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Design and pilot evaluation of competitive and cooperative exercise games for arm rehabilitation at home

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Abstract

People with chronic arm impairment should exercise intensely at home after completing their clinical rehabilitation program, but frequently lack motivation. To address this issue, we present a home rehabilitation system that motivates patients by allowing them to perform arm exercises together with friends or relatives in competitive and cooperative games. Inertial sensors are used to track the patient's arm and control the game. The system was tested with seven adults with arm impairment as well as their friends or spouses. They tested four exercise games (single-player, competitive and two different cooperative games) for 3 minutes each. Of the 7 participants, 4 preferred the competitive game, 2 preferred a cooperative game, and 1 preferred to exercise alone. Competition also increased exercise intensity (measured using inertial sensors) compared to exercising alone. Though preliminary, these results indicate that competitive exercise games could improve arm rehabilitation at home for survivors of neurological and orthopedic injuries.

I. Introduction

Diseases and injuries such as stroke commonly cause arm impairments that negatively affect human quality of life [1]. Intensive training delivered by a therapist soon after the injury can effectively restore arm function, but even top hospitals only devote a limited amount of time to rehabilitation of motor functions [2]. After leaving the hospital, patients thus need to exercise at home without therapist supervision in order to fully regain their abilities.

Several technologies have been deployed for arm rehabilitation at home, from inexpensive devices like the Microsoft Kinect [3] to complex exoskeletons [4]. However, most unsupervised patients do not comply with prescribed therapy regimens due to lack of motivation, and outcomes of technology-supported home rehabilitation are therefore significantly worse than those of clinical rehabilitation [5]. It is thus critical to motivate patients for home rehabilitation, as studies from other fields of physical therapy have shown that patients who receive additional motivation interventions exhibit better compliance with therapy regimens [6].

One approach that can increase patient motivation in motor rehabilitation is virtual reality [7]. Studies have shown that virtual environments for motor rehabilitation at home can enable recovery of arm function [8]. However, it is not clear which characteristics of a

virtual environment are important for rehabilitation [7], and it is critical to identify the best ways to motivate patients to perform arm exercises at home.

We recently developed a virtual environment for arm rehabilitation in which two people compete against each other or work together to achieve a common goal [9]. It was tested with 15 pairs of healthy people and 4 pairs of stroke survivors. We found that emotionally stable, competitive participants enjoyed competitive exercises more than exercising alone, and that this also increased self-reported effort put into the exercise. Uncompetitive participants preferred cooperative exercises, but did not put more effort into them than into exercising alone. We also observed that pairs of people who knew each other had a more enjoyable exercise than pairs of people who did not know each other.

The main disadvantage of our previous study [9] is that it was performed with two expensive arm exoskeletons and with pairs of stroke survivors. This is not a realistic situation for home rehabilitation, where patients would use inexpensive hardware and exercise with an unimpaired friend or relative. This would require careful exercise design so that it is enjoyable for both the patient and the healthy person, but would also have potential benefits compared to exercises involving two patients. For example, since the patient would exercise with a familiar person at home, the exercise could be more enjoyable than exercising with a stranger in a hospital.

To date, one prototype of a home rehabilitation system for a patient and healthy person has been presented [10]. It used a camera to track arm movements, and was preliminarily evaluated with two patients who only performed competitive rehabilitation exercises together with family members. Nonetheless, it indicated that such exercise could potentially increase patient motivation.

In this paper, we present a new prototype of an arm rehabilitation system for home use that allows both competition and cooperation between a patient and an unimpaired person. A pilot evaluation was performed with five neurological and two orthopedic patients to determine how different types of exercise (exercising alone, competing, cooperating) affect motivation and exercise intensity.

II. Materials and Methods

A. Participants

Five participants with neurological injuries (4 stroke, 1 traumatic brain injury) and two participants with orthopedic injuries (shoulder rotator cuff injury) were recruited (Table 1). The stroke and traumatic brain injury participants had already completed clinical rehabilitation while the orthopedic participants were still actively engaged in rehabilitation. Each impaired participant attended the study session with a friend or family member (unimpaired participant).

Impaired participants also completed the Box and Block test of manual dexterity [11], and grasping motions. A score of zero on the test indicates no reaching/grasping ability while scores above 60 correspond to normal arm function.

B. Hardware and Software

Impaired participants performed the exercises using the BiMeo arm rehabilitation system (Kinestica d.o.o, Slovenia) while unimpaired participants used a joystick. The BiMeo is a commercial version of a system that was previously used for human motion tracking [12], [13] and consists of three small inertial measurement units (IMUs) - a combination of accelerometer, gyroscope and magnetometer. Two are placed on the arm while the third is installed in the BiMeo's handle (see Figure 1). Raw data from the IMUs is input into a sensor fusion algorithm that calculates the joint angles and the hand position in three-dimensional space. These IMUs allow the BiMeo to track arm kinematics with good accuracy: approximately 2° for each joint angle in normal conditions and 5° in worst-case conditions [12], [13]. The position of the hand (end-effector) can also be tracked with an accuracy of ± 1 cm for each horizontal dimension in normal conditions.

Six participants were able to move their impaired arm and perform the exercises on their own. One participant had a more severely impaired arm and held the BiMeo handle with both hands, allowing the unimpaired arm to assist the impaired one. This bimanual handle is a standard function of the BiMeo, which is designed to support bimanual exercise. Participants used the BiMeo to play four exercise games that were all variants of the classic Pong game (Figure 2). The games were as follows:

- **Single-player game:** The playing field consists of two paddles (one near the top, one near the bottom of the screen) and a ball that bounces around the screen. The impaired participant moves the bottom paddle left and right by moving their arm left and right. The top paddle is controlled by the computer. Both the participant and computer try to use their paddle to intercept the ball and keep it from reaching the top/bottom of the screen. If the ball is intercepted by the paddle, it bounces off and moves toward the other side of the screen. If the ball passes the paddle, one side scores a point (e.g. if the ball passes the computer-controlled paddle, the participant scores a point).
- **Competitive game:** The playing field looks identical to the single-player version, but the unimpaired participant now controls the top paddle by moving the joystick left and right. The two participants thus compete against each other.
- **Cooperative with split field:** The playing field is twice as wide as in the first two versions, and each of the two participants controls a paddle at the bottom of the screen: the impaired participant on the right and the unimpaired participant on the left side. Each participant's paddle is limited to half the width of the screen and cannot move past the center. There is a single paddle on the top of the screen, controlled by the computer. Both participants must work together to defend their side of the field and score points against the computer, but cannot help each other.
- **Cooperative with shared field:** The playing field is similar to the single-player version, with the impaired participant's paddle near the bottom of the screen and the computer-controlled paddle near the top of the screen. However, the unimpaired participant controls an additional paddle located between the

impaired participant's paddle and the bottom of the screen. Both participants must work together to defend their side of the field, but the unimpaired participant now essentially acts as "backup" for the impaired participant.

The first three games were similar to the exercise games used in our previous study on rehabilitation robotics [9] while the fourth was newly developed for this study. The speed with which the ball moves across the screen was the same for all participants and all games, and was preset to be moderately demanding for most participants. The BiMeo's range of motion was set to 20 cm from the left to the right end of the playing field by default, but was reduced to 15 cm for two participants who had trouble moving their arm.

C. Study Protocol

All sessions were conducted in a place familiar to the participants – at their home or at a community center. At the start of the session, the study purpose and procedure were explained to both participants. After participants signed an informed consent form, they were seated in front of the computer screen and the BiMeo was attached to the impaired arm of the impaired participant, as seen in Figure 3. A brief calibration procedure was performed to adjust the center position of the hand and the range of motion to the impaired participant's capabilities. Participants were then allowed to practice all four exercise games for 30–60 seconds per game in order to familiarize themselves with them.

After the practice, the two participants played each exercise game for 3 minutes, with the four games presented in random order. After each game, the impaired participant filled out a questionnaire about that game (section II.D). After playing all four games, an overall experience questionnaire and a personality questionnaire were filled out (section II.D).

D. Questionnaires

After each 3-minute game session, participants filled out the Intrinsic Motivation Inventory (IMI) [14], which consists of 20 statements that the participant can agree or disagree with. The 20 statements measure motivation along four scales: interest/enjoyment, effort/importance, perceived competence and pressure/tension. Each of these is measured on a scale from 5 (very low) to 35 (very high). The version of the IMI used was identical to the one in our previous study, and is available there in full [9].

After completing all four games, participants were given a brief comparative game experience questionnaire. The questionnaire asks participants to rank the games in four ways: 1. from favorite to least favorite, 2. from the one requiring the most effort to the one requiring the least effort, 3. from the one that the participant felt most competent at to the one they felt least competent at, and 4. from most stressful to least stressful. This questionnaire was similar to one used in our previous study [9], which was found to be better than the IMI at distinguishing between different game experiences.

Finally, participants completed an optional personality questionnaire, the International Personality Item Pool [15]. It consists of 50 statements that a person can agree or disagree with. It measures five personality scales: extraversion, agreeableness, conscientiousness, emotional stability, and intellect/imagination. Each of these is measured on a scale from 10

(very low) to 50 (very high). Six of seven impaired participants completed this questionnaire.

E. Measurement of Exercise Intensity

The position of the BiMeo handle was recorded with a sampling frequency of 20 Hz and used to calculate the velocity and acceleration of the hand. For each exercise game, the root-mean-square (RMS) values of hand velocity and acceleration were calculated in the horizontal left-right axis over the 3-minute period. Only one axis was analyzed since the game is only controlled in this axis (moving the paddle left and right). This method essentially measures the amount of movement performed and has been shown to be an adequate approximation of energy expenditure during arm exercise in stroke [16]. It thus serves as an objective measure of exercise intensity that complements the questionnaires.

III. Results

A. Questionnaires

Table 2 shows each impaired participant's favorite and least favorite exercise game, as measured using the final comparative questionnaire. It also shows the game that subjectively required the most effort and the one that subjectively required the least effort. No trends were visible in the answers to the competence or stress questions.

Four of 7 participants picked the competitive game as their favorite, and the same participants also indicated that they put the most effort into that game. This parallels our previous findings with unimpaired subjects, which found that participants who enjoy competitive exercises report (subjectively) that they put more effort into them than into other exercises [9]. Conversely, only one participant favored the single-player mode. Four of 7 participants also reported that they put the least effort into the single-player game.

Six participants filled out the personality questionnaire. Of these 6, three had a high emotional stability score (34, 42 and 46 out of 50) while three had a low score (19, 19 and 26). All three participants with high emotional stability chose the competitive game as their favorite, as did one participant with low emotional stability. Conversely, the participant who chose the single-player game as their favorite had both the lowest emotional stability score and the lowest extraversion score in our group. This parallels the findings of our previous study with unimpaired participants, which also found that competitive exercises are more likely to be enjoyed by extraverted, emotionally stable individuals.

Though results of the IMI are not shown in detail due to lack of space, they were similar to those of the final questionnaire: 5 of 7 participants reported the highest interest/enjoyment in the competitive game, which also had the highest mean interest/enjoyment.

B. Exercise Intensity

Table 3 shows each impaired participant's RMS value of hand velocity for the different exercise games.

Perhaps the most prominent finding is that the single-player exercise game was never the one with the highest exercise intensity, and the competitive exercise game was never the one with the lowest exercise intensity. In 6 of 7 cases, the competitive game had a higher exercise intensity than the single-player game even though they are identical except for the type of opponent (human or computer). This suggests that including a human opponent can increase exercise intensity without having to substantially increase the complexity of the hardware or software.

The competitive game had the highest mean exercise intensity, followed by the cooperative game with the shared field. The lowest mean exercise intensity was observed in the cooperative game with the split field, which makes sense – as incoming balls are evenly split between the left and right side of the field, each participant only needs to intercept half the balls. Two participants had the highest exercise intensity in the split-field game, but our observations during the game indicate that this was because they would attempt to move to the other side of the field (even though moving the arm beyond the center of the field has no effect on the game) and thus exerted more effort than was useful for the game.

There was no strong connection between self-reported effort from either questionnaire and the exercise intensity measured with the IMUs. For example, the game that subjectively required the most effort (Table II) only had the highest RMS value of hand velocity for 3 of 7 participants. This could be due to a variety of reasons. For example, it is possible that the questionnaires measure both mental and physical effort while IMUs only measure physical effort. However, it does indicate that both subjective and objective measures of exercise intensity need to be examined during the evaluation of such exercise games.

IV. Discussion

A. Implications

We have evaluated an IMU-based system that supports both competitive and cooperative arm rehabilitation exercises in a home setting. The evaluation was admittedly limited by the small number of participants, but nonetheless has implications for future home rehabilitation systems.

First, we have demonstrated that competing against a friend or family member has the potential to increase the motivation and exercise intensity of a person with arm impairment without a major increase in hardware or software cost. As both motivation [6] and exercise intensity [17] have been linked to rehabilitation outcome, such competitive exercises could improve home rehabilitation outcome by encouraging patients to exercise more often and more intensely. However, as demonstrated by both this study and our previous work with unimpaired participants [9], they are not suitable for everyone: extraverted, emotionally stable individuals are more likely to benefit from them.

Cooperative exercises do have some potential for rehabilitation – for example, for patients who do not enjoy competition but would nonetheless like to exercise together with a friend or family member. However, their potential benefits are not as clear, and designers should ensure that the unimpaired co-player does not reduce the amount of exercise the patient

does. For example, in our cooperative game with the split field, the impaired player is idle part of the time since half the incoming balls are directed at the unimpaired player, resulting in lower exercise intensity. On the other hand, in our cooperative game with the shared field, an unmotivated impaired player could simply remain idle and count on the unimpaired player to do most of the work (though this behavior was not observed in our participants).

B. Limitations and Future Work

Aside from the previously emphasized limited number of participants, our study has two major weaknesses. First, participants only took part in a single session, and each game was only played for 3 minutes – significantly less than a normal rehabilitation session. Thus, we do not know if the increased motivation and exercise intensity would hold up over a longer time period or if they would lead to improved rehabilitation outcome. For instance, the increased motivation may be simply an effect of novelty, and both patients and their friends or family members may get bored of the exercises after a few sessions. Additionally, the increased exercise intensity is not necessarily useful – the motions promoted by the game may not be the kind of motions that participants use in real life, and thus may not transfer to functional improvements.

Second, the exercise difficulty was not tailored to the individual participant, which may have negatively affected enjoyment in both competitive and cooperative games. Particularly for long-term use, it would be necessary to either let participants manually adapt the exercise or implement an automated difficulty adaptation algorithm. This adaptation would need to take both participants into account to ensure that friends and family members are not bored or frustrated by the exercise.

Future research on competitive and cooperative games for home rehabilitation should first focus on intelligent exercise adaptation, as this should have a significant effect even within a single session. The effect of this exercise adaptation should be evaluated using motivation questionnaires, measures of exercise intensity (inertial sensors, electromyography) as well as measures of exercise duration – patients should be willing to exercise both longer and harder if the exercise is well-tailored to their abilities and preferences. At the same time, new competitive and cooperative game designs should be investigated to identify rehabilitation games that are optimal from the perspectives of motivation, exercise intensity and motor learning. Once optimal game designs and adaptation methods have been identified, they should be evaluated in long-term studies that focus on home rehabilitation outcome. While such studies are likely still years in the future, we hope that the observed short-term benefits of competitive exercise will translate to improved quality of life for survivors of neurological and orthopedic injuries around the world.

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Figure 1.
The BiMeo arm rehabilitation system. It consists of two inertial measurement units on the arm as well as a sensorized handle.

Figure 2. Different versions of the Pong game: top left - single player/competitive mode, top right – cooperative mode with shared field, bottom – cooperative mode with split field.

Figure 3.

Experimental setup. An impaired participant (left) wears the BiMeo device and exercises together with an unimpaired participant (right). Together, they play different versions of the Pong exercise game.

TABLE I

Participants

ID	Gender	Age	Level of Education	Injury Type	Time since injury	Impaired Side	Box & Block Score	Relationship with unimpaired participant
1	F	52	2-year college	ischemic stroke	7 years	Left	45	Friend
2	F	78	B.Sc.	ischemic stroke	15 years	Left	43	Friend
3	M	68	high school	hemorrhagic stroke	5 years	Right	4	Spouse
4	M	65	high school	traumatic brain injury	15 years	Right	41	Spouse
5	M	70	M.Sc.	ischemic stroke	2.5 years	Right	57	Friend
6	M	50	PhD	rotator cuff tear	1 year	Left	64	Coworker
7	M	28	B.Sc.	rotator cuff tear	1 year	Right	65	Friend

TABLE II

Results of comparative game experience questionnaire. SP = single-player, Coop-shared = cooperative with shared field, coop-split = cooperative with split field.

ID	Exercise game			
	<i>Favorite</i>	<i>Least favorite</i>	<i>Most effort</i>	<i>Least effort</i>
1	Competitive	Coop-split	Competitive	SP
2	Coop-split	SP	Coop-split	SP
3	SP	Coop-split	Coop-shared	Competitive
4	Coop-shared	Competitive	SP	Competitive
5	Competitive	SP	Competitive	SP
6	Competitive	SP	Competitive	SP
7	Competitive	Coop-shared	Competitive	No answer

TABLE III

Measured RMS values of hand velocity. All values are in meters/second. SP = single-player, coop-shared = cooperative with shared field, coop-split = cooperative with split field. Maximum value for each participant is underlined.

ID	Exercise game			
	<i>SP</i>	<i>Competitive</i>	<i>Coop-shared</i>	<i>Coop-split</i>
1	0.0804	<u>0.1194</u>	0.1034	0.0865
2	0.1105	<u>0.1218</u>	0.109	0.0907
3	0.0985	0.0747	<u>0.1039</u>	0.0665
4	0.1254	0.1295	0.1215	<u>0.1471</u>
5	0.0767	0.0900	0.0758	<u>0.0959</u>
6	0.0792	<u>0.1012</u>	0.0857	0.0476
7	0.0557	0.0616	<u>0.0632</u>	0.0596
Mean	0.089 m/s	0.100 m/s	0.095 m/s	0.085 m/s