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Pilot study to test effectiveness of video game on reaching performance in stroke

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Abstract

Robotic systems currently used in upper-limb rehabilitation following stroke rely on some form of visual feedback as part of the intervention program. We evaluated the effect of a video game environment (air hockey) on reaching in stroke with various levels of arm support. We used the Arm Coordination Training 3D system to provide variable arm support and to control the hockey stick. We instructed seven subjects to reach to one of three targets covering the workspace of the impaired arm during the reaching task and to reach as far as possible while playing the video game. The results from this study showed that across subjects, support levels, and targets, the reaching distances achieved with the reaching task were greater than those covered with the video game. This held even after further restricting the mapped workspace of the arm to the area most affected by the flexion synergy (effectively forcing subjects to fight the synergy to reach the hockey puck). The results from this study highlight the importance of designing video games that include specific reaching targets in the workspace compromised by the expression of the flexion synergy. Such video games would also adapt the target location online as a subject's success rate increases.

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Keywords

arm function; haptic interface; reaching; rehabilitation; robotics; shoulder abduction; stroke; therapy; upper-limb impairment; video games

INTRODUCTION

Following stroke, arm function is compromised with clear limitations in shoulder and elbow active range of motion (ROM). These limitations have an effect on hand workspace and the ability to perform activities of daily living (ADLs). Previous work has demonstrated abnormal coupling between shoulder abductor and elbow flexor muscles and between shoulder adductor and elbow extensor muscles [1]. Such coupling results in task-specific reductions in upper-limb workspace and more specifically in elbow extension ROM when loading the shoulder in abduction [2–3].

Despite promising advances in recent treatment approaches for the hemiparetic upper limb, such as electromyographic-triggered functional electrical stimulation [4], robot-aided sensory-motor training [5], bilateral isokinetic arm training [6], and constraint-induced movement therapy [7], 1.1 million people in the United States still report residual disability resulting from stroke [8]. None of these heavily investigated interventions directly address the presence of abnormal synergistic patterns of the upper limb that profoundly impair functional reaching, especially in individuals with moderate to severe stroke [9]. Our previous intervention work was successful in partially reducing the abnormal coupling of elbow flexion during isometric shoulder abduction following an 8-week training period [10]. However, the effect was not great enough for subjects to achieve full reaching ROM over hand workspace. Results from our more recent intervention work suggests that moderately to severely affected people with chronic stroke can be trained to increase their reaching workspace and functional arm use with a progressive shoulder abduction loading paradigm [11–12]. The intervention protocol consisted of reaching movements to targets in five directions near the end of reaching ROM and spanning a large portion of the workspace while supporting a percentage of the weight of the arm. In this work, the Arm Coordination Training 3D (ACT^{3D}) system [3] was used as a haptic interface to simulate the subject-specific shoulder abduction loading levels. Subjects were trained at progressively greater arm loading levels over an 8-week intervention period. Visual feedback in the form of an avatar of the arm displayed on a computer monitor was provided. The avatar and target locations were scaled to the individual subject's anthropometric parameters, and auditory feedback was provided when the required load was not being met. The results of the study showed that with a therapist present to provide motivation, the combination of robotics with simple visual feedback was effective in increasing reaching ROM at the end of the intervention. This improvement was related to significant gains in elbow extension abilities under the training conditions. Based on these encouraging results, the question arises whether the use of robotics combined with video games can provide an equal, or possibly more engaging, environment for upper-limb rehabilitation in people with stroke with equally or greater gains in terms of reaching ability and functional use of the arm.

Recent advances in robotic and video game technology have given rise to multiple systems for upper-limb rehabilitation for people with stroke [3,13–20]. Such systems combine robotics with computer graphics for delivery of a rehabilitation protocol. An increasingly common approach is the use of virtual reality games that allow interaction with a three-dimensional environment simulated in a computer and integrated with haptic feedback. Systematic reviews of the effect of robotic-based therapy on upper-limb recovery following stroke suggest significant improvement in motor control of the paretic upper limb but no significant improvement on functional abilities or ADLs [5,21]. Similar reviews on the effectiveness of virtual reality programs for stroke rehabilitation support this application, albeit with limited evidence [22–24]. All of these reviews recognize the potential for these therapeutic modalities, encouraging further research to establish their validity and provide evidence of their advantages over conventional therapy.

These rehabilitation systems differ vastly depending on the therapeutic approach. Most groups have adopted a task-oriented approach where, for example, subjects complete a pick-and-place or grasp-and-release virtual reality task [25–35]. A few groups have implemented systems based on a teaching approach where the reaching movement or task is guided by a predefined trajectory or set of rules [36–38]. Some groups have even designed therapeutic protocols based on both approaches [39–40]. Furthermore, some of these systems provide robotic assistance to the task or movement being performed either by moving the arm in a programmed trajectory or by supporting the weight of the limb [11,34–35,39–45]. Although most of these systems are prescribed for upper-limb rehabilitation, many target only the wrist and hand with limited ROM of the shoulder and elbow. Likewise, most of these systems require or provide complete gravity compensation, with a few exceptions such as the T-WREX (MARS-RERC; Chicago, Illinois) [29], ARMin (University of Zürich; Zürich, Switzerland) [19], L-EXOS (PERCRO; Pisa, Italy) [20], Freebal (Armeo-Boom, Hocoma; Rockland, Massachusetts) [34], and ACT^{3D} systems [3], which have adjustable limb-weight support abilities. However, only the ARMin and ACT^{3D} systems are able to generate loads in the vertical direction to simulate increased limb weight or object handling.

Based on previous results from our laboratory, we believe that targeted interventions that address specific impairments are effective in generating changes in upper-limb motor function and functional use of the upper limb in people with moderate to severe hemiparetic stroke [10–12]. It is therefore our goal to design rehabilitation systems that address specific impairments: more specifically, systems that use robotics combined with video games to create a haptic environment in which the weight of the limb can be manipulated while subjects perform targeted reaching movements. This study is a first step in achieving that goal by examining the effect of a fun and engaging video game environment that promotes reaching compared with target reaching with visual feedback in the form of an avatar of the arm. We evaluated the effect of the two forms of feedback on reaching distance in a group of subjects with hemiparetic stroke under various arm loading conditions. The results of the study showed greater reaching abilities during avatar feedback compared with video game feedback, suggesting the need for custom-designed video games that target the specific impairments, in this case, the abnormal coupling between shoulder abduction and elbow flexion.

METHODS

Subjects

Seven subjects with chronic unilateral hemiparetic stroke participated in the study: six males and one female, aged 50 to 80 years, and ranging from 2 to 15 years post-stroke. We screened all subjects for inclusion. Exclusion criteria included difficulty sitting for long durations, recent changes in the medical management of hypertension, and any acute or chronic painful condition in the upper limbs or spine. We collected the score for the upper-limb portion of the Fugl-Meyer Motor Assessment (FMA) [46] for each subject to determine the presence and extent of flexion synergy and to categorize the level of impairment severity. The inclusion criteria for the study required severe to moderate impairment FMA scoring with a maximum of 45 out of 66. The subjects included in the study scored between 10 and 43, representing severe to moderate expression of flexion synergy in the affected upper limb. We administered the FMA within 6 months of participation in this study. All subjects were able to support the upper limb against gravity and demonstrated an ability to generate some active elbow extension. We measured each subject's passive ROM of the affected upper limb using methods described elsewhere [47]. We required passive ROM to be at least 90° of shoulder flexion, abduction, and neutral internal and external rotation for participation in the study. We used overpressure at the end of the ROM as a medical screening measure to verify the absence of inflammatory conditions at the shoulder, elbow, wrist, and fingers [48].

Experimental Setup

We seated subjects in the experimental chair with their arm attached to the ACT^{3D} system through a forearm-hand orthosis [49]. We restrained trunk and shoulder girdle movement with a set of shoulder and lap straps attached to the experimental chair (Figure 1). Subjects were asked to move their upper limb to an initial position of 90° shoulder abduction (or close to 90° depending on the subject's passive ROM), 45° horizontal shoulder flexion, and 90° elbow flexion. We placed the wrist and hand in a neutral position in an orthosis and interfaced with the ACT^{3D} system through a gimbal. We locked the gimbal to constrain movements to a plane intersecting the center of rotation of the shoulder, thus preventing internal and external rotation at the shoulder. Note that after stroke, moderately to severely impaired subjects have difficulty controlling external rotation. Therefore, by preventing rotation of the shoulder in this degree of freedom (DOF), the motor control was simplified, concentrated to shoulder abduction and/or adduction in the loaded condition and shoulder extension and/or shoulder flexion and elbow extension and/or elbow flexion during reaching movements.

The ACT^{3D} system is instrumented with potentiometers to track the position of the gimbal and with a 6 DOF load cell (Model 45E15A4-I63, JR3 Inc; Woodland, California) to allow haptic interaction.

We developed a custom software interface to calculate the position of the arm in real time and provide visual feedback of the movement performed by the subject. The feedback was in the form of an avatar of the arm displayed on a computer monitor (avatar feedback, Figure 2(a)). The software interface also provided the option to control the computer mouse with movement of the ACT^{3D} system for use with *Air Hockey 3D* (Avalanche Team; Novosibirsk, Russian Federation; game feedback, Figure 2(b)). We initially mapped the workspace covered by movement of the hand attached to the ACT^{3D} system onto the bottom half of the video game air hockey table. In order to further challenge subjects to extend their elbow, we only mapped the hand workspace requiring elbow extension onto the air hockey table (e.g., for a right hemiparetic subject the workspace in front and to the right of the right shoulder). The mapping was linear, which meant that the distal corners of the air hockey table could not be reached. Finally, we programmed the software interface to generate a haptic table (equivalent to a physical table, only it can be generated with the ACT^{3D} system via software) as well as forces in the vertical direction (i.e., against gravity) to simulate three different loading conditions: arm fully supported condition (FS), where subjects were allowed to move on the haptic table without regard to shoulder abduction and/or adduction torques; arm floating condition (FL), where the weight of the limb was supported by the device and subjects were asked to move on the horizontal plane going through the shoulder while actively avoiding generation of shoulder torque in the abduction and/or adduction direction, which would result in the arm moving out of the plane (up or down); and a 25 percent loading condition (L25), where subjects had to support a load in the abduction direction (equivalent to lifting the arm against gravity) equal to 25 percent of their shoulder abduction maximum voluntary torque while moving their arm in the horizontal plane.

Experimental Protocol

Subjects sat in the experimental chair with their arm attached to the ACT^{3D} system and placed in the initial configuration (home target). We adjusted the height of the experimental chair so that the plane of the arm and the haptic table coincided. We used the interface software to record the position of the arm and compute the location of the shoulder for online calculation of the hand position.

Avatar Feedback—We asked subjects to perform reaching movements to three different targets (Figure 3): “shoulder flexion” target (SF) located on the opposite side of their shoulder that requires mostly shoulder flexion, “reaching” target (RE) located directly in front of their shoulder that requires both shoulder flexion and elbow extension, and “elbow extension” target (EE) located to the right of their shoulder that requires mostly elbow extension. We placed the SF and EE at arm’s length with respect to the shoulder and located the RE slightly farther than arm’s length. We instructed subjects to reach as quickly and as far as possible in the direction of the target. Reaching to each of the three targets was repeated seven times for each of the three loading conditions (FS, FL, and L25). We randomized the order of presentation of the target and loading conditions. To avoid fatigue, we gave 30-second rest periods between reaching trials.

Game Feedback—We established mapping of the hand workspace onto *Air Hockey 3D* before data collection. When *Air Hockey 3D* was initiated, we only asked subjects to play the game for a total of 3 minutes using the best of their abilities. Although we gave verbal encouragement to entice subjects to reach to all the areas of the mapped workspace, the nature of the game was such that the reaching direction was random. We repeated each game trial twice for each loading condition. In a subset of subjects (five out of seven), we adjusted the mapping to force subjects to extend their elbow to reach the full workspace of the air hockey table and collected data for another game trial. The adjusted mapping was such that only half of the distal workspace of the paretic limb in the left or right direction (depending on the side of the paretic limb) was mapped onto the air hockey table, thus forcing subjects to maximally extend their elbow to reach those areas. The notion of using visual feedback distortion to encourage subjects to move beyond their self-assessed maxima is not new and is supported by the work from Brewer et al. [50]. We rotated the air hockey trials with the reaching trials in a random fashion. We gave 1-minute rest periods after the trials to avoid fatigue.

In the FS or haptic table condition, the plane of the arm and the haptic table coincided, thus allowing subjects to move on the haptic table. In the other two loading conditions (FL and L25), we lowered the position of the haptic table so that the plane of the arm (horizontal plane passing through the shoulder) and the haptic table did not coincide. In these loading conditions, we asked subjects to move in the plane of the arm while avoiding contact with the haptic table. We used auditory feedback (buzzing noise) as well as haptic feedback to signal when the subject’s arm made contact with the haptic table. The haptic feedback consisted of a simulated viscous environment that prevented subjects from moving on the haptic table and was only turned off when they lifted their arm to match the desired load and avoid contact with the haptic table. We recorded endpoint position of the ACT^{3D} system for each trial and saved it for offline analysis.

We asked subjects to complete a survey at the end of the session that asked which visual feedback was more engaging and which feedback they would prefer in a hypothetical intervention.

Data Analysis

We computed the trajectory of the tip of the middle finger based on the geometry of the arm and the endpoint position of the ACT^{3D} system and used it for analysis of the avatar and game feedback trials. We extracted the farthest point from the home target in each reaching direction (SF, RE, and EE) with a ±15° tolerance from each of the avatar feedback trials. For the game feedback trials, we computed the outer envelope of all the movements generated by the subject on the plane with a resolution of 1°. For comparison with the avatar feedback trials, we also extracted the farthest points across envelopes from game feedback trials that matched the target direction in each avatar feedback trial for comparison between feedback modes. Note that the subjects who played *Air Hockey 3D* with an adjusted mapping of the arm's workspace to the air hockey table had an additional envelope included in the analysis.

We used a three-factor repeated measures univariate analysis of variance with interactions to determine the effect of feedback (avatar and game), target direction (SF, RE, and EE), and loading conditions (FS, FL, and L25) on the normalized reaching distance (dependent variable). We normalized the reaching distance by arm length (shoulder to tip of middle finger) to account for anthropometric differences across subjects. We tested the condition of sphericity (equal variances of the differences between factors) of the data using Mauchley's sphericity test. The data satisfied the condition of sphericity ($p > 0.05$) for all factors except for the interaction between direction and loading condition. We performed pairwise comparisons using Bonferroni's method to adjust for multiple comparisons. For all statistical tests, we defined a significant effect or difference as $p \leq 0.05$. We performed statistical analysis using SPSS (SPSS Inc; Chicago, Illinois).

RESULTS

Across subjects, reaching directions, and loading conditions, the average reaching distances achieved by the subjects with the avatar feedback were significantly greater compared with the distances reached when playing *Air Hockey 3D* ($p < 0.05$). Table 1 summarizes the within-subjects effects and Table 2 summarizes the between-subjects effects, resulting from the statistical analysis. All factors and almost all interactions had a significant effect on distance. Only the interaction between feedback mode, loading condition, and subject had no effect on distance.

Post hoc analyses (Table 3) revealed that for some individual subjects, target directions, and loading conditions, the opposite was true: subjects were able to reach farther with *Air Hockey 3D*. Figure 4 shows that subject 3 was able to reach farther in the elbow extension direction across loading conditions while subjects 5, 6, and 7 were only able to reach farther in elbow extension on both FS and FL, L25, and FL, respectively. Furthermore, *Air Hockey 3D* aided subject 6 in reaching in the RE direction during L25, and subject 1 could reach farther in the SF direction during FS. Table 3 includes the test statistics for loading conditions highlighted in gray.

Figure 5 shows typical data for a single subject (subject 2). The thin color traces show the trajectories generated when reaching to each of the three targets (SF, RE, and EE) and the blue triangles indicate the maximum reaching distance in the direction of each target. Note that the location of the targets was not scaled to the length of the arm and therefore, subjects could overshoot the target in some directions. The cyan envelopes (thick lines) represent the farthest reached distance in all directions achieved with the game for the original hand to mouse movement mapping and for the adjusted mapping that encouraged elbow extension (see "Methods" section). The black arcs represent the theoretical workspace of the arm based on its length. Figure 5 presents the avatar- and game-reaching workspace for FS (Figure 5(a)), FL (Figure 5(b)), and L25 (Figure 5(c)). For the subject illustrated here, the reaching performance compared between the avatar and game feedback was similar for all target directions and loading conditions except for the EE direction and the SF direction during L25. It is clear that the subject reached farther with the avatar feedback compared with the game feedback in these conditions.

The average difference in distance between the avatar and game feedback across subjects, target directions, and loading conditions was 6.0 cm. The difference was 2.0 cm in the EE direction, 6.3 cm in the RE direction, and 9.7 cm in the SF direction.

The reaching distances achieved with both the avatar and game feedback across subjects became significantly smaller when increasing shoulder abduction loading from FS to FL to L25 ($p < 0.05$). Figure 5 illustrates the reduction in reaching ability for a typical subject, especially when comparing L25 with FS.

All subjects chose *Air Hockey 3D* over the avatar as the more engaging feedback as well as the feedback of choice for hypothetical interventions.

DISCUSSION

This study evaluated the effect of a video game environment on reaching in stroke with various levels of support. We compared the reaching distances achieved while playing the video game with the reaching distances achieved when reaching to specific targets in the workspace with feedback provided by an avatar of the arm displayed on a computer monitor. The results of the study showed significantly greater distances achieved with the avatar visual feedback compared with the game visual feedback across subjects, loading conditions, and reaching directions. This held even after further restricting the mapped workspace of the arm to the area most affected by the flexion synergy (effectively forcing subjects to fight the synergy to reach the hockey puck). Although this result was unexpected, it was not surprising. Given the somewhat uncontrolled movement of the hockey puck, it was not unusual for subjects to adopt a defensive strategy to guard the goal line, instead of an offensive strategy that would force them to reach out against the flexion synergy. Verbal encouragement was provided in all cases, however, with little effect. Subjects avoided reaching in the areas of the workspace that required elbow extension, which demanded additional effort to fight the flexion synergy.

Task Versus Impairment-Based Rehabilitation Robotics

Although most rehabilitation robotic systems with integrated video games focus on a task-oriented therapeutic approach, recent work from a Massachusetts Institute of Technology group [51] suggests that robotic therapy aimed at impairment reduction may be the most effective use of robotic technology. This supports previous findings by Platz et al. that suggest that the specific content of training is key for motor control recovery in severely impaired people with hemiparetic stroke [52]. These studies, in conjunction with recent intervention studies performed in our laboratory [11–12,53], support our stance on the development of impairment-based robotic interventions that use video games to create a fun and engaging experience for the subject.

The choice of a game like *Air Hockey 3D* was based on its requirement for reaching movements, which combined with various levels of arm support generated by the haptic interface, translated it from a simple video game into an impairment-based therapeutic approach. Previously, Carignan and Krebs reported on the use of an air hockey game for interactive telerehabilitation based on the premise that the therapeutic outcome was improved when the therapy involved video games rather than routine exercises [54]. Additional research that compares the therapeutic effects of impairment versus functional task-oriented robotics rehabilitation systems is clearly warranted. Furthermore, development of such systems needs to be driven by scientific findings on the exact nature of the movement impairments present in people with stroke.

Rehabilitation Robotic Systems for Moderately to Severely Impaired Subjects with Stroke

Most rehabilitation robotics and virtual reality systems reported in the literature target the wrist and hand, which exhibit poor to nonexistent control in moderately to severely impaired people with stroke. Even some systems that target the shoulder and elbow require some level of hand control to hold onto the endpoint of the device, which again is only possible in mildly impaired people with stroke. However, it is the moderately to severely impaired segment of the stroke population that has the greatest need for rehabilitation programs to restore motor function of the paretic upper limb. For this reason, this study only included moderately to severely impaired subjects with stroke, and they are the focus of the intervention work and the targeted population of future development of rehabilitation video games combined with robotic systems in our group.

Future Development of Impairment-Based Rehabilitation Systems

An important finding of the current study is that video games such as *Air Hockey 3D*, where specific reaching targets are not present and do not directly affect the success in the game, may not be sufficient to promote reaching in parts of the workspace compromised by the expression of the flexion synergy post brain injury. Games in which the reaching targets are located in the workspace affected by the flexion synergy are expected to encourage better performance, while at the same time keeping the interest and motivation of the subject. An added advantage of the future development of such video games is that targets can be adjusted online as subjects become more successful in reaching them as the therapeutic protocol progresses.

In an effort to test the enthusiasm for *Air Hockey 3D*, we required subjects to complete a survey that asked which feedback method they preferred. Although we did not analyze results from the survey for statistical significance, anecdotal evidence pointed to *Air Hockey 3D* as the preferred method for performance of reaching movements. We had subjects who would continue playing the video game even after the data collection had concluded. Further investigation into the effects of using a video game such as *Air Hockey 3D* on long-term therapeutic interventions is warranted by the enthusiastic response from the subjects in our study. It is possible that although we did not see an advantage over the simple avatar feedback in a single session, the effect of impairment-based repeated exercise in an engaging environment can generate greater motor functional gains.

In recent years there has been a significant increase in the use of video game systems for exercise and physical activity in widespread populations. An example of such a system is the game *Wii Fit Plus* (Nintendo Co. LTD; Kyoto, Japan) for the Wii console system (Nintendo Co. LTD), where users can create specialized workout routines. The early success with the Wii shows that there is great interest in this approach where exercise and therapy can be a fun and engaging experience. Now is the time to apply the same principles to stroke rehabilitation in the development of virtual reality and robotic systems fully integrated with video games to enhance the outcomes of therapeutic interventions. Furthermore, it will be a requirement for these systems to integrate haptics and robotics to allow direct treatment of impairments like weakness and the loss of independent joint control. It should be noted that not all robotic systems include or even have the ability to provide haptic feedback, while the converse is also true; not all haptic systems rely on robotics. Finally, the anecdotal evidence gathered from the subjects in this study in conjunction with our experience in stroke rehabilitation elicits great enthusiasm for a video game approach. Our goal is that in the near future, people with stroke will unknowingly receive therapy while playing fun and challenging video games.

CONCLUSIONS

This study examined the effect of visual feedback on the reaching performance of moderately to severely impaired people with stroke by comparing an avatar of the arm with the *Air Hockey 3D* video game. Subjects performed the reaching tasks and played *Air Hockey 3D* under three shoulder loading conditions. The results from the study showed that the reaching distances achieved with the avatar feedback were greater on average than those achieved with *Air Hockey 3D* across conditions. In some conditions, however, subjects were able to reach farther while playing the game. In addition, subjects unanimously chose *Air Hockey 3D* over the avatar as the optimal feedback for rehabilitation interventions. Although the results of this study showed, on average, better performance for the task-oriented paradigm, the exceptions, plus the unanimous acceptance of the video game, showed that there is promise in the development of rehabilitation video games and robotic systems that target specific impairments like the loss of independent joint control. The combination of video games and robotics to create a haptic interface will allow the design of video games that include specific reaching targets in the workspace compromised by the expression of the loss of independent joint control following stroke. The ultimate goal will be to develop video games that directly address movement impairments in order to be useful for stroke rehabilitation while providing a fun and challenging experience. Further research studies will need to validate the use of video games as an effective rehabilitation tool.

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Abbreviations

ACT^{3D}	Arm Coordination Training 3D
ADL	activity of daily living
DOF	degree of freedom
EE	elbow extension target
FL	arm floating condition
FMA	Fugl-Meyer Motor Assessment
FS	arm fully supported condition
L25	25 percent loading condition
RE	reaching target
ROM	range of motion
SF	shoulder flexion target

References

1. Dewald JP, Pope PS, Given JD, Buchanan TS, Rymer WZ. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain. 1995; 118(Pt 2):495–510.10.1093/brain/118.2.495 [PubMed: 7735890]

2. Beer RF, Dewald JP, Dawson ML, Rymer WZ. Target-dependent differences between free and constrained arm movements in chronic hemiparesis. Exp Brain Res. 2004; 156(4):458–70.10.1007/s00221-003-1807-8 [PubMed: 14968276]
3. Sukal TM, Ellis MD, Dewald JP. Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: Neuroscientific implications. Exp Brain Res. 2007; 183(2):215–23.10.1007/s00221-007-1029-6 [PubMed: 17634933]
4. De Kroon JR, IJzerman MJ, Chae J, Lankhorst GJ, Zilvold G. Relation between stimulation characteristics and clinical outcome in studies using electrical stimulation to improve motor control of the upper extremity in stroke. J Rehabil Med. 2005; 37(2):65–74.10.1080/16501970410024190 [PubMed: 15788340]
5. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. Neurorehabil Neural Repair. 2008; 22(2):111–21.10.1177/1545968307305457 [PubMed: 17876068]
6. McCombe Waller S, Whitall J. Bilateral arm training: Why and who benefits? NeuroRehabilitation. 2008; 23(1):29–41. [PubMed: 18356587]
7. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D. EXCITE Investigators. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The EXCITE randomized clinical trial. JAMA. 2006; 296(17):2095–2104. [PubMed: 17077374]
8. Thom T, Haase N, Rosamond W, Howard VJ, Rumsfeld J, Manolio T, Zheng ZJ, Flegal K, O'Donnell C, Kittner S, Lloyd-Jones D, Goff DC Jr, Hong Y, Adams R, Friday G, Furie K, Gorelick P, Kissela B, Marler J, Meigs J, Roger V, Sidney S, Sorlie P, Steinberger J, Wasserthiel-Smoller S, Wilson M, Wolf P. American Heart Association Statistics Committee and Stroke Statistics Subcommittee. Heart disease and stroke statistics—2006 update: A report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee. Circulation. 2006; 113(6):e85–151.10.1161/CIRCULATIONAHA.105.171600 [PubMed: 16407573]
9. Dewald JP, Sheshardi V, Dawson ML, Beer RF. Upper limb discoordination in hemiparetic stroke: Implications for neurorehabilitation. Top Stroke Rehabil. 2001; 8(1):1–12.10.1310/WA7K-NGDF-NHKK-JAGD [PubMed: 14523747]
10. Ellis MD, Holubar BG, Acosta AM, Beer RF, Dewald JP. Modifiability of abnormal isometric elbow and shoulder joint torque coupling after stroke. Muscle Nerve. 2005; 32(2):170–78.10.1002/mus.20343 [PubMed: 15880629]
11. Ellis MD, Sukal-Moulton TM, Dewald JP. Impairment-based 3-D robotic intervention improves upper extremity work area in chronic stroke: Targeting abnormal joint torque coupling with progressive shoulder abduction loading. IEEE Trans Robot. 2009; 25(3):549–55. [PubMed: 20657711]
12. Ellis MD, Sukal-Moulton T, Dewald JP. Progressive shoulder abduction loading is a crucial element of arm rehabilitation in chronic stroke. Neurorehabil Neural Repair. 2009; 23(8):862–69.10.1177/1545968309332927 [PubMed: 19454622]
13. Reinkensmeyer DJ, Kahn LE, Averbuch M, McKenna-Cole A, Schmit BD, Rymer WZ. Understanding and treating arm movement impairment after chronic brain injury: Progress with the ARM guide. J Rehabil Res Dev. 2000; 37(6):653–62. [PubMed: 11321001]
14. Krebs HI, Hogan N, Volpe BT, Aisen ML, Edelstein L, Diels C. Overview of clinical trials with MIT-MANUS: A robot-aided neuro-rehabilitation facility. Technol Health Care. 1999; 7(6):419–23. [PubMed: 10665675]
15. Burgar CG, Lum PS, Shor PC, Machiel Van der Loos HF. Development of robots for rehabilitation therapy: The Palo Alto VA/Stanford experience. J Rehabil Res Dev. 2000; 37(6):663–73. [PubMed: 11321002]
16. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. Arch Phys Med Rehabil. 2003; 84(6):915–20.10.1016/S0003-9993(02)04954-7 [PubMed: 12808550]
17. Masiero S, Celia A, Armani M, Rosati G. A novel robot device in rehabilitation of post-stroke hemiplegic upper limbs. Aging Clin Exp Res. 2006; 18(6):531–35. [PubMed: 17255643]

18. Fazekas G, Horvath M, Toth A. A novel robot training system designed to supplement upper limb physiotherapy of patients with spastic hemiparesis. Int J Rehabil Res. 2006; 29(3):251–54.10.1097/01.mrr.0000230050.16604.d9 [PubMed: 16900048]
19. Nef T, Mihelj M, Riener R. ARMin: A robot for patient-cooperative arm therapy. Med Biol Eng Comput. 2007; 45(9):887–900.10.1007/s11517-007-0226-6 [PubMed: 17674069]
20. Bergamasco, M.; Borelli, L.; Carboncini, MC.; Frisoli, A.; Marcheschi, S.; Montagner, A.; Procopio, C.; Rossi, B.; Salsedo, F.; Tolaini, M. Arm rehabilitation with a robotic exoskeleton in virtual reality. Proceedings of the IEEE 10th International Conference on Rehabilitation Robotics; 2007 Jun 13–15; Noordwijk, the Netherlands. p. 631-42.
21. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, IJzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. J Rehabil Res Dev. 2006; 43(2):171–84.10.1682/JRRD.2005.04.0076 [PubMed: 16847784]
22. Henderson A, Korner-Bitensky N, Levin M. Virtual reality in stroke rehabilitation: A systematic review of its effectiveness for upper limb motor recovery. Top Stroke Rehabil. 2007; 14(2):52–61.10.1310/tsr1402-52 [PubMed: 17517575]
23. Mumford N, Wilson PH. Virtual reality in acquired brain injury upper limb rehabilitation: Evidence-based evaluation of clinical research. Brain Inj. 2009; 23(3):179–91.10.1080/02699050802695566 [PubMed: 19205954]
24. Lucca LF. Virtual reality and motor rehabilitation of the upper limb after stroke: A generation of progress? J Rehabil Med. 2009; 41(12):1003–1100.10.2340/16501977-0405 [PubMed: 19841832]
25. Broeren J, Claesson L, Goude D, Rydmark M, Sunnerhagen KS. Virtual rehabilitation in an activity centre for community-dwelling persons with stroke. The possibilities of 3-dimensional computer games. Cerebrovasc Dis. 2008; 26(3):289–96.10.1159/000149576 [PubMed: 18667809]
26. Broeren J, Rydmark M, Sunnerhagen KS. Virtual reality and haptics as a training device for movement rehabilitation after stroke: A single-case study. Arch Phys Med Rehabil. 2004; 85(8): 1247–50.10.1016/j.apmr.2003.09.020 [PubMed: 15295748]
27. Fischer HC, Stubblefield K, Kline T, Luo X, Kenyon RV, Kamper DG. Hand rehabilitation following stroke: A pilot study of assisted finger extension training in a virtual environment. Top Stroke Rehabil. 2007; 14(1):1–12.10.1310/tsr1401-1 [PubMed: 17311785]
28. Holden MK, Dyar TA, Dayan-Cimadoro L. Telerehabilitation using a virtual environment improves upper extremity function in patients with stroke. IEEE Trans Neural Syst Rehabil Eng. 2007; 15(1):36–42.10.1109/TNSRE.2007.891388 [PubMed: 17436874]
29. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabil Neural Repair. 2009; 23(5):505–14.10.1177/1545968308331148 [PubMed: 19237734]
30. Kuttuva M, Boian R, Merians A, Burdea G, Bouzit M, Lewis J, Fensterheim D. The Rutgers Arm, a rehabilitation system in virtual reality: A pilot study. Cyberpsychol Behav. 2006; 9(2):148–51.10.1089/cpb.2006.9.148 [PubMed: 16640468]
31. Reinkensmeyer DJ, Pang CT, Nessler JA, Painter CC. Web-based telerehabilitation for the upper extremity after stroke. IEEE Trans Neural Syst Rehabil Eng. 2002; 10(2):102–8.10.1109/TNSRE.2002.1031978 [PubMed: 12236447]
32. Sivak M, Mavroidis C, Holden MK. Design of a low cost multiple user virtual environment for rehabilitation (MUVER) of patients with stroke. Stud Health Technol Inform. 2009; 142:319–24. [PubMed: 19377177]
33. Stewart JC, Yeh SC, Jung Y, Yoon H, Whitford M, Chen SY, Li L, McLaughlin M, Rizzo A, Winstein CJ. Intervention to enhance skilled arm and hand movements after stroke: A feasibility study using a new virtual reality system. J Neuroeng Rehabil. 2007; 4:21.10.1186/1743-0003-4-21 [PubMed: 17587459]
34. Van der Kooij H, Prange GB, Krabben T, Renzenbrink GJ, De Boer J, Hermens HJ, Jannink MA. Preliminary results of training with gravity compensation of the arm in chronic stroke survivors. Conf Proc IEEE Eng Med Biol Soc. 2009; 2009:2426–29. [PubMed: 19965202]
35. Nef T, Quinter G, Müller R, Riener R. Effects of arm training with the robotic device ARMin I in chronic stroke: Three single cases. Neurodegener Dis. 2009; 6(5–6):240–51.10.1159/000262444 [PubMed: 19940461]

36. Merians AS, Poizner H, Boian R, Burdea G, Adamovich S. Sensorimotor training in a virtual reality environment: Does it improve functional recovery poststroke? Neurorehabil Neural Repair. 2006; 20(2):252–67.10.1177/1545968306286914 [PubMed: 16679503]
37. Piron L, Turolla A, Agostini M, Zucconi C, Cortese F, Zampolini M, Zannini M, Dam M, Ventura L, Battauz M, Tonin P. Exercises for paretic upper limb after stroke: A combined virtual-reality and telemedicine approach. J Rehabil Med. 2009; 41(12):1016–1102.10.2340/16501977-0459 [PubMed: 19841835]
38. Adamovich SV, Merians AS, Boian R, Tremaine M, Burdea GS, Recce M, Poizner H. A virtual reality based exercise system for hand rehabilitation post-stroke: Transfer to function. Conf Proc IEEE Eng Med Biol Soc. 2004; 7:4936–39. [PubMed: 17271420]
39. Staubli P, Nef T, Klamroth-Marganska V, Riener R. Effects of intensive arm training with the rehabilitation robot ARMin II in chronic stroke patients: Four single-cases. J Neuroeng Rehabil. 2009; 6:46.10.1186/1743-0003-6-46 [PubMed: 20017939]
40. Frisoli A, Bergamasco M, Carboncini MC, Rossi B. Robotic assisted rehabilitation in virtual reality with the L-EXOS. Stud Health Technol Inform. 2009; 145:40–54. [PubMed: 19592785]
41. Housman, SJ.; Le, V.; Rahman, T.; Sanchez, RJ.; Reinkensmeyer, DJ. Arm-training with T-WREX after chronic stroke: Preliminary results of a randomized controlled trial. Proceedings of the IEEE 10th International Conference on Rehabilitation Robotics; 2007 Jun 13–15; Noordwijk, the Netherlands. Los Alamitos (CA): IEEE; 2007.
42. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. Arch Phys Med Rehabil. 2002; 83(7):952–59.10.1053/apmr.2001.33101 [PubMed: 12098155]
43. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study. J Neuroeng Rehabil. 2006; 3:12.10.1186/1743-0003-3-12 [PubMed: 16790067]
44. Hesse S, Werner C, Pohl M, Rueckriem S, Mehrholz J, Lingnau ML. Computerized arm training improves the motor control of the severely affected arm after stroke: A single-blinded randomized trial in two centers. Stroke. 2005; 36(9):1960–66.10.1161/01.STR.0000177865.37334.ce [PubMed: 16109908]
45. MacClellan LR, Bradham DD, Whitall J, Volpe B, Wilson PD, Ohlhoff J, Meister C, Hogan N, Krebs HI, Bever CT Jr. Robotic upper-limb neurorehabilitation in chronic stroke patients. J Rehabil Res Dev. 2005; 42(6):717–22.10.1682/JRRD.2004.606.0068 [PubMed: 16680609]
46. Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. Scand J Rehabil Med. 1975; 7(1):13–31. [PubMed: 1135616]
47. Norkin, CC.; White, DJ. Measurement of joint motion: A guide to goniometry. Philadelphia (PA): F. A. Davis; 2009.
48. Hertling, D.; Kessler, RM. Management of common musculoskeletal disorders: Physical therapy principles and methods. Philadelphia (PA): J. B. Lippincott; 1996.
49. Sukal, TM.; Ellis, MD.; Dewald, JP. Source of work area reduction following hemiparetic stroke and preliminary intervention using the ACT 3D system. Proceedings of the Engineering in Medicine and Biology Society; 2006 Aug 30–Sep 3; New York, NY. Los Alamitos (CA): IEEE; 2006.
50. Brewer BR, Klatzky R, Matsuoka Y. Visual feedback distortion in a robotic environment for hand rehabilitation. Brain Res Bull. 2008; 75(6):804–13.10.1016/j.brainresbull.2008.01.006 [PubMed: 18394527]
51. Krebs HI, Mernoff S, Fasoli SE, Hughes R, Stein J, Hogan N. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: A pilot study. NeuroRehabilitation. 2008; 23(1):81–87. [PubMed: 18356591]
52. Platz T, Eickhof C, Van Kaick S, Engel U, Pinkowski C, Kalok S, Pause M. Impairment-oriented training or Bobath therapy for severe arm paresis after stroke: A single-blind, multicentre randomized controlled trial. Clin Rehabil. 2005; 19(7):714–24.10.1191/0269215505cr904oa [PubMed: 16250190]

53. Ellis MD, Acosta AM, Yao J, Dewald JP. Position-dependent torque coupling and associated muscle activation in the hemiparetic upper extremity. Exp Brain Res. 2007; 176(4):594–602.10.1007/s00221-006-0637-x [PubMed: 16924488]
54. Carignan CR, Krebs HI. Telerehabilitation robotics: Bright lights, big future? J Rehabil Res Dev. 2006; 43(5):695–710.10.1682/JRRD.2005.05.0085 [PubMed: 17123209]

Figure 1.

Experimental setup. Arm Coordination Training 3D system* provided haptic interface to simulate various loading conditions while subjects performed arm reaching movements with avatar and game feedback. *Sukal TM, Ellis MD, Dewald JP. Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: Neuroscientific implications. Exp Brain Res. 2007;183(2):215–23.[PMID: 17634933] DOI:10.1007/s00221-007-1029-6

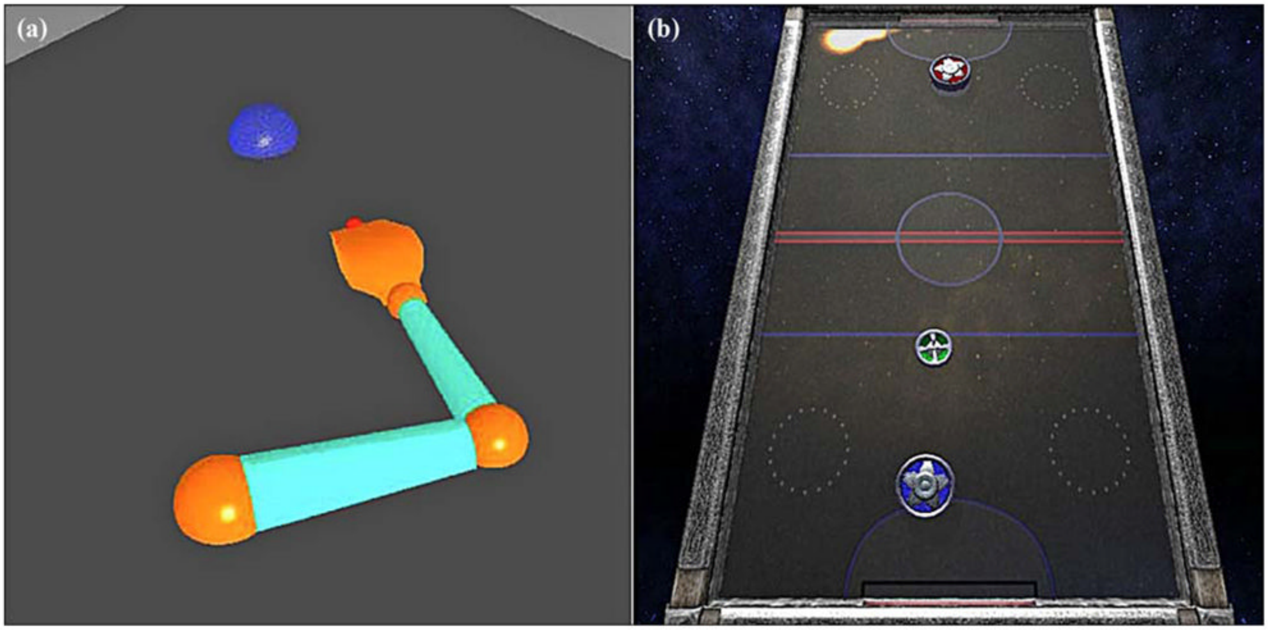

Figure 2.
Visual feedback. **(a)** Avatar of arm displayed on computer monitor with example target. **(b)** *Air Hockey 3D* (Avalanch Team; Novosibirsk, Russian Federation) video game. Notice that player side of table is on bottom half of display. Workspace of arm was mapped onto this half of table.

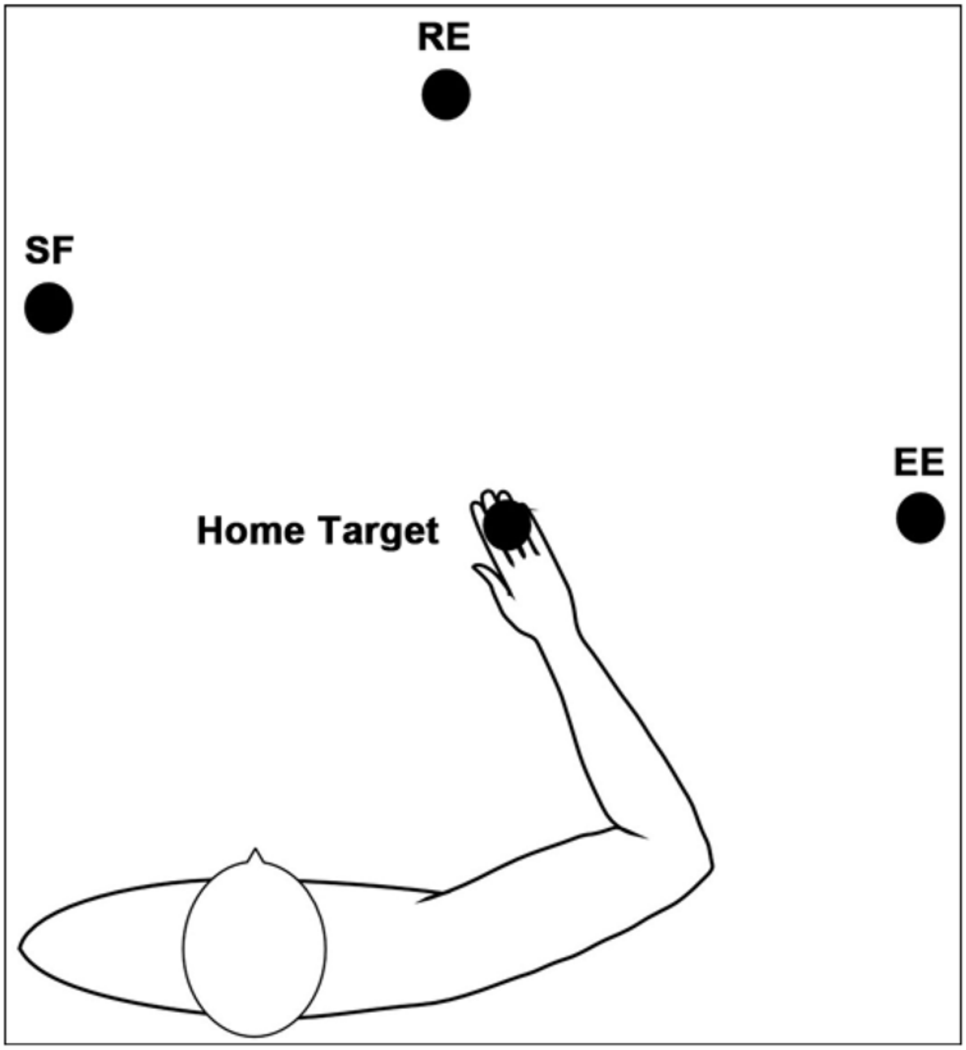

Figure 3.

Location of reaching targets used in avatar feedback trials. EE = elbow extension target, SF = shoulder flexion target, RE = reaching target.

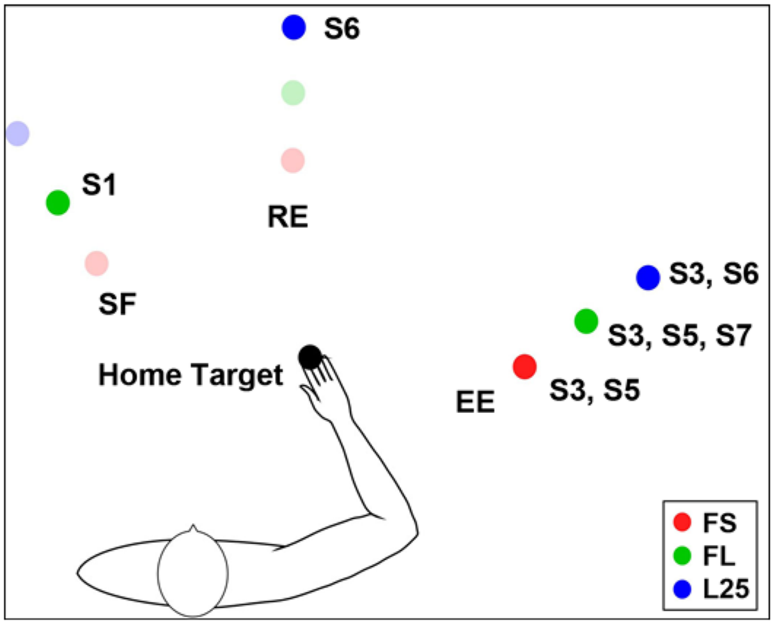

Figure 4.
Reaching performance. Five out of seven subjects were able to reach farther while playing video game compared with avatar feedback in certain target directions (SF, RE, or EE) and loading conditions (FS, FL, or L25) as indicated by blue, green, and red colored dots. Difference in reaching distance in each of these conditions was statistically significant ($p < 0.05$). EE = elbow extension target, FL = arm floating condition, FS = arm fully supported condition, L25 = 25% loading condition, RE = reaching target, S = subject, SF = shoulder flexion target.

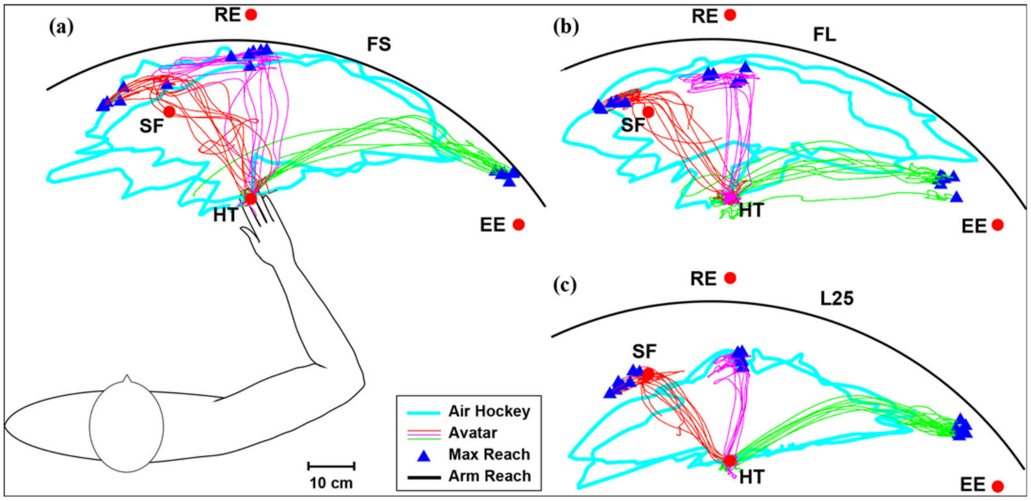

Figure 5.

Reaching performance. Each panel shows reaching performance for both avatar feedback (thin color lines) and game feedback (thick cyan lines). Subjects performed reaching movements with avatar feedback to three targets (SF, RE, and EE). Blue triangles indicate maximum reaching distance in direction of each target. Black arcs represent theoretical maximum arm reach based on arm length. Reaching performance on **(a)** FS, **(b)** FL, and **(c)** L25. EE = elbow extension target, FL = arm floating condition, FS = arm fully supported condition, HT = home target, L25 = 25% loading condition, Max = maximum, RE = reaching target, SF = shoulder flexion target.

Table 1

Statistical analysis results: tests of within-subjects effects.

Factor/Interaction	**Type III Sum of Squares**	***df***	**Mean Square**	***F*-Value**	***p*-Value**
Mode	0.535	1.000	0.535	258.864	$2.68E^{-16}$
Mode × Subject	0.655	5.000	0.131	63.440	$4.85E^{-15}$
Error (mode)	0.062	30.000	0.002	—	—
Load	0.713	2.000	0.357	67.325	$4.64E^{-16}$
Load × Subject	0.186	10.000	0.019	3.503	0.001
Error (load)	0.318	60.000	0.005	—	—
Direction	3.680	2.000	1.840	553.942	$2.10E^{-39}$
Direction × Subject	1.997	10.000	0.200	60.117	$1.75E^{-27}$
Error (direction)	0.199	60.000	0.003	—	—
Mode × Load	0.091	2.000	0.046	19.646	$2.74E^{-7}$
Mode × Load × Subject	0.045	10.000	0.004	1.928	0.059
Error (mode × load)	0.140	60.000	0.002	—	—
Mode × Direction	0.145	2.000	0.072	25.236	$1.11E^{-8}$
Mode × Direction × Subject	1.113	10.000	0.111	38.813	$1.69E^{-22}$
Error (mode × direction)	0.172	60.000	0.003	—	—
Load × Direction	0.108*	3.084	0.035	6.413	$4.77E^{-4}$
Load × Direction × Subject	0.383*	15.422	0.025	4.538	$1.86E^{-6}$
Error (load × direction)	0.506*	92.529	0.005	—	—
Mode × Load × Direction	0.067	4.000	0.017	7.016	$4.13E^{-5}$
Mode × Load × Direction × Subject	0.186	20.000	0.009	3.905	$1.45E^{-6}$
Error (mode × load × direction)	0.286	120.000	0.002	—	—

Note: Design = mode load direction mode × load mode × direction load × direction load × direction × mode.

[*] Sphericity assumption not met, *df* adjusted (Greenhouse-Geisser).

df = degrees of freedom.

Table 2

Statistical analysis results: tests of between-subjects effects.

Factor	Type III Sum of Squares	*df*	Mean Square	*F*-Value	*p*-Value
Intercept	83.217	1.000	83.217	55,817.591	$1.2E^{-50}$
Subject	0.067	5.000	0.013	9.000	$2.61E^{-5}$
Error	0.045	30.000	0.001	—	—

df = degrees of freedom.

Table 3

Results from post hoc comparisons. Test statistics for loading conditions highlighted in gray.

Direction	Load	Subject	Mean Difference (game–avatar)	*F*-Value	*p*-Value
EE	FS	2	−0.223	43.855	$6.96E^{-11}$
		3	0.128	16.753	$4.74E^{-5}$
		4	−0.187	35.901	$3.29E^{-9}$
		5	0.118	14.350	$1.65E^{-4}$
	FL	2	−0.214	47.248	$1.37E^{-11}$
		3	0.258	58.555	$6.42E^{-14}$
		4	−0.095	9.335	0.002
		5	0.104	11.197	0.001
		7	0.117	14.013	$1.96E^{-4}$
	L25	2	−0.284	83.239	$7.31E^{-19}$
		3	0.202	41.830	$1.85E^{-10}$
		4	−0.249	63.840	$5.42E^{-15}$
		6	0.072	5.348	0.021
RE	FS	1	−0.066	4.545	0.033
		2	−0.170	29.624	$7.22E^{-8}$
		3	−0.181	33.891	$8.81E^{-9}$
		4	−0.138	19.561	$1.13E^{-5}$
		5	−0.114	13.376	$2.74E^{-4}$
	FL	2	−0.144	21.326	$4.60E^{-6}$
		3	−0.187	35.959	$3.20E^{-9}$
		2	−0.132	17.884	$2.65E^{-5}$
		3	−0.124	15.860	$7.52E^{-5}$
		6	0.147	22.358	$2.73E^{-6}$
SF	FS	1	−0.074	5.704	0.017
		2	−0.192	37.918	$1.23E^{-9}$
		3	−0.184	34.875	$5.44E^{-9}$
		4	−0.158	25.591	$5.37E^{-7}$

Direction	Load	Subject	Mean Difference (game–avatar)	*F*-Value	*p*-Value
		5	−0.083	7.133	0.008
	FL	1	0.068	4.741	0.030
		2	−0.142	20.621	$6.57E^{-6}$
		3	−0.273	76.479	$1.59E^{-17}$
	L25	1	−0.087	7.854	0.005
		2	−0.093	8.836	0.003
		3	−0.342	120.532	$5.09E^{-26}$
		4	−0.088	7.885	0.005

EE = elbow extension target, FL = arm floating condition, FS = arm fully supported condition, L25 = 25 percent loading condition, RE = reaching target, SF = shoulder flexion target.