheel stroke subjects

Figure 6

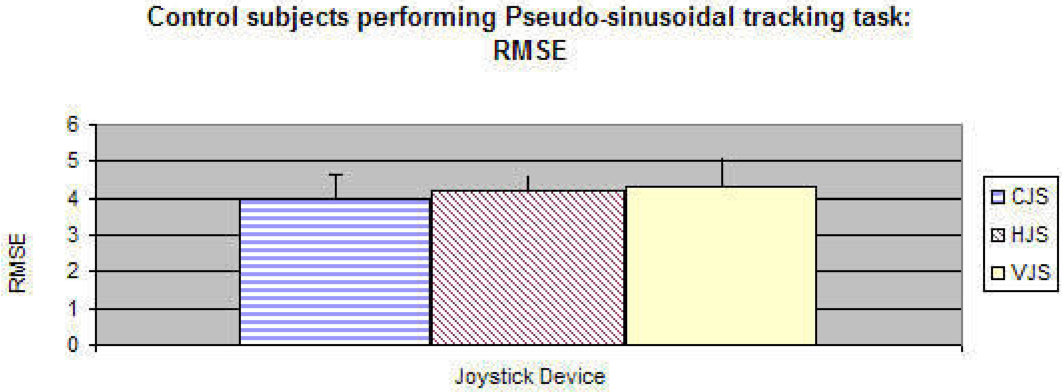
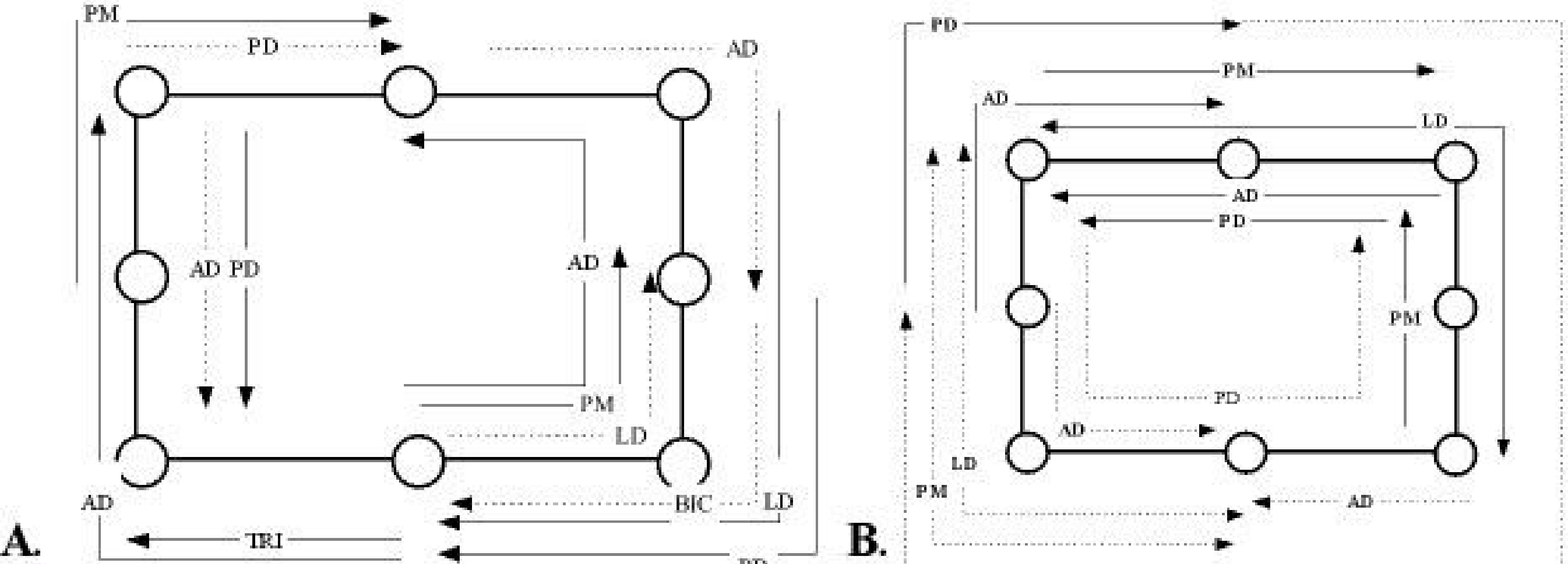

Control subjects performing Pseudo-sinusoidal tracking task:
RMSE
6
5
4
3
2
1
0
RMSE
Joystick Device
▤ CJS
▨ HJS
☐ VJS

Figure 7


A.
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PD
PM
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AD
LD
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AD
PD

Figure 8