

Changes in Arm Kinematics of Chronic Stroke Individuals following “Assist-As-Asked” Robot-Assisted Training in Virtual and Physical Environments: A Proof-of-Concept Study

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Abstract

Introduction: In this proof-of-concept study, we introduce a custom-developed robot-assisted training protocol, named “Assist-As-Asked”, aiming at improving arm function of chronic stroke subjects with moderate-to-severe upper extremity motor impairment. The study goals were to investigate the feasibility and potential adverse effects of this training protocol in both physical and virtual environments.

Methods: A sample of convenience of four chronic stroke subjects participated in 10-~~half-half~~-hour sessions. The task was to practice reaching six targets in both virtual and physical environments. The robotic arm used the Assist-As-Asked paradigm in which it helped subjects to complete movements when asked by them. Changes in the kinematics of the reaching movements and the participants' perception of the reaching practice in both environments were the ~~primary~~ outcome measures of interest. ~~The participants' perception of the reaching practice in both environments and change in scores of Upper Extremity section of Fugl-Meyer Assessment were the secondary outcome measures.~~

Results: Subjects improved their reaching performance, ~~which was accompanied by 3-5 points improvement in Fugl-Meyer Assessment Upper Extremity score.~~ and None of the m-subjects reported any adverse events. There were no differences between the two environments in terms of kinematic measures even though subjects had different opinions about the environment preference.

Conclusions: Using the Assist-As-Asked protocol in moderate-to-severe chronic stroke survivors is feasible and it can be used with both physical and virtual environments with no evidence of one of them to be superior to the other based on users' perspectives and movement kinematics.

Keywords: stroke, rehabilitation robotics, robot-assisted therapy, virtual reality, arm reaching, upper extremity, motor learning, chronic hemiplegia

1 Background

At 6 months post-stroke, only 5%-20% of hemiplegic stroke survivors show complete recovery of arm function while 30%-66% show no sign of function in their paretic arm¹. While the intensity of therapy and increase in number of repetitions have been shown to directly impact stroke recovery^{2,3}, lack of resources and related costs have prevented conventional therapy to be replaced by intensive therapy. Therefore, in stroke survivors who have reached their chronic stage, we are faced with a subpopulation of individuals with moderate-to-severe ~~(MTS)~~⁴ upper limb (UL) motor impairments who are still suffering from decreased UL function, impairing their ability to perform daily activities independently, and are not receiving any rehabilitation services. ~~Developing a suitable and cost-effective therapeutic solution for this subpopulation is an important task.~~

~~The notion of “one size fits all” does not apply in neurorehabilitation of stroke; different treatment protocols and therapeutic techniques should be tailored individually based on each patient’s needs, physical capabilities, condition, performance and even biomarkers. While virtual environment (VE)-based rehabilitation systems are mostly used in mild-to-moderate stroke patients⁵, Properly designed robot-assisted therapy (RT) systems⁶⁻⁸ that target the requirements of ~~MTS~~moderate-to-severe stroke patients can be exploited in clinical settings and even in home settings⁹ to provide an intensive therapy which can be more effective than conventional therapy; studies have shown that RT (which takes much less time and effort of a therapist compared to conventional therapy) is as effective as dose-equivalent intensive conventional therapy¹⁰ and sometimes even more effective when designed properly, e.g. RT with three dimensional (3D) tasks¹¹.~~

~~To achieve the high number of repetitions required for regaining motor function, keeping patients actively engaged during the therapy session and having them adhere to~~

~~the rehabilitation program is of the utmost importance. Motivation plays a key role in this regard. Virtual environment (VE) based rehabilitation systems greatly benefit from this concept, i.e. increasing patients' motivation, besides other advantages that they offer¹². However, VE based rehabilitation systems are mostly used in mild to moderate stroke patients⁵ because of their nature of not being able to provide direct movement assistance to MTS stroke patients with none/limited UL movement.~~ A hybrid system in which a robotic device is coupled with a VE might benefit the MTS moderate-to-severe stroke patients. But a question rises about whether this is necessary in the case of MTS moderate-to-severe stroke or not; robots enable MTS moderate-to-severe stroke patients to complete the unsuccessful movements and also can provide feedback about their performance; these are important motivation factors¹³. In addition, there is no need for having a complex VE scene for them as higher repetition of simple tasks seems to be preferable than a task-oriented practice where patients have a hard time or are unable to complete the task¹⁴. So, in designing such an RT system for, the role of robot may be more prominent than the VE itself. Therefore, there is a question as to whether there is any superiority coupling the robot with a VE than coupling it with a physical environment (PE) and whether movements made in the VE are like those made in the PE, when the task requirements are the same.

~~While there is a shift in rehabilitation from *Impairment-Oriented Training* to *Task-Oriented Training*¹⁵, an RT study showed that in MTS chronic stroke individuals, training the arm and hand in a task-oriented training was not superior than training the arm alone (an impairment-oriented training approach) in terms of restoring the UL functionality¹⁶. A recent randomized controlled trial on chronic stroke individuals with moderate UL motor deficit also reported that a structured task-oriented training is not superior to a dose-matched (or even a lower dose of) usual and customary occupational~~

~~therapy¹⁷. In other words, in an MTS chronic stroke patient, at least some basic elements of motor control need to be restored, i.e. restoring the patient's UL function into mild to moderate motor impairment level, before starting a task-oriented training. Based on this concept, an impairment-oriented training approach in sub-acute stroke individuals with severe arm paresis has been shown to be effective in improving UL motor function¹⁸ and the authors suggested that the severity of the paresis should be a key factor in choosing the therapeutic approach.~~

~~By considering all the above~~In this study, we have developed a robot-assisted protocol aiming at improving arm function of chronic stroke subjects with MTS moderate-to-severe upper extremity motor impairment. The “Assist-As-Asked” paradigm is introduced in this new scheme where-in which the robot only helps a subject when the subject asks specifically for help. As a prerequisite for a large-scale randomized controlled trial, a feasibility study was required. Therefore, we performed this study on four subjects to evaluate the system's usability and to determine whether our robot-assisted arm reaching protocol is beneficial in retraining the arm function of chronic stroke individuals with MTS moderate-to-severe UL motor impairment. In addition, we evaluated the users' perceptions about the system in both environments in terms of motivation and preference. We expected that this novel robot-assisted protocol would improve chronic stroke subject's motor performance over the course of the training and hypothesized that the choice of environment would not affect the kinematics of the reaching task.

2 Methods

2.1 Subjects

For this proof-of-concept study, we recruited a sample of convenience of 4 chronic

stroke subjects from the Greater Montreal area in Canada (Table 1). ~~In a preparatory test, these stroke subjects required robotic assistance for completion of the reaching task. All the stroke participants were right handed with right side hemiparesis and capable of understanding verbal instructions in either French or English.~~ None of the subjects had hemispatial neglect or any visual problem which was not corrected by eyewear, any upper limb surgery, any pain interfering with the arm function ~~(the Shoulder Pain section of the Chedoke-McMaster stroke assessment (C-M)¹⁹ was between stages of 1 and 4)~~, any neurological or neuromuscular conditions other than stroke, or any structural changes secondary to stroke (passive range of motion of the elbow and shoulder restricted more than 20°). ~~Table 1 shows the characteristics of the four stroke subjects who participated in this study.~~ The study protocol was presented to Centre for Interdisciplinary Research in Rehabilitation (CRIR) research ethics committee in Montreal and got approved by the committee (approval number: CRIR-1051-0215). All subjects provided their written informed consent.

Table 1: INSERT HERE

2.2 RT Protocol

The HapticMaster (MOOG Inc.) robotic arm²⁰ was used as the primary tool for providing anti-gravity and guiding force to the subjects when needed and also for measuring the subjects' arm movements in 3D space. The HapticMaster is a three degree-of-freedom, programmable endpoint robot which spans a workspace of approximately 1 m³, with low friction and is equipped with force and position sensors (Figure 1). The system can be programmed to create pre-defined and feedback-controlled 3D force fields. A forearm splint, in which the subject's arm is placed, is linked to the robot arm through a universal joint providing three rotational degrees-of-

freedom (passive). The robot arm runs at a fixed update rate of 2500 Hz which guarantees a smooth and realistic experience by users. The force can be measured and applied with a precision of 0.01 N precision and the position measurements are accurate to 0.012 mm.

The robot arm assisted the arm movements of subjects in 3 ways. A) Virtual Tunnel: before the start of the reaching movement, a virtual tunnel (radius: 4 cm) was created, linking the starting position to the target of interest, thus preventing unwanted deviation of the subjects' arm movement from the ideal straight-line path. B) Gravity Support: It always provided gravity support by not letting the subject's forearm drop. C) Assist-As-Asked Paradigm: When a subject asked for help to complete a movement, the robot arm provided a guiding force to assist the subject in completing the reaching task; when assistance was turned on, the robot produced a virtual spring, with elastic constant of $k = 400 \text{ N/m}$. The spring was then moved at a constant velocity of 5 cm/s towards the selected target, thus smoothly helping the subject in reaching that target. The maximum amplitude of the guiding force was set at 150 N. The effect was like having a spring attached between the subject's forearm and the target, then pulling from the target end of the spring at a constant velocity. During the experiment sessions, the experimenter was near the subject all the time and the robot arm was equipped with software and hardware safety switches, so that the subject or the experimenter could rapidly turn it off.

2.3 Experimental Setup and Procedure

Subjects were required to perform the same reaching task in both PE and VE (Figure 1) in ten sessions over a course of a month. In each session, subjects were seated on a chair, either in front of a vertical board when performing in PE, or a screen when

performing in VE. The affected forearm, i.e. right, was attached to the forearm splint of the robot arm. Based on a pseudo-randomization, subjects either started the experiment in PE followed by VE, or vice versa, in each session.

The experiment in PE consisted of a reaching task to six buttons/targets placed on two rows, each with three buttons with a diameter of 6 cm (Figure 1A). The targets were numbered 1, 2, 3 from left to right on the top row and 4, 5, 6 on the bottom row. These six targets were attached to a hinged wooden board. The board was placed so that the middle and right targets (2, 3, 5 & 6) were positioned in front of the subject, parallel to the coronal plane; the two leftmost buttons (1 & 4) were angled at $\sim 130^\circ$. This arrangement of buttons was preferred to account for the shorter range of motions when reaching for the objects placed contralateral to the moving arm. The top and bottom rows of targets were spaced 25 cm apart; the left- and the right-side buttons were placed 15 cm and 30 cm away from the middle buttons, respectively. A light-emitting diode was placed on top of each button. The height of the experiment board was adjusted in a way that the middle bottom target (#5) was at the level of the subject's xiphoid process of the sternum. Then, based on the subject's right arm length, the experiment board was moved at a distance from the subject so that 30° of elbow flexion was required to reach the middle bottom target (#5). The starting position was set at the 14 cm in front of the xiphoid process of the sternum. This configuration allowed different upper limb muscle group activations when reaching for the 6 targets; it covered flexion, extension and abduction in different directions.

VE mimicked PE: a virtual scene showing the wooden board with six call buttons (Figure 1B). VE was created by projecting images at 120 Hz to a projection screen, providing a 3D perspective view of the experimental scene. VE was calibrated to have the same metrics as for PE. The position of the robot arm's end effector was

displayed as a hand in VE. Movements of the robot arm and hand were reproduced onto the 3D VE on a one-to-one scale.

Figure 1: INSERT HERE.

In either environment, subjects were instructed to move at a comfortable speed while doing their best to reach and press the target buttons without using any compensatory trunk movements; the experimenter was monitoring every trial and if an excessive compensatory movement, i.e. leaning forward, was observed, that trial was repeated. If a subject could not reach the target, s/he asked for the robot's assistance by saying the word "force" and the experimenter turned the guiding force on so that the robot would assist in completing the rest of the reaching movement. To allow subjects to try their best in performing the task before asking for the robot assistance, we did not limit their number of reaching attempts or time in any of the trials. During the robot assistance, the subject was still encouraged to continue his/her effort. In PE, one of the light-emitting diodes above the targets was pseudo-randomly turned on to indicate the reach target. In VE, the target button was visually highlighted. In PE, the movement end was indicated in the recording when the target button of interest was physically touched by the subject. In VE, as there was no physical target button present, the robot arm stopped the subject when the target of interest was reached in the virtual space and a "click" sound was played, like that of a physical button. When the subject completed a trial, either with or without help of the robot arm, the percentage of the movement distance that was completed without the robot's assistance was displayed as feedback on a monitor placed above the experiment board in PE and displayed on the screen in VE. The robot arm then actively moved the subject's arm back to the starting position. During each session, there were 5 reaching trials to each button, for a total of 30 trials in each environment, summing up to 60 trials per session. There was a short break (less

than 5 min) when switching between the two environments. If a subject asked for a break between trials, it was given. Any occurrence of adverse events, such as increased pain, motion sickness, dizziness and headaches during engagement with the system as well as development of new symptoms during the course of experiment, were recorded for reporting.

2.4 Outcome Measures and Analyses

To analyse the movement, the trajectory data was digitally low-pass filtered using a Butterworth filter with cut-off frequency of 6 Hz (dual pass). Then several kinematic metrics from the trajectory data were extracted as the primary outcome measures of interest. The analysis only focused on the portion of movement that was solely performed by the subject, without assistance from the robot. The kinematic metrics were: 1) *movement completion ratio*, defined as the ratio of the straight-line distance completed by the subject over the distance between the starting point and the target; this measure quantifies the amount of subject's self movement without robot's assistance and is used to track subject's UL motor performance. 2) *mean speed* over the path line (i.e. trajectory); while both peak and mean speed measures are widely used, the mean speed is used for quantifying the movement speed of stroke subjects due to typical presence of multiple peaks in the speed profile of stroke subjects²¹. 3) *shakiness*, defined as the number of acceleration profile zero crossings over the path line. A lower shakiness value represents a smoother movement in terms of being less jerky. The movement start was defined as the first instance of subject's speed in target direction exceeding 2% of the peak speed²¹ and the movement end was defined as the closest point to the target of interest reached by subject himself. However, the last five percent of the trajectory in terms of distance was excluded from the movement analysis due to

the following reason. Subjects were only instructed to reach to the targets (the only set goal); thus, when they reached close to their movement limit, they sometimes struggled to go further. This made the last five percent of some reaching movements very different from the other parts of the trajectory. To have an accompanying clinical measure to the kinematics outcome measures, the Upper Extremity section of Fugl-Meyer Assessment (FMA-UE) was used as the secondary outcome measure²²; the FMA-UE was measured at the first session prior to the start of the experiment and after the last session following the completion of the experiment for all the subjects.

As the PE and VE were done in the same session, carryover effect analysis was performed on the “movement completion ratio” measure to investigate whether having such an experimental design allows comparison between the two environments. In other words, we investigated whether training in the first environment (e.g. PE) affected the training in the next environment (e.g. VE) within one session (i.e. carryover effect). To this aim, the order of environments in each session was compared with the difference in performance between the two environments over four categories of *less*, *more*, *equal*, and *plateau* performance. Two “movement completion ratio” measurements were considered equal if were within 5% difference. As subjects reached plateau in some of the trials, we defined the plateau session as the session in which a subject’s self movement graph reached its highest peak with no apparent decline in improvement (no more than 5% change in average decline of the following sessions). ~~Those plateau trials were separated from the equal category and were added as the fourth category.~~

Along with the kinematic metrics, a custom questionnaire was developed to assess how the stroke subjects perceived and experienced the reaching task in both environments using a modified version of the Intrinsic Motivation Inventory (modified-IMI)²³ combined with a modified Short Feedback Questionnaire (modified-SFQ)²⁴.

The modified-IMI consisted of ten questions divided into five items:

Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness. The modified-SFQ consisted of two questions about Repeating the experiment and Comfort of the experiment. There were three additional questions about which environment they preferred, which one was easier for them and whether they felt fatigued.

With a small sample size, no statistical comparison was performed. Instead each subject's results are illustrated and reported in both environments.

3 Results

The results are presented for both environments to provide an illustration of their differences. During the course of the experiment, none of the subjects reported any adverse events such as increased pain or development of new symptoms. Training sessions varied between 30 and 40 minutes. Over the 10 sessions of training, the movement completion ratio of ~~we observed evident changes in movement completion ratio of~~ all the subjects increased; i.e. more self movement and less robot assistance; ~~the subjects became more independent in completing the reaching task and did not require much help from the robot~~ when compared to the first session. In average, the movement completion ratio increased 30%. Breaking down to targets, in average there were 44%, 47%, 28%, 9%, 20%, and 32% increase in movement completion ratio across targets 1 to 6, respectively. In all the subjects, multiple reaching attempts during a single trial before asking for the robot assistance were observed. Figure 2 shows the forearm trajectories of one of the subjects in both environments during the first and last session; the progression/improvement can be well seen in the figure in which the black lines represent the subject's self-movement trajectories without any robotic assistance and the

green (lighter) lines represent the portion of movement completed with the robot's assistance. The shaky trajectories of the robot assistance show that the subject continued interaction with the robot during the robot assistance.

Figure 2: INSERT HERE.

To illustrate each subject's improvement in reaching performance following the 10 sessions of practice, we showed each subject's self movement in the first session versus the last session in reaching to the six targets of interest in both environments in Figure 3A. Clear improvements in each subject's reaching in both environments can be observed in this figure. This improvement in reaching was achieved in most cases in less than 10 sessions and reached a plateau; this plateau was dependent on the subject and the target (Figure 3B) but not the environment. There were negligible and inconclusive differences between PE and VE in terms of the plateau session number and the amount of final self movement completion. Subjects 1 and 4 never reached a plateau in targets 1, 2, & 3 and 3, respectively, while completing 60% and 90% of the whole movement in those targets, respectively. For Subject 2, while the plateau was reached in the third session in target 3, it was stopped at 35% of the whole movement for the rest of sessions and the subject could not improve his independent reaching movement towards that target. Target 4 (bottom left) was the easiest target for the subjects to attain 100% of movement completion ratio. It was followed by target 5 and then 6 (bottom middle and right, respectively). The upper targets were harder for the subjects to improve their reaching performance during the study sessions. ~~Changes in the average shakiness measure between the sessions that the subjects reached a plateau and the sessions after the plateau are illustrated in~~ Figure 3C. ~~illustrates There has been a~~ reduction in the average shakiness measure after reaching the plateau in all the subjects except for Subject 1 (and Subject 4 at targets 1 & 2 in PE). We did not find any

noticeable differences between the two environments (PE and VE) in terms of changes in shakiness measure.

Figure 3: INSERT HERE.

In terms of Mean Speed outcome measure, the visual inspection of all the subjects' data did not reveal any trend across the ten sessions of practice. However, some differences/trends in the mean speed between the targets were noticed. Figure 3D shows the average and standard deviation of the mean speed over the ten sessions of the study in reaching each target for each subject. No noticeable differences between the two environments can be seen in this figure. The common trend among all the subjects was in the lower targets (i.e. targets 4, 5 and 6) in which all the subjects, in either environment, demonstrated the highest speed when reaching for target 4, followed by targets 5 and then 6.

The results of carryover effect analysis are displayed in Table 2. The "PE-VE" represents that PE trials were performed first by the subjects followed by VE, while the "VE-PE" shows the reverse order. The differences between the "movement completion ratio" of PE and VE (VE was subtracted from PE) was categorized into 4 sections of "PE<VE" (less), "PE>VE" (more), "PE=VE" (equal within 5% difference) and "PLATEAU" (in both PE and VE, the "movement completion ratio" has reached 95%-100%). The "No. of Trials" in the "PE-VE" order shows that if there was a carryover effect, we would have seen a higher number of trials in "PE<VE" category; however, this is not the case and all the three categories have similar number of trials. On the other hand, in the "VE-PE" order, presence of carryover effect should have caused higher number of trials in "PE>VE" category which is not the case. In addition, the mean difference and its standard deviation do not show much difference between the categories based on the environment order. Figure 4 shows one of the subject's

“movement completion ratio” (self movement) over the 10 sessions with the order of the environments being displayed. Similar to the carryover effect analysis, no evident carryover effect can be observed.

Table 2: INSERT HERE.

Figure 4: INSERT HERE.

The changes in FMA-UE scores prior to the start and following the end of the study are shown in Figure 5. All subjects showed improvement in their FMA-UE score following the completion of the study. These improvements were between 3 and 5 points. At the sixth session, S3 reported (with a lot of emotion) that while she had not been able to push the elevator button in the last 20 years following her stroke, she has become able to do it; we checked this with her on the last session and she said she has become very comfortable in doing it. She mentioned that this has been the most effective therapy she has taken, and she wanted to know if there was a way she could continue the robot-assisted therapy sessions. Another subject, S4, showed a lot of excitement when he became able to reach the targets during the sessions. S4 also reported that prior to this study, he had instances of burning his affected hand when opening the oven door, but now he has more control of using his affected hand when handling the oven door and have not had any burning incidence. These statements were self-reported by these two subjects.

Figure 5: INSERT HERE.

The responses to the custom questionnaire are summarized in Figure 6. We did not find any noticeable difference between the two environments in terms of subjective experience. All the subjects expressed positive feedback in terms of enjoyment and interest, and were comfortable in either environment. All of them were positive about repeating the task in either environment; two of them felt more toward PE and one felt

~~more toward VE. They~~ were all satisfied with their perceived performance/competence in both environments. ~~All of them, put “a lot of effort” in PE while two mentioned putting lesser effort in VE compared to PE. They~~ felt some pressure in doing the tasks in both environments and reported feeling some fatigue. In other items, subjects were divided and sometimes preferred PE and sometimes VE. ~~except one subject who felt being under a lot of pressure to do the task in PE. Two of them felt that the activity was very useful for their affected arm in either PE or VE, one felt that the activity in VE is very useful but somewhat useful in PE, and the other one reported the opposite. The total IMI scores (out of 35) in PE vs. VE for participants 1 to 4 were 27 vs 23, 25 vs 24, 29 vs 28 and 32 vs 30, respectively. In terms of environment preference, two subjects chose PE and two chose VE. In terms of the environment being easier for the reaching task, one of them chose both environments as equal, two chose VE and one chose PE. Finally, all the subjects reported feeling some fatigue; two in PE and two in VE.~~

Receiving feedback on their movement was very important to the subjects. They were all asking how much of self-movement they achieved the session before for each target and were trying to improve their reaching performance based on that score.

Figure 6: INSERT HERE.

4 Discussion

~~This study illustrates the potential benefits of the designed RT protocol in retraining of the arm function of MTS chronic stroke subjects. A~~In this study, all the subjects increased their shoulder and elbow active range of motion ~~by and improving improved~~ their arm reaching performance between the first and last session. ~~None of the subjects reported any adverse events.~~ We consider two possible factors ~~involved~~ in achieving such results. First, in developing this RT protocol specific to MTS moderate-to-severe

chronic stroke patients, due to the severity of their UL impairment, we only focused on arm reaching training ~~of these individuals~~ as opposed to training a functional task involving both arm and hand, ~~due to the severity of their UL impairment. This is a purposeful design~~ based on the results obtained by the Krebs group¹⁶. We ~~therefore~~ focused on reducing the arm impairment in this subpopulation before proceeding to any functional task training. However, our protocol ~~is~~ was not a pure impairment-oriented training, but a simple goal directed ~~simple~~ training which was attainable by the subjects. Such a simple goal-oriented task may have allowed ~~let~~ the subjects ~~to~~ become focused on the task, i.e. reaching, and be very attentive and aware of their performance results (i.e. the feedback).

Second, we used the Assist-As-Asked paradigm in the RT protocol, rather than the well-known Assist-As-Needed (AAN) paradigm²⁵. In an AAN paradigm, the subject's movement is continuously monitored by the robot and the amount of assistance required to achieve a given task ~~is estimated based on the subject's performance and~~ is then provided by the robot. ~~In terms of retraining the UL of stroke patients using RT, the AAN paradigm has been used with different robotic devices²⁵. In robotic gait therapy, the AAN paradigm is shown to be more effective than a continuous assistance paradigm for elements such as balance and rhythmic patterns of movement with limited degree of freedom²⁶. It has been suggested that~~ While in the AAN paradigm the subject still tries to perform the movement, this paradigm might not let ~~the subjects~~ perform at his/her ~~their~~ full potential, and leads ~~ing~~ to submaximal or lower efforts by the subjects. ~~Subjects may simply wait to let the robot move their arm. To overcome this drawback and therefore,~~ a strategy involving reducing the amount of assistance had been suggested and implemented¹¹. However, On the other hand, our Assist-As-Asked paradigm ~~lets subjects try their best during the reaching task and might~~

~~help subjects reach their peak performance before asking for robot assistance-; In the current study, we observed that all the subjects had trials in which multiple reaching attempts (during a single trial) were done before asking for the robotany assistance. In addition, all the subjects and they were quite responsive to the feedback about their movement; they were all asking how much of self movement they achieved the session before for each target and were trying to improve their reaching performance based on that score. That being said, That being said, it can be argued that a lazy stroke subject or a one with a lack of motivation could still not try his/her best and rely too much on the robot assistance in the Assist-As-Asked paradigm. The same problem can appear in an AAN paradigm for the same type of subject. Ddeveloping a modified version of the Assist-As-Asked paradigm that ensures subjects reach their peak performance before asking for assistance and comparing its effectiveness with other RT paradigms should be pursued in future studies; such an evaluation can be done by monitoring the amount of subject's effort during each trial (e.g. measuring the subject's maximum voluntary force by the robot at the beginning of each session and setting a percentage of that as the minimum force threshold to be applied by the subject, setting a minimum number of attempts, or setting a minimum amount of time) prior to providing robot assistance. Further study is required to compare the effectiveness of the Assist-As-Asked paradigm with other RT paradigms such as the AAN paradigm.~~

The improvements in reaching were achieved in most cases in fewer than 10 sessions of practice and reached their plateau which was subject and target dependent. For two of the subjects that did not reach plateau in the top row targets, i.e. subjects 1 and 4, increasing the number of sessions might have helped them to improve their reaching performance in those targets. For Subject 2, the plateau was stopped at 35% of movement completion ratio when reaching to target 3, which required the most amount

~~of shoulder abduction, shoulder flexion and elbow extension among the targets; for such a case, changing the target location to a more reachable position based on his ability might have helped him. Also, having higher number of repetitions within a session and increasing the number of sessions would have helped. This was seen in the bottom row targets where reaching to target 4 was the easiest for the subjects to complete followed by targets 5 and 6. This might be due to the location of the targets which required less shoulder abduction, shoulder flexion and elbow extension. In other words implying that, the RT protocol and number of therapy sessions should not be fixed for all the subjects but should be adjusted based on their performance individually tailored.~~

~~In most cases where subjects reached a plateau in their movement completion ratio (11 out of 14 plateau cases in PE and 11 out of 13 in VE), the shakiness decreased following the movement completion plateau afterwards. Due to a lack of neuroimaging studies, ~~†~~The underlying neurological mechanism responsible for these improvements in the kinematic measures are still not known ²⁷. However, the theory of sub-movements blending during motor recovery in stroke has shown states that during post-stroke recovery, the criterion for refinement of movement patterns is not constrained to improving smoothness measures such as shakiness, but more toward gaining back the function; following the regain of the function, the shakiness decreases ²¹. In other words, shakiness exhibits a non-monotonic behaviour during motor recovery.~~

Therefore, ~~the lesson that can be learned is that~~ the decision to stop the training of a movement should not only be based on the movement completion plateau but also on tunings of other movement parameters ~~of movement~~ such as shakiness. Tracking these changes is possible in RT ²⁸.

While improvements in kinematic measures were evident and measurable, the FMA-UE only changed 3 to 5 units of score, which was below the minimal detectable

change (MDC) of 5.2²⁹ and/or minimal clinically important difference (MCID) of 7³⁰. A recent study, however, has shown that the MCID can be accepted at 4³¹. As we only focused on training the arm, not the wrist and hand, we did not expect a major improvement in FMA-UE. Further, the tests in FMA-UE do not differentiate between the two aspects of movement: strength and motor control³². Therefore, it might not be a clear representative of the improvements by the subjects achieved with the RT. ~~Presence of a control group would have allowed attributing the FMA-UE changes to the Assist-As-Asked protocol.~~ In addition, both FMA-UE score variation and the assessor's bias giving more score in post evaluation should be considered as a design limitation of this study.

~~We only performed one baseline (pre) measurement of FMA-UE and did not perform multi-baseline evaluations because all the stroke subjects were in their long-term chronic stage and we expected a stable and non-varying baseline in terms of motor impairment level for all of them: the onset of stroke in three of the subjects was more than two and half years (2.7, 6.6 and 20.9 years post-stroke) and in one of them was more than a year and half (1.6 years post-stroke) (Table 1). However, lack of multi-baseline evaluations is still a limitation of this study. Instead, we used kinematic measures as the primary outcome measures. Due to intrinsic nature of the robotic arm to measure kinematics and kinetics data, we quantified the improvements in subjects' reaching in every session. Kinematic measurements are sensitive to small and more specific changes in body parts movements³³, not dependent on experimenters' observations, recorded by precise and accurate equipment, highly repeatable with high resolution²⁸, and represent physically measurable outcomes. That being said, the improvements seen in the kinematic measures of the reaching task are likely influenced by the subjects learning the task over the 10 sessions of practice and therefore cannot be~~

~~directly contributed to impairment reduction unless accompanied by improvements in clinical measures. In this study, two of the subjects reported increased usage of their arm in daily activities which presents transfer of learning the reaching task to real world applications. However, we could not perform follow-up measures to study whether there were any maintained long term effects.~~ In future works, several clinical measures, ~~such as FMA-UE, Stroke Impact Scale and Motor Activity Log,~~ should be used as the main outcome measures of interest in evaluating the effectiveness of the Assist-As-Asked protocol; ~~such a study should also include~~ with multiple baseline, post and follow-up measures to investigate its long-term effect.

The results of this proof-of-concept study shows that it is feasible to use the Assist-As-Asked protocol in both physical and virtual environments. ~~Regarding the choice of environment, w~~We did not find any noticeable and/or meaningful differences in terms of the movement kinematic variables (~~movement completion, mean speed and shakiness~~) between the two environments. ~~This can be explained by a~~A study on healthy subjects comparing reaching tasks in a physical versus virtual environment PE vs VE in presence/absence of visual/haptic feedback³⁴ ~~in which the results~~ showed that the subjects' performance were similar in both environments when the subjects had visuo-haptic feedback in VE³⁴. In this study, besides the presence of visual feedback in PE and VE, both PE and VE shared the same haptic feedback in terms of forearm attachment to the robot arm and the robot arm provided haptic feedback at the end-point in VE ~~for the subjects by stopping them when the virtual button was reached. Also, both PE and VE shared the same haptic feedback in terms of forearm attachment to the robot arm.~~ Subjective experience of the subjects participants ~~in terms of motivation and preference~~ was also similar between the two environments. In other words, the choice of environment was more of a personal preference than having any effect on the outcomes.

~~In summary, in designing an RT platform for MTS chronic stroke survivors, choice of environment, either physical or virtual, does not necessarily influence the outcome of therapy sessions; the choice of environment should be decided based on other factors, such as cost, feasibility, etc.~~

The current study has several limitations in the study design. The main one is the small number of subjects ~~that are investigated. As there were only four participants in this study, and therefore the~~ results presented here must be cautiously interpreted and only used for designing a larger experiment. Another issue was the experimental design in which both PE and VE were performed in the same session (AB design) and whether this would have resulted in carryover effects. ~~This design was very ideal for analysis of the subjective perception of the participants about the reaching practice in both environments. In terms of kinematics of reaching performance, the carryover effect analysis (Table 2) showed that there were no immediate carryover effects (intra-session) on the reaching performance. However, this does not rule out longer carryover effects (inter-session) of one environment over the other.~~ Having used an alternating intervention design, such as ABAC design, in which the PE and VE were not used concurrently, would have been more suitable ~~for this multiple case study. An ideal experimental design to compare the effect of environment on RT would be a~~ A between-subject design ~~to compare the effect of environment on RT, which~~ might not be practical considering the high between-subject variability in stroke survivors.

5 Conclusion

This proof-of-concept study demonstrated that using the Assist-As-Asked protocol in moderate-to-severe chronic stroke survivors is feasible. It was also shown that the Assist-As-Asked protocol can be used with both physical and virtual

environments with no evidence of a one to be superior to the other based on users' perspectives and movement kinematics.

6 Declarations

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Conflicting interests: The authors declare that there is no conflict of interest.

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Guarantor: NN.

Contributorship: NN was involved in all part of this research work, including study design, patient recruitment, data processing/analysis/interpretation, statistical analysis and the manuscript writing. Both PA and JF were involved in study design, data interpretation, and providing critical review as well as providing funding. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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Tables

Table 1: Characteristics of chronic stroke individuals participated in this study.

Participant	Gender	Age (years)	<u>Handedness</u>	Time since Stroke (years)	C-M	FMA-UE	Type of Stroke	Side of Hemiparesis
1	M	53.1	<u>Right</u>	1.6	3	15	Ischemic	Right
2	M	59.8	<u>Right</u>	2.7	3	13	Hemorrhagic	Right
3	F	49.0	<u>Right</u>	20.9	3	18	Ischemic	Right
4	M	53.2	<u>Right</u>	6.6	3	14	Ischemic	Right

Table 2: Carryover Effect Analysis on All the Trials of All the Subjects

		No. of Trials		Mean Difference (%)		Standard Deviation (%)	
		PE-VE	VE-PE	PE-VE	VE-PE	PE-VE	VE-PE
Movement Completion Ratio Difference Category:	PE<VE	23	22	-11.5	-17.1	5.4	10.4
	PE>VE	27	12	15.7	12.2	11.0	7.6
	PE=VE	24	15	0.4	-0.4	3.1	3.0
	PLATEAU	64	53	-0.3	0.1	1.2	1.2

Figure Captions

Figure 1: A. The Physical Environment and B. The Virtual Environment

Figure 2: Typical trajectories for session 1 and session 10 in both environments. Black lines represent the trajectory performed by the subject (no robot assistance). After 10 sessions of practice, the improvements in reaching without robot assistance are quite evident. No noteworthy difference can be seen between the two environments in terms of reaching trajectories.

Figure 3: **A.** Changes in subjects' self movement in reaching between session 1 (Pre) and session 10 (Post). **B.** The session number that each subject reached their self movement plateau during the 10 sessions of reaching practice; subject's self movement following plateau is indicated. Values more than 10 sessions indicate that the plateau was not reached (~~S1 in T1, T2 and T3 and S4 in T3~~). ~~The amount of subject's self movement following plateau is also indicated as a percentage on top of each bar (rounded to the nearest tens place). In the cases that the plateau was not reached, the subject's self movement at the last session is also indicated on top of the bar.~~ **C.** Changes in the Shakiness measure between the plateau session (marked as Pre) and the last session (marked as Post). At those that plateau was not reached only the shakiness measure of the last (10th) session is shown on Pre value. At those that plateau was reached right at the first session, the shakiness measure of the last (10th) session is shown on Post value. **D.** Difference in Mean Speed between targets for each subject in both environments. ~~Each bar shows the average of the mean speed outcome measure for a specific target through all the sessions and~~ The error bars shows ~~its~~ standard

deviation. S1 to S4 indicate subject IDs. T1 to T6 indicate target numbers. PE and VE represent Physical and Virtual environments.

Figure 4: The order of environments across the ten sessions of training is shown for one of the subjects. No evident carryover effect can be observed.

Figure 5: Changes in the FMA-UE scores of all the subjects before the start (Pre) and after the completion (Post) of the study. S1 to S4 are subject IDs.

Figure 6: The responses to the custom questionnaire, consisting of modified-IMI, modified-SFQ and questions about the choice of environment (Env.). The modified-IMI and modified-SFQ used a 7-point Likert scale while the choice of environment were dichotomous questions. S1 to S4 are subject IDs.

Figures

Figure 1:

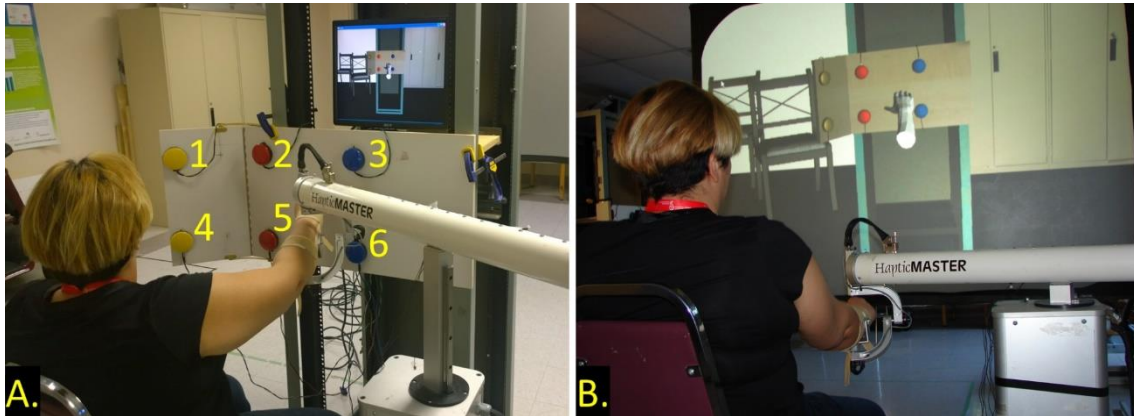


Figure 2:

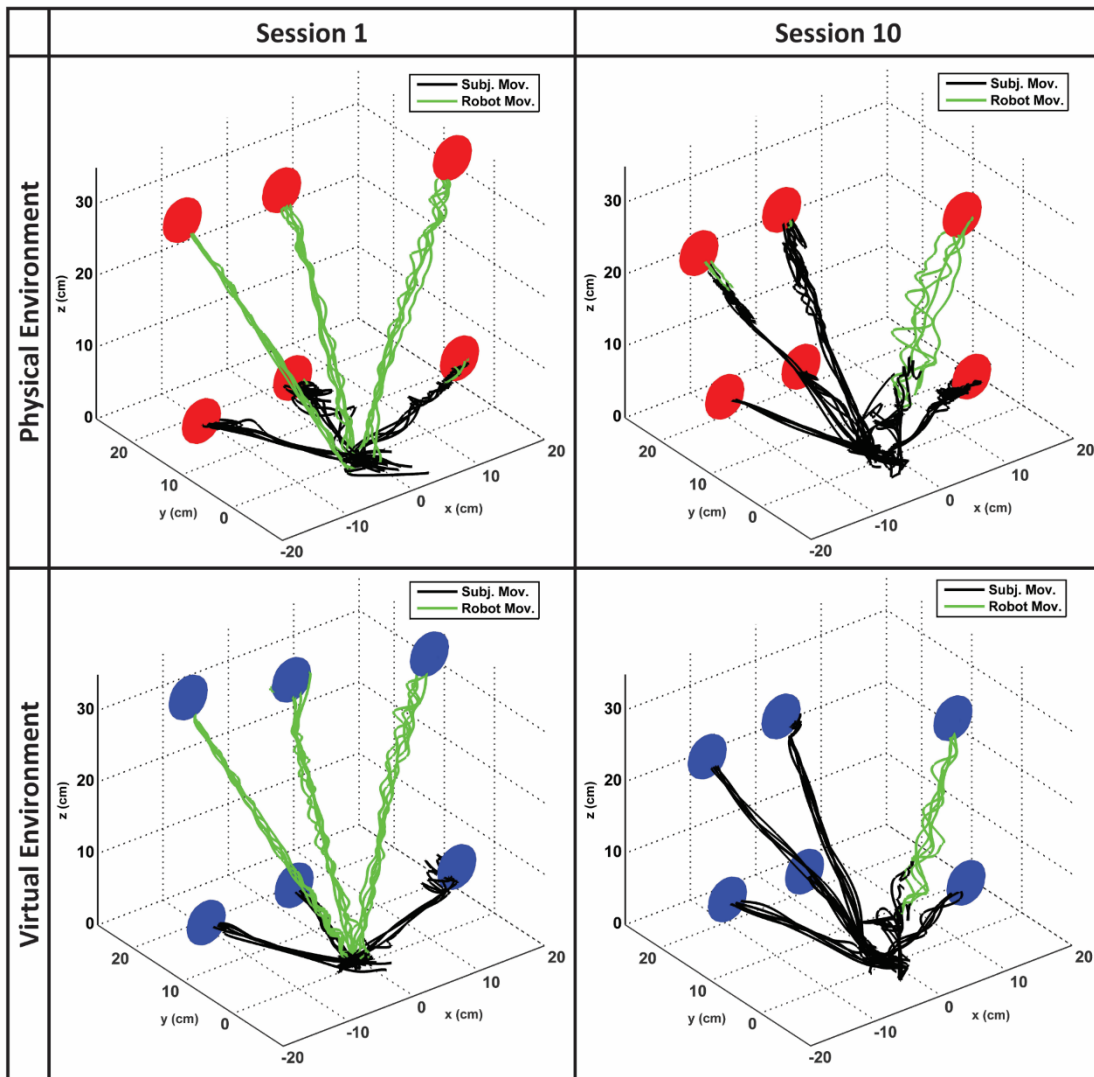


Figure 3:

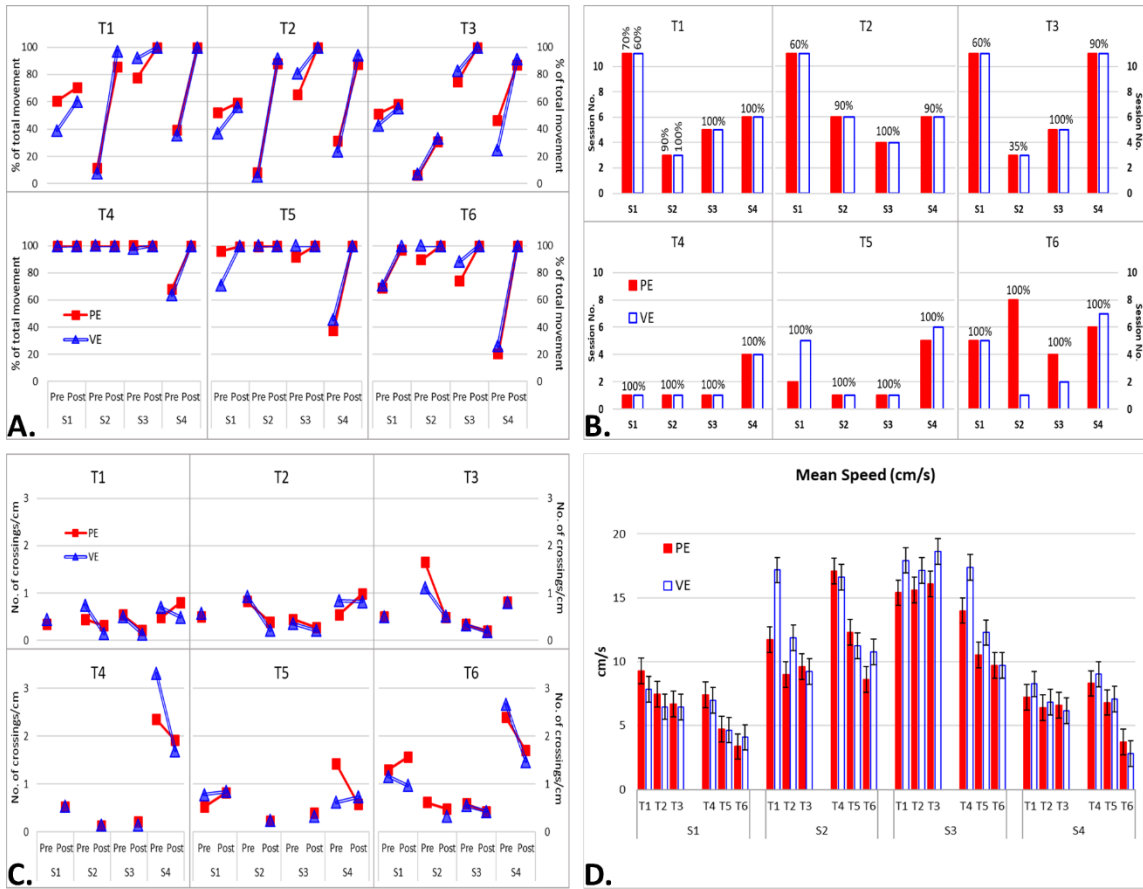


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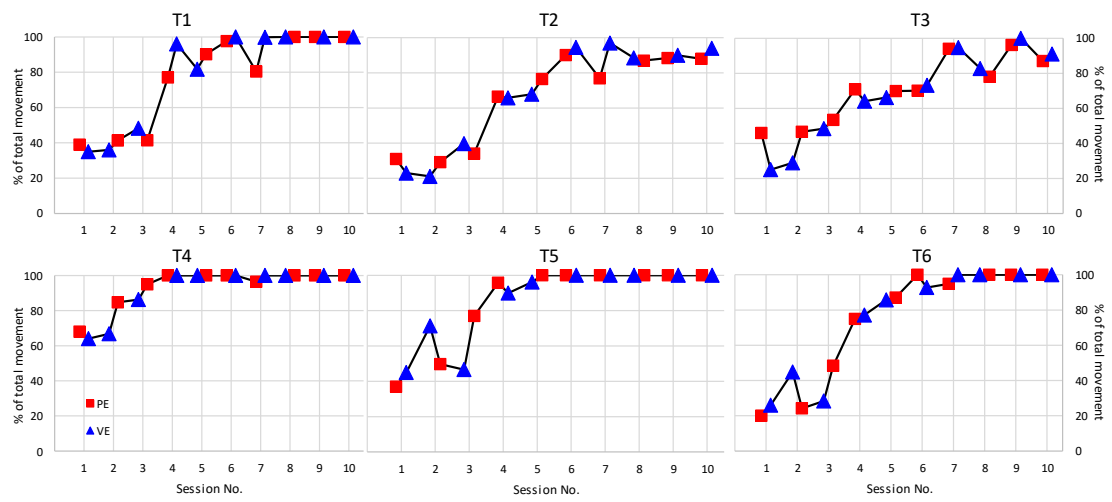


Figure 5:

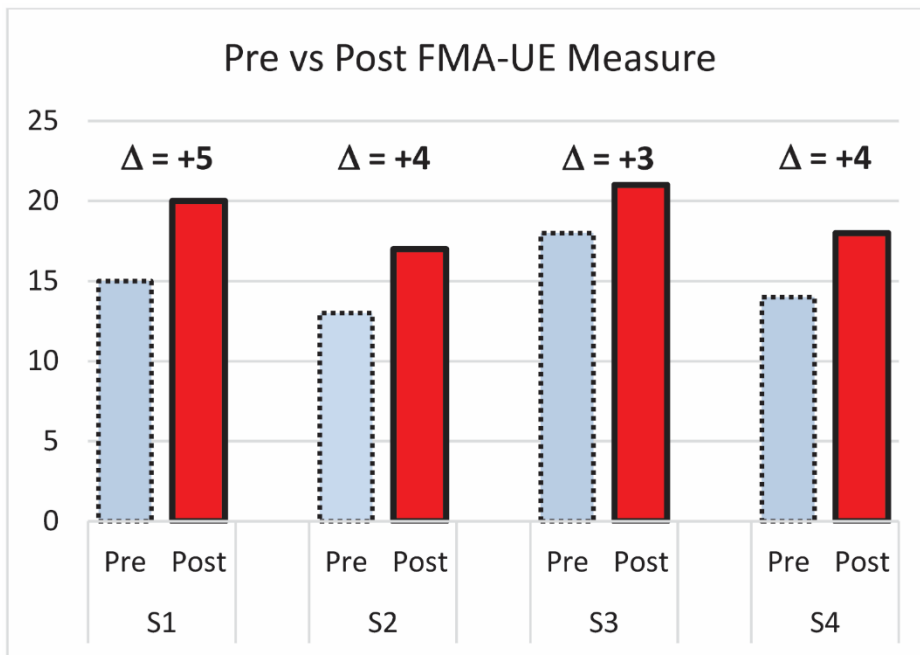


Figure 6:

