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Robotic Rehabilitation Game Design for Chronic Stroke

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Abstract

Objective: This study investigates games intended for use with an upper-limb exoskeleton robot operated unilaterally and bilaterally. Games are evaluated in terms of usability and preference for stroke survivors. Game design considerations relating to the human to machine interface, are also discussed.
Subjects and Methods: Ten hemiparetic stroke survivors completed 12 90-minute sessions using an upper-limb robotic exoskeleton unilaterally and bilaterally. During the sessions subjects played seven different games designed for rehabilitation. At the conclusion of their sessions subjects completed an 83-question survey.
Results: Subjects preferred static games to dynamic games. Preferred games elicited greater effort.
Conclusions: Intermediate goals in addition to ultimate goals should be set with both static and dynamic games such that even with the patient's limited range of motion, speed, or coordination, the game should be playable and provide a sense of accomplishment to the patient. Marking the games' ultimate goals that can be accomplished only by healthy subjects, such as range of motion and workspace, provide references and encouragement to the patient for improving motor control and performance through the process of playing the game.

Introduction

Approximately 750,000 individuals suffer a stroke each year in the United States.[1] The majority of survivors experience hemiparesis and require rehabilitation. Robotics has grown in popularity to assist patients in retraining.[1] Concurrently, games intended for rehabilitation have proliferated.[2] Naturally, playing such games in conjunction with a therapy robot will affect the gaming experience, and this paper will focus on those aspects. In the context of physical therapy, the game play is better described as "movement training" with the goal of providing rehabilitation.

The clinical framework of this research was to compare motor control recovery using three different treatment modalities: two-armed mirror-imaged bilateral symmetric therapy (bilateral), single-armed unilateral therapy (unilateral), and conventional physical therapy (usual care).[3] The study did not include controls for the types of games that were played. Like many such evaluations, the therapeutic effect of each game is confounded with the other games.[4] Therefore, the scope of this report is constrained to evaluate game usability and user's preference.[5] Evaluations of unilateral versus bilateral versus usual care are reported in part by other studies.[6,7] Certain aspects of game design and robotic control were intended to evaluate unilateral and bilateral movement training. Such considerations are not taken up in detail in this article. However, design considerations for integrating games with the robot are discussed.

Several commercially available gaming systems have been used to provide an unassisted interface between the disabled arm and a virtual therapy game. These systems include the Nintendo® Wii (Nintendo of America, Redmond, WA), the Sony (New York, NY) PlayStation® 3, and the Microsoft® (Redmond) Xbox.[8–11] For these systems the patients must actively move their arm(s) without physical assistance from the system.[12] For cases where assistance is desired, a robot is required.

The robot might provide full or partial assistance. In full assistance the robot could move even a passive, flaccid arm through its motions. Full assistance has been shown to result in diminished therapeutic effects.[13] The assistance provided in this study was partial assistance. The subjects had to actively move their arm(s) to play the games. The robot gave only assistance as needed.[14] Partial assistance has been shown to provide more effective therapy.[15]

Subjects and Methods

Subjects

Ten subjects affected by stroke received robotic-based movement training. Subjects ranged in age from 23 to 69 years and were in their chronic phase of recovery (>6 months

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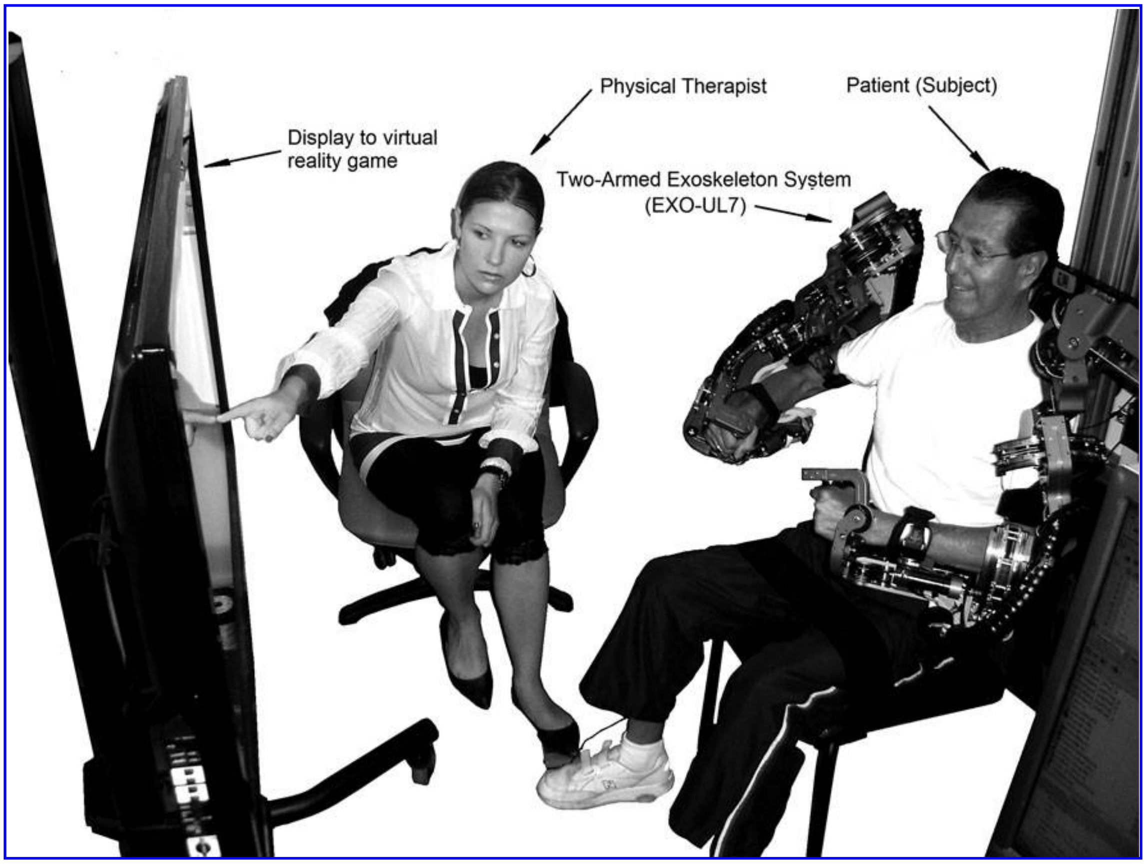

FIG. 1. The patient (subject) is pictured wearing the EXO. The physical therapist was referred to as a "coach" in the survey.

post-stroke). Stroke survivors may have reduced cognitive function.[16] Therefore, subjects were required to understand and follow instructions in English with a minimum score of 18 on the Mini-Mental Status Examination. Subjects had to score between 16 and 39 on the upper-limb portion of the Fugl–Meyer assessment.

Each subject was scheduled to participate in 12 sessions. Each session was 90 minutes in duration. Subjects played seven different games for 10–15 minutes each. The experimental setup is depicted in Figure 1.

The research was approved by the University of California, San Francisco, Committee on Human Research. All subjects provided written consent prior to participating.

Apparatus

The EXO-UL7 used for this study consists of two robotic exoskeleton arms for the upper limbs.[17–22] For bilateral movement training, a teleoperation mode was used in which the least affected arm was the master, and the affected arm was the slave. For bilateral, when a subject moved his or her unaffected arm, the EXO-UL7 provided mirror-image partial assistance for the affected arm.[7] Only the "Flower" game provided unilaterally assisted movement training. For unilateral assistance, the robot helped move the subject's affected arm to play the game, while the unaffected arm remained at rest.

Games

The goal of each game is summarized in Table 1 and visual screen is depicted in Figure 2. Two of the games, "Flower" and "Paint," were intended to provide constrained reaching tasks that were used to prepost data analysis and diagnostics. "Flower" comprised 12 ball target sets in various configurations. Figure 2a depicts one such set. The purpose of "Flower" was to quantify various reaching trajectory metrics.[23] The "Paint" game provided a touchable surface and was intended to quantify changes in range of motion (ROM) (Fig. 2b). "Paint" quantified the percentage of the surface that was touched, or "painted."

The games "Reach," "Pong," "Pinball," "Circle," and "Handball" were designed to be not only therapeutic, but also intellectually stimulating. The "Reach" game was intended to improve ROM and is similar in design to "Paint." Dynamic

Table 1. Games

Game	*Static/ Dynamic*	*Goal of game*
"Flower"	S	For each set, touch center ball with the ball fixed at fingertips.
"Paint"	S	Touch as many balls as possible along a semi-spherical array.
"Reach"	S	Touch as many balls as possible.
"Pong"	D	Deflect a ball against a computer opponent with a paddle.
Pinball	D	Left and right paddle actuation using wrist flexion
"Circle"	D	Similar to "Pong," the ball is constrained to a cylinder.
"Handball"	D	Subject bounces a ball off of a distant wall.

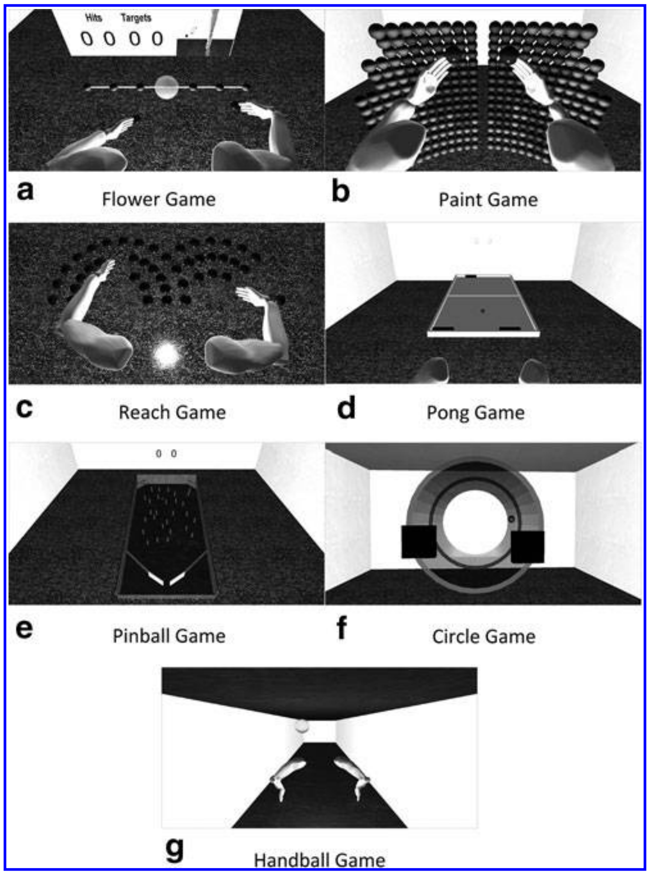

FIG. 2. **(a–g)** Screen shots from the various games. Note that only the avatar arms are rendered for greater visibility.

games were analogous to the well-known "Pong-style" games. In "Pong-style" games the play involves a paddle that is used to deflect a moving ball. These types of games have been recommended as a good choice for motor deficit rehabilitation.[24] "Pong-style," dynamic games included "Pong," "Pinball," "Circle," and "Handball." Static games including "Flower," "Paint," and "Reach" involved fixed targets.

Measures

Position and force information were recorded for each game. Joint position data for both arms were measured using optical encoders. Forces and torques were measured with ATI (Apex, NC) Mini40 transducers. The humerus transducer was located at the lateral upper right arm, the forearm transducer was located near the ulnar styloid, and the hand transducer was located roughly between the handle and the exoskeleton structure.

Following the completion of the experimental protocol an 83-question survey was administered. Seventy-eight questions were based on a 5-point Likert scale.

One question asked subjects to rank games in order of preference. A Friedman test was performed on the ranking using the following expression:

$$\chi^2 = \frac{N\sum(\mu_g - \mu_{all})^2}{k(k+1)/12} \tag{1}$$

where N is the number of respondents, and k is degrees of freedom (i.e., the number of games being ranked). The symbol μ_g denotes the group average score for each game, and μ_{all} is the average score for all games. The numerical scores used in Eq. 1 were equal to the (number of games) + 1 − (game ranking).

Forces were recorded along orthonormal axes and are reported here as the magnitude of their vector sum. Average forces (μ values) were calculated using the following expression:

$$\mu = \frac{\sum\sqrt{x_i^2 + y_i^2 + z_i^2}}{n} \tag{2}$$

For Eq. 2, n is the number of samples. The variables x, y, and z are the projections of force onto the coordinate frame defined by the force sensor for the i^{th} timestamp in the dataset.

Results

The Pareto chart in Figure 3 depicts the game rankings. Analysis according to Eq. 1 resulted in a χ^2 of 36.3, $k = 7$, and a P value < 0.001.[18] The data suggest that the observed differences among the average rankings for the seven games is not due to random variability. A Friedman test was then done to evaluate only the relative ranking of the "Paint," "Flower," and "Reach" games ($k = 3$). There was no statistically significant difference for the ranking of these three games ($P = 0.16$). In other words, even though the top three games consistently ranked in the top 3, their relative ranking was in no particular order.

Responses were evaluated by how strongly respondents agreed or disagreed with survey statements. Rows a–g in Table 2 summarize statements that elicited strong affects. Rows h–j summarize opinions on robotic assistance. Rows k–p summarize subjects' opinions about adding hardware and software features that were not included in this study.

The "Flower" and "Paint" games had a region in the upper-distal corner of the reachable space that was difficult to touch for nearly every stroke subject. This region is drawn in Figure 4.

Correlation matrices were generated for all Likert scale responses. Two statements with a large Pearson's correlation coefficient ($\rho > 0.7$) would suggest that the two statements could be interpreted as saying much the same thing. Table 3 summarizes the questions with significant correlations.

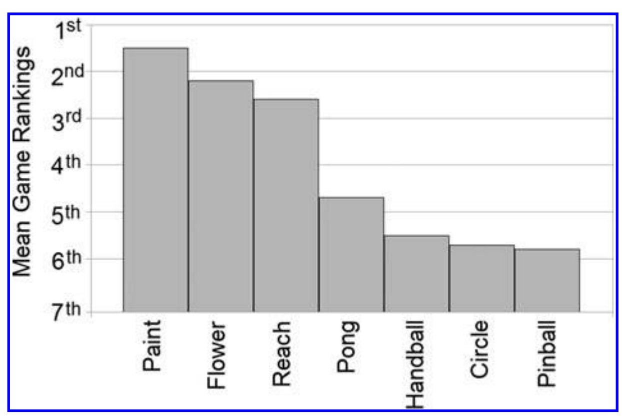

FIG. 3. Pareto chart of average game rankings. Respondents were asked to rank their favorite game as #1, their second favorite game as #2, and so on.

Table 2. Conspicuous Survey Responses for Games

	Question	Average response	Percentile	Question summary
Strong agreement				
a	12	4.5	99%	"Paint": Easy to learn
b	19	4.3	97%	"Paint": Entertaining
c	20	4.1	96%	"Paint": Perceived improvement
d	21	4.4	95%	"Reach": Easy to learn
Strong disagreement				
e	2	2.0	4%	"Flower": Too difficult to play
f	13	1.7	4%	"Paint": Too difficult to play
g	36	2.0	4%	"Pong": Physically tiring
Assistance				
h	11	2.0	1%	Full assistance as better than partial assistance
i	69	3.7	80%	Assistance needed for all games
j	10	3.8	83%	Unilateral assistance preferred for "Flower" game
Extra features				
k	66	3.4	62%	Include sound effects
l	67	3.5	68%	Include haptic interactions with virtual objects
m	76	3.3	66%	Include three-dimensional monitors
n	77	3.0	45%	Include virtual reality helmet with head tracking
o	71	3.6	76%	Include real time scoring
p	72	3.7	81%	Include scoring history from past sessions

Likert scale questions ranged from 1 for "strongly disagree" to 5 for "strongly agree."

Figure 5 depicts the hand trajectory of subject 6 in session 9 trying to reach a target (data not shown) that is located near the boundary of the subject's limited ROM.

The more area reached by subjects in the "Paint" game is a measure of proficiency. Figure 6 depicts the percentage area reached in "Paint" for all subjects over the course of the study. The reaching trajectories in Figure 5 were captured during session 9. Note that by session 9 subjects are relatively proficient at Paint" (Fig. 6). Therefore, the inability of the subject to reach the entire surface in Figure 5 is more a function of their disability than in learning the game, indicating improved motor control over time.

Figure 7 depicts a subject making multiple reaching attempts for a target at the subject's limited ROM boundary. The subject was observed using ballistic motions to reach difficult targets. Another strategy included approaching targets from different directions. At other times subjects would simply strain with their hand fixed in space as they tried to move a bit farther.

For perspective on the amount of assistance provided, bilateral partial assistance forces for one session of "Paint" are provided in Table 4 and were calculated according to Eq. 2. Peak forces in Table 4 might have resulted from small impacts or from bumps of the subject's arms against the force sensors during game play. On average, the robot provided a modest 16 N of partial assistance.

Finally, subjects were asked how long they would prefer to play each type of game for 90-minute session. The mean response was 10.9 minutes, with a standard deviation of 2.5 minutes.

Discussion

Range of motion (ROM)

The ranking in Figure 3 shows a preference for static games over the dynamic games. This is partially explained by certain difficulties observed during game play. ROM is one of the more difficult aspects of game design for the disabled.[25] Among other things, the reachable space for stroke survivors is often diminished.[26] Although ROM limitations caused frustration for some games, in other games it was a source of welcome challenge. As an example of limited ROM causing frustration, consider "Pong." While playing "Pong" subjects must sometimes move beyond their limited ROM. As is depicted in Figure 8, if the ball is traveling to a location far enough to the right, then the subject may miss the ball and lose a point. Similar situations occurred for "Circle," "Pinball," and "Handball." Accordingly, games should be designed such that ROM does not impede game play.

The "Paint," "Flower," and "Reach" games are examples of games that successfully exploit limited ROM by engendered more effort. With regard to "Paint," the hand trajectory in Figure 5 reveals the tendency of subjects to dwell on targets at the boundary of their ROM. In the first minute of play (Fig. 5a), the subject has already reached a large swath of the surface. By 430 seconds the subject has reached approximately 97 percent of the surface. Approximately half of the time was spent trying to reach the remaining 3 percent of the surface at the boundary of the subject's ROM. As is evident from the repeated reaching attempts in Figure 7, the "Flower" game provides another good example for promoting greater effort. In contrast, for dynamic games the subjects were only given isolated attempts to deflect the ball before losing a point. If the ball was repeatedly missed at a location outside of the subject's ROM, the subjects often became frustrated and disinterested.

Although static games were preferred, the games did lack a sense of pace. One possible game improvement for static games might be to make time more of a significant factor. Subjects could be given a time limit for reaching static targets.[27] Perhaps the game could include a scoring scheme that rewards faster reaching. To this end, one subject commented on his survey about "Paint" that "A countdown timer would have made [the game] more challenging as well with every second going past causing deduction in points and another ball being unlit."

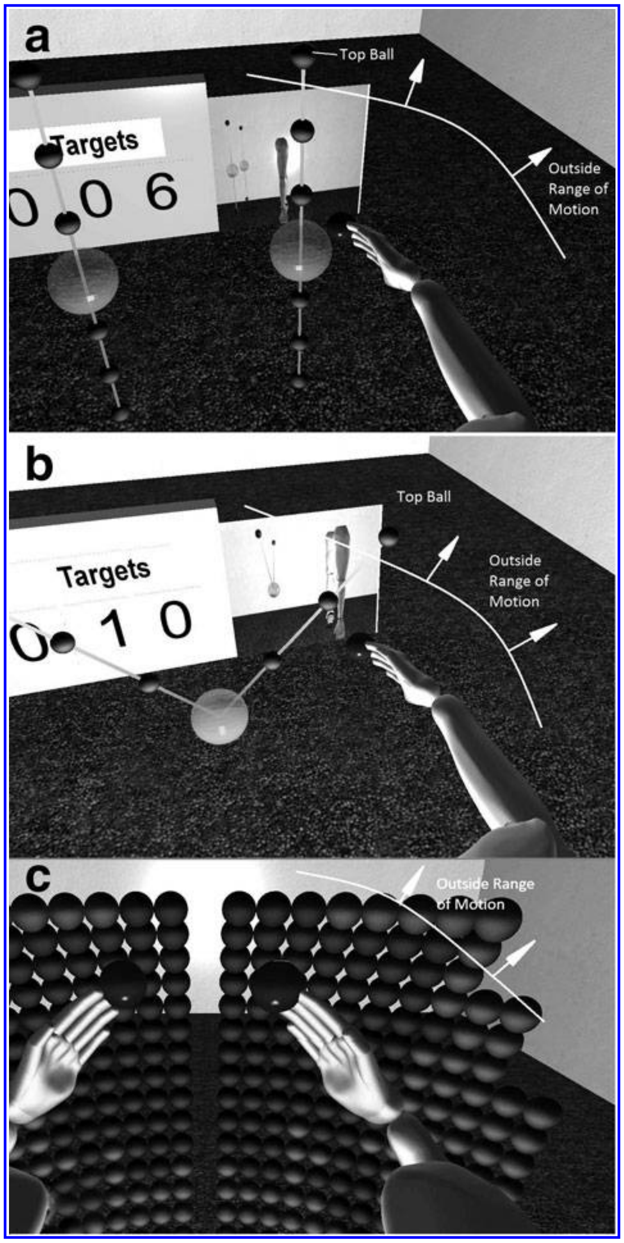

FIG. 4. **(a–c)** Difficult to reach areas resulting from limited range of motion in the paretic right arm. Note that range of motion is subject specific and that these boundaries are generalizations.

Preferences of stroke survivors

Games that are tailored to a particular type of disability are not necessarily going to be favored by the general population.[27] An unexpected result of this study was the fact that diagnostic tools, "Flower" and "Paint," were not only well tolerated but were actually preferred. They scored highest in terms of preference and perceived therapeutic benefit. Indeed, some commercial games have been adapted as therapy games, and, in some cases, commercial games have been used directly as a form of therapy.[28] In part, the motivation for adapting such games is to draw attention from arduous rehabilitation exercises.[25,29] It is often assumed that games for stroke survivors must be easier to play than games designed for the general public. "Pong" fits this requirement in being easy to play and understand.[16] However, oversimplifying the games is also a potential mistake. Anecdotally, not very many adults recreationally play "Pong-style" games, and "Pong" was not preferred in this study. To that end, "Pong" was once a popular format in early videogames. Likewise, all of the dynamic games in this study were modeled after popular commercial games to some extent. Conversely, the static games were never expected to be especially interesting. After all, the static games were tantamount to nothing more than moving a cursor to fixed locations. Therefore, the preference for static games ("Paint," "Flower," and "Reach") suggests that they are good examples of games that are specifically preferred by the stroke population.

Table 3. Questions with High Correlation

	Question	P	*Summary of questions*
a	73	0.84	Feedback—affirmative language
	74		Feedback—critical language
b	71	0.70	Feedback—current score
	72		Feedback—scoring history
c	6, 17, 26, 35, 44, 53, 62	0.83	Usability—graphics
	1, 12, 21, 30, 39, 48, 57		Usability—game rules
d	6, 17, 26, 35, 44, 53, 62	0.74	Usability—graphics
	4, 15, 25, 33, 43, 52, 61		Usability—Control
e	6, 17, 26, 35, 44, 53, 62	0.79	Usability—graphics
	8, 19, 28, 37, 46, 55, 64		Entertainment value
f	9, 20, 29, 38, 47, 56, 65	0.79	Therapeutic affect—perceived
	8, 19, 28, 37, 46, 55, 64		Entertainment value

Significant correlations existed between survey questions.

The strong opinion given in Table 2, rows a–g, are consistent with the game rankings. Subjects tended to score "Paint," "Flower," and "Reach" in a favorable light. Conversely, unpopular games, such as "Pong," received unfavorable scores. Several questions were designed to gauge subjects' opinions on robotic assistance. Subjects believed that partial robotic assistance was beneficial (see rows j and k), and they strongly believed that the robot should only provide partial assistance (row i).

Subjects were also asked for their opinions on additional hardware and software features (Table 2, rows l–q). Subjects were only tepidly in favor of including all of the features given. An analysis of variance was performed on the data in Table 2, rows l–q. Overall, no single feature had a statistically significant difference in user preference from the others. All things being equal, haptics, three-dimensional displays, and head tracking helmets could add significant costs to the system. Alternatively, a scoring systems or sound effects are relatively easy and inexpensive to implement. Thus, from a cost perspective, a good scoring system and sound effects are recommended.[30,31]

Making realistic games for stroke survivors proved problematic. The "Handball" beta-version game used a basketball-sized, fast-moving sphere that rebounded proportionately to the subject's arm speed when swatted. During preliminary game evaluations with a stroke survivor, the

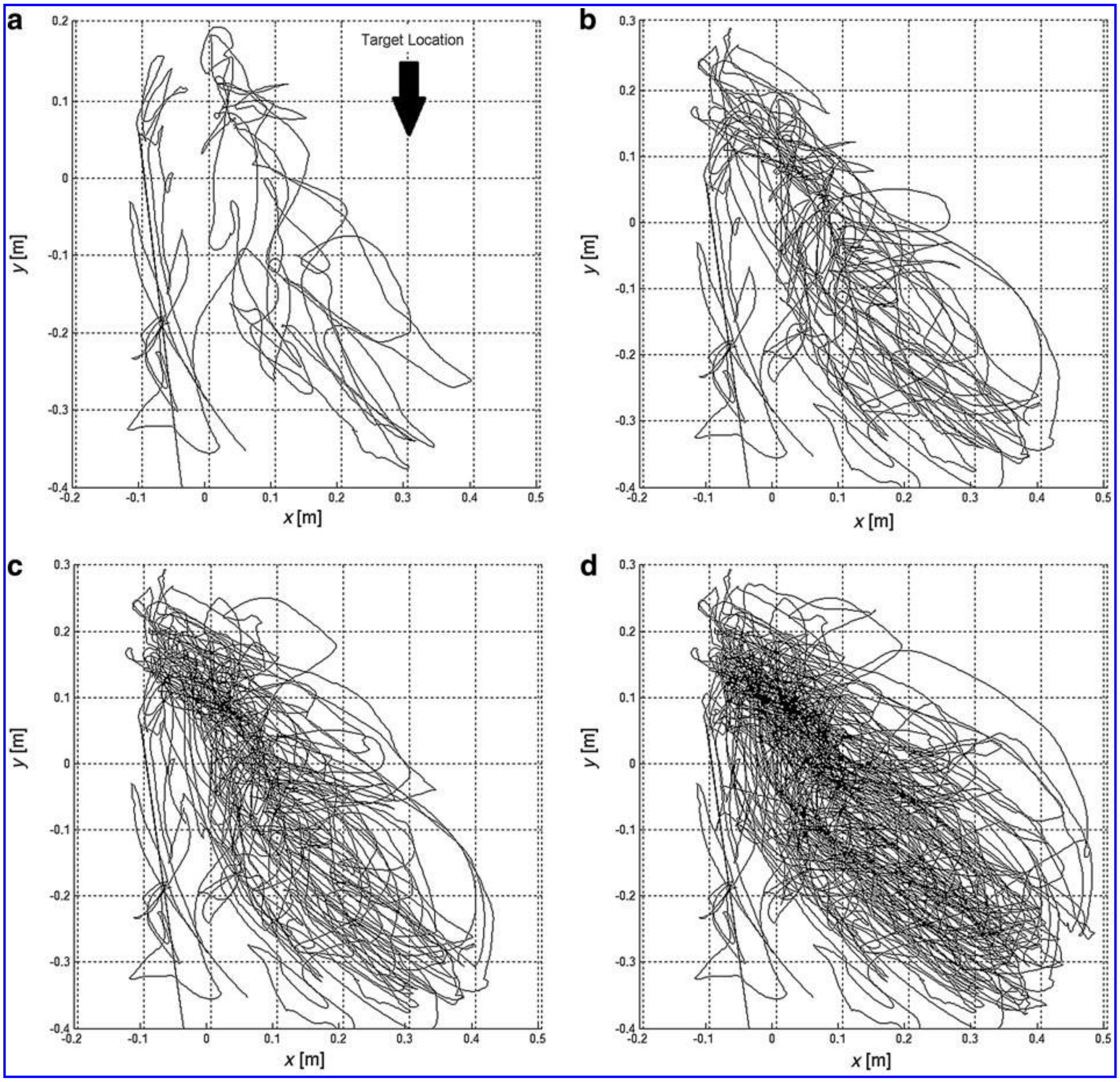

FIG. 5. Right-hand trajectory as seen from the subject's point of view during the game of "Paint" after **(a)** 60 seconds, **(b)** 200 seconds, **(c)** 430 seconds, and **(d)** 860 seconds. The difficult to reach portion is in the upper right corner.

game was far too difficult to play.[32] In an effort to simplify the game the ball size was increased, the speed was reduced, and the effect of gravity was eliminated. The player only needed to touch the ball for it to rebound energetically. The ball was set to continuously bounce so that the player did not even have to touch the ball in order to keep the game going.

Correlations

Correlations are summarized in Table 3. Different statements appearing to elicit the same response can reveal underlying views on game design. There were high correlations for Table 3, rows a and b. However, the questions in correlations in rows a and b measured very similar constructs. Therefore, correlations in rows a and b might be regarded as trivial. Correlations in rows c–e relate to questions that were asked for every game. Graphics that made the games easier to understand were correlated with easy-to-understand game rules and controls. Easy-to-interpret graphics were also correlated with the game's entertainment value. Therefore, correlations in rows c–e suggest that a strong graphical interface is an important attribute in terms of usability and entertainment value. It is interesting that row f showed a correlation between the game's perceived therapeutic affect and its entertainment value. One interpretation of the correlation in row f is that subjects derived more enjoyment from games that they perceive as being more beneficial. As such, games that attempt to conceal the fact that they are intended for rehabilitation might actually diminish the subject's enjoyment.

Robotic considerations

Games that utilize too few joints might encourage "compensation." It is known that stroke survivors tend to

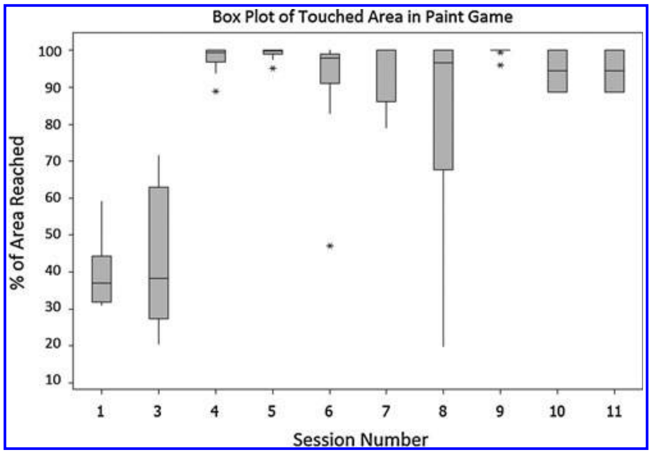

FIG. 6. Box plot depicting the percentage of the reaching area on the "Paint" game as a function of the therapy session.

compensate for arm impairment by exaggerating scapular and/or trunk motion. The "Pinball" game only required wrist flexion to actuate the paddles. Two subjects were observed moving their shoulder and scapula while playing "Pinball." This motion translated through the arm and pushed the wrist forward and back. In this way the subjects used shoulder motions to compensate for limited wrist ROM. Compensation is not viewed as true motor recovery.[33] Therefore, game design should minimize compensation. Games that require movement of only a single joint might encourage compensation.

Mitigating compensation is robot specific. Beyond "Pinball," many subjects exploited fit imperfections to translating their glenohumeral joint relative to the robot in order to achieve shoulder abduction, flexion, and rotation compensation. Such fit imperfections include restraint looseness, padded interfaces, soft flesh interfaces, and small misalignments between the robot and subject joint axes. These factors may permit the subject to reposition his or her limbs with respect to the robot, thus allowing distal joints to compensate for the joint being targeted. Because of the varying dimensions between patients, eliminating such imperfections entirely could prove impractical. Although compensation is a potential problem for all robots, specific game design recommendations to mitigate compensation are robot specific and are not discussed in detail here. Nevertheless, game designers should consider compensation in terms of the hardware being used.

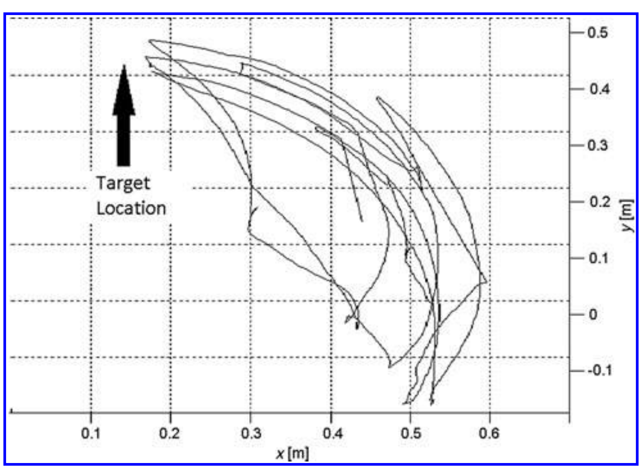

FIG. 7. Traces of the movement and position in a projected plane of the "Flower" game. Subject 6 in session 9 making ballistic reaching attempts for the target at the range of motion boundary. A 40-second time interval is depicted.

Table 4. Partial Assistance Forces

	Mean (N)	*Maximum (N)*	*SD (N)*
Humerus	16.2	71.8	8.3
Forearm	16.7	67.8	8.5
Hand	16.2	94.5	11.1

Data are forces on the right affected arm during bilateral motion for the "Flower" game. Mean and standard deviation (SD) were calculated along the axes of maximum recorded force.

Providing assistance for dynamic games proved difficult. Providing assistance for "Flower" was relatively straightforward. In "Flower," the end effector (hand location on robot) was programmed to be attracted to the fixed targets' locations, or equilibrium positions. In time-varying, dynamic, unstructured games, such as "Pong," "Handball," or "Circle," the arm movement is indeterminate. The robotic assistance for such games could require relatively fast arm movements along unpredictable trajectories. Assistance was not provided for dynamic games, and no subjects were injured. In summary, the design process should define and verify control algorithms for robotic assistance prior to, or in conjunction with, preliminary game design.

Beyond the possible therapeutic effects of bilateral motion training, bilateral movements greatly simplified robotic assistance for dynamic games. The robot simply mirrored the motions of the unaffected arm, and the assistance was therefore very predictable to users. In this way, bilateral robotic assistance is an advantageous tool for providing assistance in dynamic games.

In conclusion, when designing rehabilitation games for stroke survivors it is tempting to view diminished ROM as a complication that potentially detracts from an otherwise fun game. In this view the game should conceal limited ROM as if the patient is playing a game naturally without any disability. However, this study implies that game design for stroke survivors should instead emphasize ROM limitations by

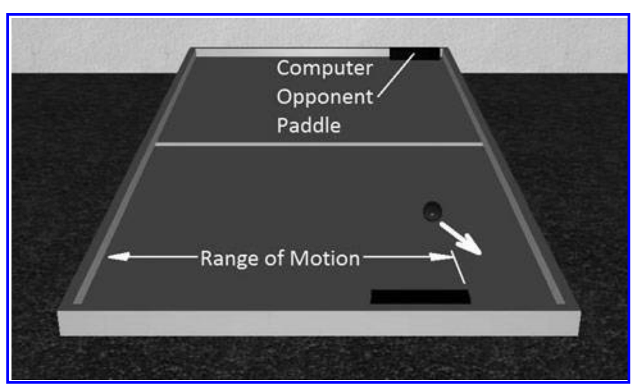

FIG. 8. The picture depicts a subject unable to move the paddle any farther to the right while playing the "Pong" game.

building it into the game. Thus, the most intuitive and engaging rehabilitation games for stroke survivors appear to be games that make the patient's physical disability an objective of game play.

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Author Disclosure Statement

No competing financial interests exist.

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