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KINEMATIC ANALYSIS OF VIRTUAL REALITY TASK INTENSITY INDUCED BY A REHABILITATION ROBOTIC SYSTEM IN STROKE PATIENTS

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ABSTRACT

Robotic systems provide a paradigm shift in maximizing neural plasticity as part of human motor control recovery following stroke. Such a system shifts the treatment from therapist dependent to patient dependent by its potential to increase the treatment dose and intensity, as long as the patient can tolerate it. The experimental protocol included 10 post stroke hemiparetic subjects in a chronic stage. Subjects were treated with an upper limb exoskeleton system (EXO-UL7) using a unilateral mode, and a bilateral mode. Seven virtual reality tasks were utilized in the protocol. A kinematic-based methodology was used to study the intensity of the virtual reality tasks in each one of the operational modes. The proposed method is well suited for early evaluation of a given virtual reality task, or movement assistance modality during the development process. Pilot study data were analyzed using the proposed methodology. This allowed for the identification of kinetic differences between the assistance modalities by assessing the intensity of the virtual reality tasks.

INTRODUCTION

Approximately 795,000 suffer strokes each year [1]. For most survivors, rehabilitation therapy is required to repair and regain basic activities of daily living skills. It was found that the central nervous system (CNS) has the ability to restore neural pathways through extensive, and progressive rehabilitation. However, conventional therapy is labor intensive, highly repetitive, and lengthy. For the past decade, efforts to find an effective and efficient alternate have given rise to the popularity of robot-assisted therapy. Robotic systems have inherent advantages in that they can measure and store force and motion data. They also have high motion accuracy and repeatability [2]. In addition, interfacing these systems with therapy games can provide an entertainment aspect. Therefore, they can alleviate the monotony of performing highly repetitive tasks.

A number of researchers have proposed, and built robotic systems intended for various types of rehabilitation [3], [4]. Such systems often present a range of engineering challenges. These challenges include: the human to machine interface [5], rehabilitation game design [6], and control algorithms that might assist, or provide resistance as needed [7]. Integration of these factors are complicated by the fact that the ultimate goal is to provide some kind of therapeutic improvement. Thus, the overall design will require a cross-functional blend of mechatronics, game design, control, and clinical expertise. Most importantly, even after such a system is developed, the only way to evaluate it is to conduct some kind of clinical trial, or intervention involving patients [8]. Such trials can present significant costs as well as risks to patients. For this reason, rather than being able to assess hardware and software individually, clinical evaluations are often conducted with relatively minimal testing. At the conclusion of clinical trials, evaluating the merits of each design factor individually is difficult or impossible due to confounding [9].

The games being described in this work were developed for use in a pilot study. Because of the small subject population, this study does not constitute a true clinical trial. During game development, it was difficult to know how the intended patient population would interact with the games. In particular, it was difficult to know which joints, or what pairs of joints, would be targeted in any given game. Therefore, many of the games were not designed with particular joints in mind. Instead, the designs were based, to some extent, on known, commercially popular games. At the conclusion of this pilot study, kinematic data were analyzed in order to evaluate each game along with their impact on each joint.

This paper proposes a methodology to quantify the task intensities of robotic systems. Previous studies have proposed various metrics by which to measure therapeutic improvement [10]. However, using such approaches to evaluate a given system still requires an intervention. Instead, the metric proposed in this paper is intended to evaluate the system *before* the trial ever begins. No change in patient performance is required to evaluate the system. In this way the method could provide a practical means to iterate therapeutic robotic design without incurring the costs, risks, and time associated with clinical trials.

(A) (B)

FIG. 1 A) PATIENT WITH LEFT PARETIC ARM PERFORMING MOVEMENT TRAINING IN UNILATERAL MODE. B) PATIENT IN THE BILATERAL GROUP WITH RIGHT ARM IMPAIRED. THE LEFT HEALTHY ARM IS ACTING AS THE MASTER TO MOVE THE RIGHT ARM.

METHODS

All subjects were greater than 6 months post-stroke with impairment in their left or right upper-limb. This research was approved by the University of California, San Francisco, Committee on Human Research. All subjects provided written consent prior to participating. Treatment modalities were randomly assigned to each subject, 5 subjects for each mode. Each subject participated in 12 sessions lasting 90 minutes. For each session, subjects played 7 games for duration of 10 - 15 minutes [11]. Subjects were connected to the exoskeleton using Velcro straps on three locations, the upper arm, lower, and handle at the exoskeleton end-effector. Subjects were seated on a chair. The subject's torsos were secured using elastic bands. One band wrapped around the torso and the chair backrest. Another band wrapped around the thigh and underneath the chair. A 50 in. monitor displayed the game and was positioned directly in front of the exoskeleton.

The exoskeleton system (EXO-UL7)[12], [13] includes two wearable robotic arms for the upper limbs. It has 7 degrees of freedom (DOF) for each arm that match the 7-DOF of the human arm. The anthropometric design of the system generates a workspace that covers 95% of the workspace of the arm of a healthy subject. This allows the subject who wears the exoskeleton to put his or her arm at any point in space required for activities of daily living. Subjects interface with the system using 6-axis force/torque sensor located at the upper arm, lower arm, and hand. Each joint is fitted with optical encoders for joint position measurements. Measurements are taken at a 100 Hz sampling rate.

Two treatment modalities were assessed, Unilateral Movement Training (UMT) and Bilateral Symmetric Movement Training (BSMT) [14]. For UMT, the impaired arm controls the exoskeleton. One of the games, Flower, utilized partial assistance on top of UMT mode. This mode provides proper joint configuration while partially guiding the arm towards the target. BSMT, on the other hand, provides partial assistance of the impaired arm (slave) by mirroring joint trajectories of the healthy arm (master). A PID controller was used for error correction between two arms. Gravity compensation was employed for all modalities.

The exoskeleton interfaces with a virtual environment that was developed in Microsoft Robotics Developer Studio (MSRDS). Seven rehabilitation games were created. For improved visualization during game play, a virtual model of the human arm and body were included. The game environment received joint angle information from the EXO-UL7 via a UDP network connection.

The games being discussed in this work provide an interactive graphical environment for subjects. Additionally, because the games work in conjunction with a robot, they provide a platform that allows for the imposition of forces, haptic feedback, and guided movement of the patient's arms. In this sense, the game design could be viewed as a therapeutic protocol. Table 1 contains a brief description of the games and their respective goals. The following paragraphs provide a more detailed description of each game.

For the Paint game, Fig. 1 (a), an array of red ball targets are positioned in a semi-spherical fashion in front of the human model. Red targets turns to green as subjects touch them. The goal is to turn (paint) as many red targets to green as possible. For UMT, only half of the balls must be painted. For BSMT, both arms are used to paint the entire surface. Targets located at the edge of the semi-sphere were intended to promote range of motion (ROM).

For the Flower game, Fig. 1 (b), a blue start target is rendered in the middle of the screen at approximately chest height. From the start target, three red targets are placed along straight lines. The game rules are to touch the start target first, and then to touch the outermost target. A stage is complete when the hand returns back to the start target. This game has eleven different target orientations. For each orientation, red targets are positioned along lines.

For the Reach game, Fig. 1 (c), three concentric circles of targets are placed at waist height in front of each arm model. Targets fall to the ground after being touched. The goal is to knock as many targets to the ground as possible. After all targets are touched the targets then reappear in their original position and the process is repeated. This game continues to repeat until 10 to 15 minutes has elapsed.

For the Circle game, Fig. 1 (d), a cylinder is rendered in front of the model. This game is similar to the well-known Pong-style game except that the ball is constrained to move along the surface of a cylinder. Paddles are used to deflect the ball. UMT uses one paddle while BSMT uses two paddles. The paddles are moved using relative hand positioning.

The Pong game, Fig. 1 (e) is designed like the traditional Pong game where the objective is to block the ball from going across the subject's side. Configuring the difficulty level varies the ball speed and computer opponent's blocking ability. Throughout the experiment, most subjects played at the easiest difficulty level. Only one paddle is rendered for UMT. Two paddles are used for BSMT. Paddles were controlled using the subject's relative hand positions.

For the Pinball game, Fig. 1 (f), the conventional wooden pinball table is rendered in front of the model. At the beginning of each game, random numbers of pegs are populated at random locations on the surface of the pinball table. Unlike the traditional pinball game where the user releases the ball, in this game a research assistant presses a button to release the ball. The flippers were controlled using a single joint, wrist flexion and extension.

Finally, for the Handball game, Fig. 1 (g), the goal of the game is to hit a dynamically moving ball towards the opposite wall. The ball is attracted towards the paretic limb side during unilateral mode. Both arms can be used to hit the ball in bilateral symmetric mode. This game exploits the subject's ROM, and trajectory planning while anticipating ball dynamics.

As was mentioned earlier, the only UMT game to provide partial assistance was the Flower game. To accomplish this, the hand was attracted towards the target position. For any given target position, an estimated swivel angle is calculated in order to resolve the redundancies in the human arm. Both the estimated swivel angle and the target position are used to calculate the joint angles using inverse kinematics [15].

TABLE 1. SUMMARY OF GAMES

Game	**Goal of Game**
Flower	Touch target balls in various orientations.
Paint	Touch as many balls as possible along a semi-spherical array.
Reach	Touch as many balls as possible along a horizontal plain.
Pong	Deflect a ball against a computer opponent with a paddle.
Pinball	Left and right paddle actuation using wrist flexion.
Circle	Similar to Pong, the ball is constrained to a cylinder.
Handball	Subjects bounce a ball off of a distant wall.

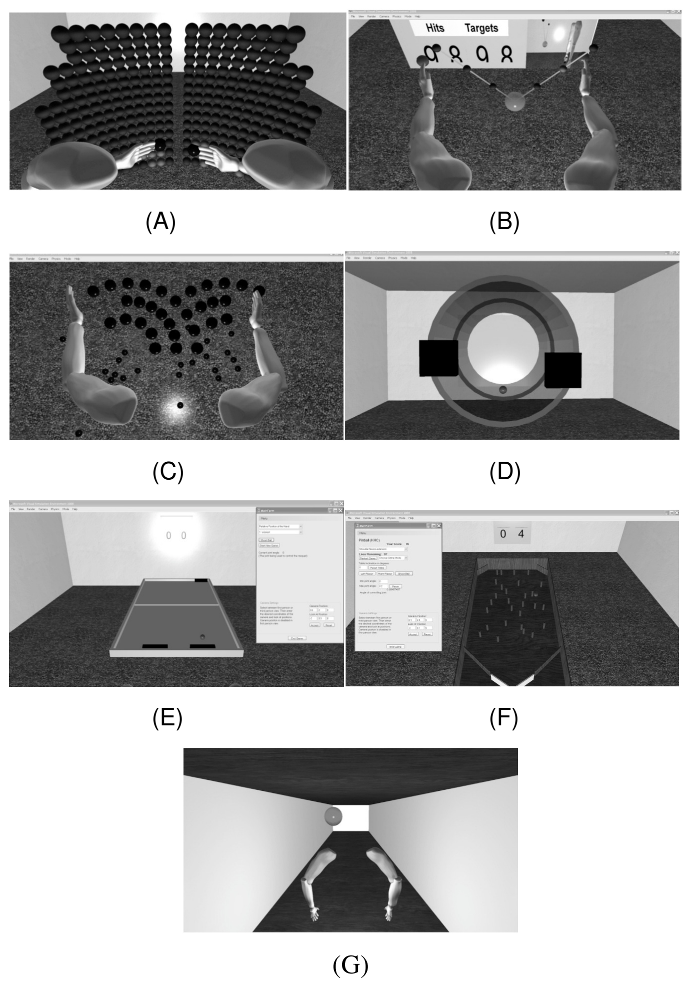

FIG. 2 SCREEN SHOTS FROM THE VARIOUS GAMES.

Games such as Reach, or Paint, require sweeping movements though the workspace. A game such as Flower requires point-to-point reaching tasks. Games such as Circle, Pong, or Handball were somewhat a mixture of both. In terms of quality of movement, games such as Reach or Paint emphasize quality in terms of hand trajectories. Alternatively, a game like Flower emphasizes quality of movement in terms of target acquisition. In all cases, the quality of movement required to effectively play these games is greatly affected by the size of the target (or ball) and the size of the end-effector (or paddle).

LIMITATIONS

Foremost, clinical data are not presented here. Therefore, the extent to which a given dataset corresponded to clinical measures of improvement is not discussed [16]. Instead, the proposed approach quantifies the amount of exercise a given treatment will elicit from each joint. In other words, it is best thought of as a way to quantify the dosage provided, and not necessarily as a way to quantify, or predict the efficacy of a given game/assistance mode. Lastly, this method most accurately applies to robotic joins with axes of rotation that are approximately the same as the patient's joint axes.

MATHEMATICS

To quantify movement training for a given game/modality, eight numbers are calculated. The first seven numbers relate to the proportions of joint rotation for the 7 DOF robot/arm. These include 3 DOF in the shoulder, 2 DOF in the elbow, and 2 DOF in the wrist. In words, the axes are defined as follows: Joint 1, is a combination of shoulder flexion and abduction, Joint 2, is a combination of shoulder flexion and adduction, Joint 3, shoulder inner rotation, Joint 4, elbow flexion, Joint 5, elbow/wrist supination, Joint 6, wrist flexion, and joint 7, wrist ulnar deviation. In this way a row vector is defined as follows,

$$\left| p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6 \quad p_7 \right| \tag{1}$$

where p_1 is the proportion of rotation for joint 1, p_2 is the proportion of rotation of joint 2, and so on. Because these proportions account for 100% of the total joint rotation during one game, the sum of the p_j elements in (1) equals 1. An eighth number is calculated for the total "intensity" of the training during a game and is given by I. Thus, the intensity of training for the j^{th} joint is given by p_j*I.

Of course, (1) require some measure of movement training intensity. One approach is to calculate total angular position, velocity, and acceleration for a given joint. As a start, consider angular position. A change in angular position is given as $\Delta\Theta$. Summing $\Delta\Theta$ for successive samples in the data set is infeasible because rotations in one direction will cancel out with rotations in the other direction. Therefore, a more suitable calculation for angular position of the j^{th} joint is to take the RMS as follows,

$$RMS_{\Theta,j} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta\Theta_{i,j}^2} \tag{2}$$

were n is the number of joint measurements and i is the i^{th} measurement. Angular velocity, ω, is given by $\Delta\Theta/\Delta t$. Therefore, the RMS for ω is given by

$$RMS_{\omega,j} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\Delta\Theta_{i,j}}{T_s}\right)^2} \tag{3}$$

where T_s is the sample time. In this case, the sampling rate was 100 Hz and T_s = 0.01 s. Because T_s is a constant, (3) is essentially the same calculation as (2) except that it is scaled by a constant value $1/T_s$. Therefore, calculating the RMS of angular position and angular velocity is of little value and the discussion that follows considers only angular velocity and acceleration.

In an effort to minimize the affects of noise and finite sampling times, 5-point numerical differentiation was used to calculate the RMS values. Thus, the RMS calculation that was used for velocity was

$$RMS_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{-\Theta_{i+2,j} + 8\Theta_{i+1,j} - 8\Theta_{i-1,j} + \Theta_{i-2,j}}{12T_s}\right)^2} \tag{4}$$

and for angular acceleration,

$$RMS_{\alpha,j} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{-\Theta_{i+2,j} + 16\Theta_{i+1,j} - 30\Theta_{i,j} + 16\Theta_{i-1,j} - \Theta_{i-2,j}}{12T_{s^2}}\right)^2} \tag{5}$$

where the subscript j indicates the j^{th} joint and i indicates the i^{th} recorded joint angle in the data set. With the RMS calculation for angular velocity and acceleration in hand, calculating the proportional contributions of each joint according to (1) is obtained by the following equation.

$$\left| p_1 \quad p_2 \quad p_3 \quad p_4 \quad p_5 \quad p_6 \quad p_7 \right| = \left(\sum_{j=1}^{7} RMS_j\right)^{-1} \left| RMS_1 \quad RMS_2 \quad RMS_3 \quad RMS_4 \quad RMS_5 \quad RMS_6 \quad RMS_7 \right| \tag{6}$$

The proportions given in (6) are presented as percentages throughout this paper. Intensity I is calculated for each game of each trial for all 7 joints by the following equation.

$$I = \frac{1}{7}\sum_{j=1}^{7} RMS_j \tag{7}$$

RESULTS

The summary statistics given in Fig. 3 depicts UMT percentage contributions by joint for velocity (4) and acceleration (5). Each element in (6) is summarized statistically as a 95% confidence interval (CI) for velocity and acceleration. Notice that angular velocity and acceleration track fairly closely for each joint. In general, the percent contributions of each joint, and the training intensities, were approximately equivalent for velocity and acceleration for all data. Put another way, measuring velocity according to (4) resulted in similar results to calculating acceleration according to (5). Therefore, considering the differences between USMT and UMT in terms of velocity and acceleration are of little value.

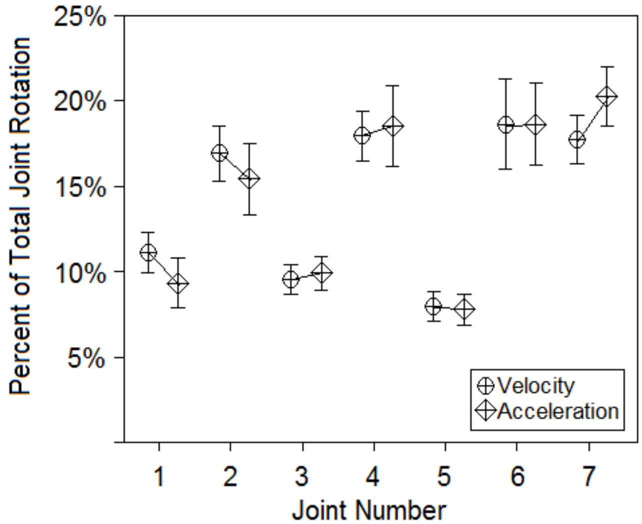

FIG. 3 JOINT PERCENTAGES FOR VELOCITY AND ACCELERATION FOR ALL UNILATERAL SUBJECTS ACROSS ALL GAMES. CIRCLES AND DIAMONDS INDICATE AVERAGE VALUES, WHISKERS INDICATE THE 95% CI.

In principal, subject-to-subject differences in ROM could cause discrepancies between (4) and (5). For example, a subject who uses lower acceleration through a larger angle might achieve a comparable velocity RMS in (4) to another subject who moves through a smaller angle under higher accelerations. However, both subjects would have very different acceleration RMS values according to (5). The similarities between velocity and acceleration in Figure 3 suggest that this scenario was not the case. Moreover, most therapy games would not even permit such a scenario. For example, in a game like Pong, Circle, or Handball, subjects must deflect a moving ball. The required speed, accelerations, and ROM are dictated by the game. Thus, with the proviso that acceleration would have been an equally valid measure, the remainder of this paper will consider only velocity.

Figure 4 compares BSMT and UMT for percents contribution and intensity of the affected arms for all games and subjects. Circles and diamonds represent mean values for BSMT and UMT respectively.

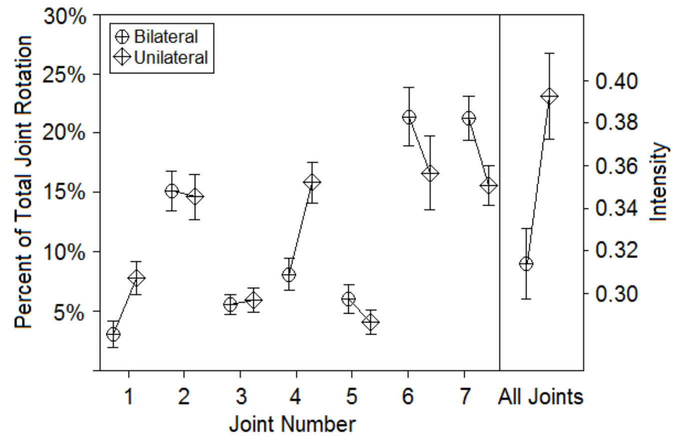

FIGURE 4. BILATERAL VERSUS UNILATERAL TRAINING FOR ALL GAMES. CIRCLES AND DIAMONDS INDICATE AVERAGE VALUES, WHISKERS INDICATE THE 95% CI.

In terms of velocity, Figure 4 shows that BSMT resulted in a larger proportion of shoulder movement (Joint 1) and elbow movement (Joint 4). Additionally, the intensity of the training was significantly larger for BSMT. A 2-sample t-test for intensity showed that bilateral training was significantly higher, p-value < 0.001. Multiplying the percent contribution of Joints 1 by the corresponding overall intensities for BSMT and UMT results in a Joint 1 intensity of 2.8 for BSMT and 3.5 for UMT. Therefore, even though the overall intensity of BSMT was significantly higher than UMT, UMT still caused to the subjects to move their shoulder more vigorously along the Joint 1 axes. This was also the case for the elbow (Joint 4).

Depicted in Figure 5 are the percent contributions of the Paint game versus the Pinball game. Notice that the contributions of rotation corresponding to the wrist (Joint 6 and 7) are much higher for Pinball than Paint. The Paint game has higher contributions from the shoulder and elbow.

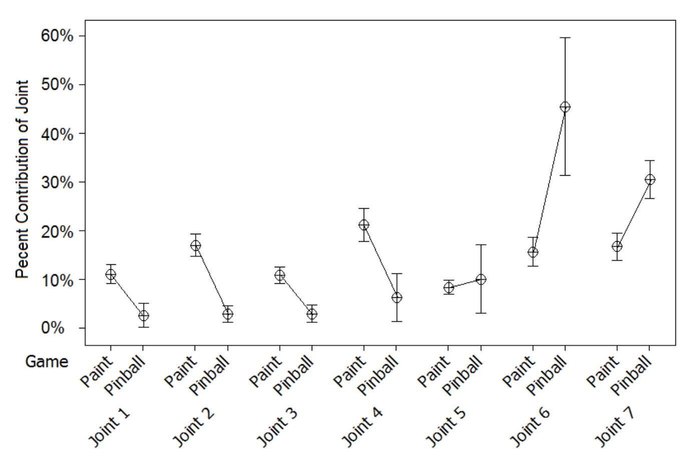

FIGURE 5. PAINT GAME VERSUS PINBALL GAME.

DISCUSSION

A method was presented in this work that provides a way to assess movement training in terms of what joints are exercised and by how much. With respect to robotic BSMT and UMT, using this method it was found that position, velocity, and acceleration are approximately equivalent measures. This method also allowed for comparative analysis of training modalities and clinical results.

With respect to Figure 1, BSMT resulted in higher overall joint velocities as measured by *I*. Therefore, it might be said that the affected arm moved more vigorously during BSMT training. This result is explained by the fact that the EXO-UL7 provided assistance in moving the affected arm as it attempted to enforce mirror-imaged symmetry between both arms. Because the unaffected arm will move more vigorously than a paretic arm moving unilaterally, this result was consistent with what was expected. Additionally, Figure 1 also shows that Joints 1 (shoulder) and Joint 4 (elbow) are more vigorously moved for UMT than for BSMT despite the lower overall intensity for UMT. Because BSMT reflects normal, healthy movement in the unaffected arm, this result shows that paretic arm movements differentiated themselves from healthy arms by relying more on Joint 1 and Joint 4. Thus, in terms of total movement, BSMT might provide intense training overall, UMT provides more intensity for the shoulder and elbow.

Only two of the seven games were compared directly, Paint and Pinball. As is described in Table 1, the Pinball game required only wrist flexion to actuate the Pinball paddles while Paint required sweeping, full-arm motions to "paint" a virtual surface. It is therefore not surprising that Joint 6 (wrist flexion) accounted for highest proportion movement for Pinball while Paint required a larger proportion of shoulder and elbow rotation. Notice also that the Pinball game involved a significant amount of Joint 7 (wrist radial-ulnar deviation) rotation. Therefore, it appears that hemiparetic subjects had a difficult time moving their wrist along the flexion-extension axes only. Figure 2 also shows that the Pinball game resulted in a significant amount of rotation in the entire arm, not just the wrist. This seemingly unusual finding is explainable in part by the involuntary joint synergies that are characteristic of paretic arms [17]. This result also points to a game design deficiency. Stroke survivors often have limited ROM in the wrist. In an effort to move their wrist joints, subjects were observed translating their entire arm within the robot thereby pushing and pulling their wrist through larger flexion-extension angles than the wrist could achieve by itself. Even though this could be regarded as "cheating", compensation such as this is actually a well-known phenomenon for stroke survivors [18]. Therefore, if isolated joint rotation is desired, (such as in the wrist) a better design for Pinball should somehow discourage compensation by changing the game, control, or the mechanics of the human to machine interface.

CONCLUSION

The system evaluation method described in this paper provides a useful tool in understanding how a patient will interact with a given system. It allows a concise way to describe what joints are exercised, and by how much. Additionally, it allows designers to identify shortcomings, or unforeseen interactions between their systems and prospective patients.

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