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Comparison of two difficulty adaptation strategies for competitive arm rehabilitation exercises

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Abstract

This paper presents two different strategies for difficulty adaptation in a competitive arm rehabilitation game: a manual adaptation strategy and an automatic performance-based adaptation strategy. The two strategies were implemented in a competitive game controlled with an inertial-sensor-based home rehabilitation device. They were first evaluated with 32 pairs of unimpaired participants, who played the game with manual adaptation, automated adaptation, or no adaptation. Each variant was played for 9 minutes. Then, the manual and automatic adaptation were also tested by 5 pairs consisting of a person with arm impairment (due to neurological injury) and their unimpaired friend or relative. Throughout the game, motivation was measured with questionnaires while exercise intensity was tracked using the inertial sensors. Results showed that both manual and automatic difficulty adaptation lead to higher motivation and exercise intensity than no adaptation. Unimpaired participants showed no clear preference between manual and automatic adaptation while 4 of 5 impaired participants preferred automatic adaptation. For future use, we propose a combination of manual and automatic adaptation that should be evaluated with more impaired participants in longer multisession experiments.

I. Introduction

Rehabilitation technologies have become an important tool in the treatment of motor impairments caused by neurological injuries such as stroke or spinal cord injuries. Rehabilitation robots have shown results comparable to human therapists in large multicenter clinical studies [1], [2], and lower-cost technologies (both actuated robots and passive motion trackers) are now frequently used in home rehabilitation without therapist supervision [3], [4].

Rehabilitation robots and motion trackers are frequently combined with serious games and virtual environments that allow patients to perform different tasks on a computer screen by moving their limbs [5]. A major goal of these games is to increase patient motivation: by providing interesting goals, challenges, and audiovisual elements, they hope to keep patients exercising longer and more intensely. This is particularly important, for example, in home rehabilitation, where many patients do not comply with prescribed exercise regimens due to lack of motivation [6].

Different ways of increasing motivation for exercise have been explored in the literature. Recently, a promising approach has emerged in the form of interpersonal rehabilitation games: games that allow patients to compete or cooperate with other patients, therapists, or unimpaired loved ones. While only evaluated in single brief sessions, such interpersonal exercise games are more enjoyable than exercising alone [7]–[10]. Competitive exercises are especially promising, as they may increase exercise intensity [7], [10], which is critical for rehabilitation.

Existing studies on competitive exercises, however, have mainly used a constant difficulty setting that does not change throughout the session. To ensure an enjoyable, intensive experience over multiple long sessions, it is critical to intelligently adapt difficulty, keeping both players engaged. In exercises performed by a single patient, this is commonly done with automated difficulty adaptation algorithms that adapt to the patient's performance [11], [12]. However, such difficulty adaptation would be much more complex in competitive exercises, as the performance of both players would need to be taken into account. As the two players may have significantly different skill levels (e.g. a patient competing against an unimpaired loved one [8], [10]), it would also be necessary to adapt multiple difficulty parameters. Several automated difficulty adaptation algorithms have been proposed to deal with this issue [13], [14], but have seen practically no evaluation.

There is also an alternative to automated difficulty adaptation: we could allow participants to manually adapt difficulty however they want. As participants should be aware of their own internal states during exercise, this could be more accurate than any automatic algorithm. However, patients with brain injuries may not be able to appropriately adapt game difficulty. Furthermore, participants may prioritize a fun experience over intensive, useful exercise, as shown by Nagle et al. [15] for cognitive rehabilitation.

In this paper, we introduce two difficulty adaptation strategies for competitive arm rehabilitation games: an automated algorithm that adapts difficulty settings based on performance of both players, and a manual method that allows participants to change difficulty at regular intervals. Both are compared to a non-adaptive variant of the same game (where difficulty remains constant) with regard to effects on motivation and exercise intensity over a 9-minute exercise period. By evaluating this impact of difficulty adaptation strategies, the paper presents a guideline for how future long-term studies of competitive arm rehabilitation exercises could adapt difficulty over time.

II. Materials and Methods

A. Participants

Two groups of participants were recruited for the study:

- Thirty-two pairs of unimpaired participants with no previous history of arm injury (44 males, 20 females, 25.6 ± 6.9 years of age). In each pair, the two participants were friends. They were recruited among the population of Laramie, Wyoming, and most were undergraduate students.

- Five pairs consisting of one participant with arm impairment due to neurological injuries (Table 1) and their unimpaired friend or family member. Each impaired participant performed the Box and Block Test of manual dexterity [16] prior to the test (Table 1).

B. Hardware

One participant in each pair (the impaired participant in the impaired-unimpaired pairs, a randomly chosen participant in the unimpaired-unimpaired pairs) used the Bimeo arm rehabilitation system (Kinestica d.o.o., Slovenia) to play the competitive rehabilitation game. The Bimeo consists of three inertial measurement units (IMUs), of which one is placed on the upper arm, one on the forearm, and one is integrated in a spherical handle. The system can track arm joint angles with accuracies of approximately 2° in normal conditions and 5° in worst-case conditions [17]. It was used in the wrist configuration (Fig. 1), which requires participants to use their wrist and forearm to move the Bimeo handle left and right, with a range of motion up to 20° from the vertical plane in each direction. The other participant in the pair played the rehabilitation game with a commercially available Logitech joystick, tilting it left and right from the vertical plane in a similar matter to the Bimeo. This hardware setup was designed for one impaired and one unimpaired participant, and was validated in our previous study [10].

C. Competitive arm rehabilitation game

Participants played a two-player competitive Pong game (Fig. 2). Each player controls one paddle: the person using the Bimeo moves the bottom (green) paddle while the person using the joystick moves the top (red) paddle. A ball bounces across the screen, and players have to intercept it with their paddle by moving left and right so that the ball does not reach the top or bottom of the screen. If that happens, the opponent scores a point and the ball is reset to a central position.

The difficulty of the game can be varied by changing the speed of the ball and size of the paddles. We created and tested three variants of the game that varied according to the type of difficulty adaptation performed:

- No adaptation (NA): The game is as described above. The speed of the ball and size of the paddles are constant throughout the entire game, and are set to the default value used in our previous study [10].
- Manual adaptation (MA): The game is similar to the NA variant; however, every one-minute interval, participants can make one change to the difficulty parameters. They can choose between increasing/decreasing the ball speed by one increment, increasing/decreasing the size of both paddles by one increment, or increasing the size of one paddle and decreasing the size of the other. They can also choose to make no change, but can only do this once in the 9-minute interval. Participants make their choice by verbally informing the experimenter, who makes the difficulty change by pressing buttons on the keyboard.
- Automatic adaptation (AA): The game is similar to the NA variant; however, difficulty is adapted every one-minute interval by an automatic algorithm. The

algorithm looks at the number of points scored by each player in the last one-minute interval, compares these points, and makes one change to the difficulty settings. It chooses among the same possibilities that are available to the players in the MA variant. The rules of the algorithm are:

```

1:  if (timeSinceLastAdaptation > 60)
2:      if (RedScore < 5 && GreenScore < 5)
3:          Speed = Speed + 0.5;
4:      else if (RedScore > 5 && GreenScore > 5)
5:          Speed = Speed - 0.5;
6:          if (Speed < 0.5)
7:              Speed = 0.5;
8:              GreenSize = GreenSize + 0.05;
9:              RedSize = RedSize + 0.05;
10:         else if (RedScore < (GreenScore + 5))
11:             GreenSize = GreenSize + 0.05;
12:             RedSize = RedSize - 0.05;
13:             if (RedSize < 0.1)
14:                 RedSize = 0.1;
15:                 GreenSize = GreenSize + 0.05;
16:         else if ((RedScore + 5) < GreenScore)
17:             GreenSize = GreenSize - 0.05;
18:             RedSize = RedSize + 0.05;
19:             if (GreenSize < 0.1)
20:                 GreenSize = 0.1;
21:                 RedSize = RedSize + 0.05;
22:         GreenScore = 0; //reset score for next interval
23:         RedScore = 0;
24:     end

```

The reasoning behind the automated algorithm was that it should be able to adapt multiple difficulty parameters and function for pairs where one participant is more skilled than the other. If both players are approximately equally skilled, we can adapt a parameter that affects both players equally (the ball speed). However, if one player is more skilled than the other, we can challenge the better player and make the game easier for the worse player – as done via paddle size.

C. Experimental Setup and Protocol

The study procedure was explained to both participants at the beginning of the session. After they agreed to perform the test and signed an informed consent form, they were seated in front of the computer screen. The Bimeo was attached to one participant while the other familiarized themselves with the joystick. Both participants were able to briefly test the game, and the possible difficulty changes were demonstrated.

Each pair played 2 different variants of the game in random order. The 32 unimpaired pairs were divided into 3 groups: 10 pairs played the NA and MA variants; 10 pairs played the NA

and AA variants; and 12 pairs played the MA and AA variants. All 5 impaired-unimpaired pairs played the MA and AA variants of the game. Due to the low number of impaired participants, we considered it less important to study the NA variant, which was expected to be less effective than the other two.

Each variant of the game was played for 9 minutes, allowing for a total of 8 difficulty adaptations. The NA variant was played with a default ball speed of 2 (as in our previous study [10]) while the MA and AA variants started with a random ball speed between 1 and 4 (equal to half and twice the default value, respectively). The hand position of the Bimeo player, game score, and difficulty settings were recorded throughout the session. After each variant of the game, both participants filled out questionnaires about their experience (see next section). This study procedure was adapted from a previous study about the effects of game difficulty adaptation on user experience [18].

D. Questionnaires

After each 9-minute game variant, participants filled out the Intrinsic Motivation Inventory (IMI) questionnaire. Though many versions of the questionnaire exist [19], we used a version that consists of only 8 statements that the participant can agree with or disagree on a Likert scale from 1 to 7. The questionnaire measures four scales: interest/enjoyment, effort/importance, perceived competence and pressure/tension. Each scale is measured with two items, resulting in a value between 2 and 14 for each scale. This variant of the questionnaire was validated using data from our previous study and found to give results similar to a longer 20-item version while being much more user-friendly, particularly for impaired participants [10].

Participants also filled out the Ten Item Personality Inventory (TIPI) [20] that measures multiple personality aspects as well as a pre-game questionnaire asking participants about their age, gender, and how much they enjoy competing with other people in general on a scale from 1 to 7, 1 meaning not at all and 7 meaning very much.

After completing both game variants, participants were asked to choose their preferred game variant between the two that they played. There were five possible answers: strongly preferred first variant, weakly preferred first variant, no preference, weakly preferred second variant, and strongly preferred second variant.

E. Measurement of Exercise Intensity

The Bimeo handle position was recorded with a sampling frequency of 20 Hz, allowing us to calculate the hand velocity and root-mean-square (RMS) value of hand velocity in the horizontal left-right direction. This RMS value was used as an objective measurement of exercise intensity; only the left-right measurement was used since it is the only one that affects the game. The RMS value of hand velocity (measured using IMUs) was previously validated as an exercise intensity measure in arm rehabilitation [21].

III. Results - Unimpaired Pairs

Unless stated otherwise, all results for the unimpaired pairs were analyzed across all 64 participants (32 pairs), regardless of the hardware used for exercise.

A. Questionnaires

The pre-game questionnaire asked participants how much they enjoyed competition on a scale from 1 to 7, with 1 indicating not at all and 7 indicating very much. The mean and standard deviation of the answer were 5.9 ± 1.3 . Only 6 of the 64 participants answered with less than a 5.

The question about preferred game variant showed that:

- In pairs that played the NA and MA variants (10 pairs), 18 out of 20 unimpaired participants preferred the MA variant, while the other 2 preferred the NA variant.
- In pairs that played the NA and AA variants (10 pairs), 17 out of 20 unimpaired participants preferred the AA variant, while the other 3 preferred the NA variant.
- In pairs that played the MA and AA variants (12 pairs), 13 of 24 unimpaired participants preferred the MA variant while the other 11 participants preferred the AA variant.
- None of the 64 participants chose the 'no preference' answer.

Results for all 4 scales of the IMI are presented in Table 2. Paired t-tests were conducted for the three different groups and for each IMI scale separately. They found that, in pairs that played the NA and MA variants, the MA variant resulted in higher enjoyment/interest ($p = 0.001$), effort/importance ($p = 0.001$) and pressure/tension ($p = 0.004$). Similarly, in pairs that played NA and AA variants, the AA variant resulted in higher enjoyment/interest ($p = 0.006$), effort/importance ($p = 0.018$) and pressure/tension ($p = 0.014$). No significant differences between variants were found in the group that played the MA and AA variants.

B. Exercise Intensity and Other Game Parameters

The RMS value of hand velocity, calculated over each 9-minute game variant, is presented in Table 3. Other parameters that were tracked during the exercise are listed in the same table below. The mean end score difference represents the point difference between the two players at the end of the 9-minute game, averaged across all participants who played that game variant. Similarly, the mean ball speed and paddle sizes at the end of the 9-minute round are listed in Table 3 for all 3 game variants.

The mean RMS value of hand velocity for each minute of the 9-minute game round was calculated for each game variant across all participants that played that variant with the Bimeo (since it is measured using the Bimeo's sensors). It is presented in Fig. 3.

IV. Results – Impaired-Unimpaired Pairs

Results are presented only for impaired participants (who played the game using the Bimeo).

A. Questionnaires

The question about preferred game variant showed that 3 impaired participants strongly preferred the AA variant, 1 weakly preferred the AA variant and 1 weakly preferred the MA variant. Results for all 4 scales of the IMI are presented in Table 4 as mean values over all 5 impaired participants.

B. Exercise Intensity and Other Exercise Parameters

Each impaired participant's RMS value of hand velocity is shown in Table 5 for both game variants.

At the end of each 9-minute game round,

- The mean end score difference between players was 8.0 points for the MA variant and 1.8 for the AA variant.
- The impaired participant's mean paddle size was 120% of the default size in the MA variant and 95% of the default size in the AA variant.
- The unimpaired participant's mean paddle size was 105% of the default size in the MA variant and 115% of the default size in the AA variant.

The mean ball speed was 3.1 for the MA variant and 3.2 for the AA variant (with initial speed being 2).

V. Discussion

A. Unimpaired participant pairs

Any kind of difficulty adaptation is preferred over no adaptation by most unimpaired participants, as seen in Table 2 and in the choice of preferred game variant. However, it is unclear whether manual or automatic adaptation is better from a motivation perspective, as both result in similar results on all four IMI scales. Both types of adaptation also resulted in higher exercise intensity (as measured by RMS of hand velocity in Table 3) than no adaptation, but there was almost no difference in intensity between the two adaptation methods. Exercise intensity increased with time for both adaptation types, as seen in Fig. 3.

From the mean end score difference, we can observe that the automatic adaptation mode variant successfully balances the performance of both players, as it results in the lowest score difference between them. Mean end speed was the highest in the manual adaptation variant, and we observed that many participants would set the game at a very high speed to make it more fun without caring about the score. To compensate, they also tended to make the paddles larger, as observed in the high mean end paddle size. However, this may not be a sustainable long-term strategy for rehabilitation – in longer sessions, overly high speeds would likely result in participants becoming tired or annoyed too quickly. Automatic adaptation, on the other hand, resulted in a slightly lower mean end speed and smaller paddles, which would result in less intense, but more precise movements that may be more relevant for rehabilitation.

In general, results from unimpaired participant pairs indicate that players can manually adapt difficulty about as well as a relatively simple performance-based algorithm – as evidenced by similar enjoyment and exercise intensity values in both adaptation variants. A possible interpretation of this is that participants can be trusted to make changes manually and that automatic algorithms are not necessary; another interpretation, however, is that automatic algorithms are useful since they can achieve similar results to manual adaptation and relieve participants of the burden of manually adapting difficulty. Before recommending a particular approach, let us first look at the five impaired participants.

B. Impaired-unimpaired participant pairs

As results from the unimpaired participant pairs clearly showed that both types of adaptation are preferable to no adaptation, all five pairs with impaired participants tested only the manual and automatic difficulty adaptation variants. In contrast to the unimpaired participant pairs, impaired participants had a clear preference between game variants: four of five preferred automatic difficulty adaptation.

As IMI and exercise intensity measures did not show a clear advantage between the two adaptation variants, we conducted brief interviews with the impaired participants to ask them why they preferred their chosen variant. All four impaired participants who preferred automatic adaptation gave the same answer: they did not like having to constantly think about how they wanted to change difficulty. For example, two participants stated that the game was generally more fun and intense with manual adaptation, but that the decision-making process required too much additional energy. On the other hand, the participant who preferred manual adaptation used a significantly different strategy than automatic adaptation: since both the impaired and unimpaired participant were relatively poor at the game, they both immediately enlarged their paddles and played with the default speed – unlike the behavior of the automatic method, which decreased the speed without enlarging the paddles.

C. Combining manual and automatic adaptation

As the impaired participants were far more representative of the end-user population than the unimpaired participant pairs (who were also much younger than impaired participants), we suggest a combined approach to difficulty adaptation in competitive rehabilitation exercises: Use an automatic algorithm to periodically adapt difficulty, but allow participants to easily override its decisions whenever they want. In our opinion, this will both reduce the cognitive workload of the participants (who will not necessarily need to think about difficulty adaptation) while ensuring that participants can still employ their own adaptation strategies if the automatic ones are inappropriate for them. A similar approach was previously suggested (though not tested) by Nagle et al. [15] for cognitive rehabilitation involving a single patient, and we believe that it would also be useful for competitive motor rehabilitation exercises.

D. Limitations and next steps

While the current study does demonstrate that both manual and automatic difficulty adaptation increase motivation and exercise intensity in competitive arm rehabilitation

games, it does have several limitations. For example, we did not test pairs consisting of two impaired participants. While pairs consisting of one impaired and one unimpaired participant are realistic for, e.g., home rehabilitation [8], [10], findings from them may not apply to, e.g., clinical rehabilitation where two patients may compete against each other. Furthermore, the evaluated automatic adaptation algorithm was relatively simple, and more complex adaptation algorithms such as those previously proposed for competitive exercises [13] may achieve better results. If competitive exercises are used with powered rehabilitation robots, difficulty adaptation could even involve haptic elements such as the robot's resistance [22].

The critical next step, we believe, is to test competitive arm rehabilitation games (with difficulty adaptation) over longer time periods. The current evaluation was done over 9-minute periods, but typical rehabilitation protocols consist of more than ten sessions, with each session including 30–60 minutes of exercise [1], [2]. Even over a shorter period (e.g. 3–4 sessions), longer-term effects of difficulty adaptation may become apparent, and other factors such as novelty may become more important.

VI. Conclusion

Our study shows that, in our competitive arm rehabilitation game, both manual and automated difficulty adaptation are preferable to no adaptation at all. Unimpaired participants did not show a clear preference between manual and automatic adaptation, and had similar levels of enjoyment and exercise intensity in both variants. Participants with neurological injuries, on the other hand, leaned toward automatic adaptation, which was considered to be less demanding and distracting.

As a practical solution to difficulty adaptation in competitive rehabilitation exercises, we propose a combination of manual and automatic adaptation: having an algorithm that periodically adapts difficulty settings based on the performance of both players, but also allow players to manually override the algorithm if desired. Equipped with such an adaptation method, competitive rehabilitation exercises should be able to optimize motivation and exercise intensity. In the long term, this high motivation and exercise intensity could lead to improved rehabilitation outcome compared to exercising alone, making competitive exercises a promising strategy in the treatment of chronic motor impairment.

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Figure 1.

The Bimeo arm rehabilitation system in the wrist and forearm training configuration. Two inertial sensors are attached to the arm while the hand rests on a support sphere that contains the third inertial sensor.

Figure 2.

Pong game screenshot. The bottom paddle is controlled by one participant using the Bimeo while the top paddle is controlled by the other participant using a joystick. The current game duration, score, ball speed and time until next automated difficulty adaptation are shown on the right side of the playing field. Paddles are shown at their default (starting) size.

Figure 3.

The average RMS values across unimpaired participants using Bimeo for each minute of the 9-minute game round and for each of the three game variants separately.

TABLE I

Characteristics of impaired participants.

ID	Gender	Age	How competitive are you? (1-7)	Injury Type	Time since injury	Impaired Arm	Box & Block Score	Relationship with unimpaired participant
1	F	86	2	traumatic brain injury	2 years	left	31	spouse
2	M	48	6	spinal cord injury	2.5 years	right	24	professional caregiver
3	F	56	5	ischemic stroke	12 years	left	27	spouse
4	M	83	1	ischemic stroke	11 years	left	31	grandparent
5	F	55	2	ischemic stroke	7 years	left	51	sister

TABLE II

Means and standard deviations for the four Intrinsic Motivation Inventory (IMI) scales in each game variant, across all unimpaired participants.

IMI scale	Type of difficulty adaptation		
	<i>No adaptation</i>	<i>Manual adaptation</i>	<i>Automatic adaptation</i>
Enjoyment/Interest	9.6 ± 2.9	11.0 ± 2.5	10.9 ± 2.6
Effort/Importance	9.8 ± 2.5	11.1 ± 2.8	10.9 ± 3.1
Perceived Competence	9.3 ± 2.8	9.5 ± 2.9	9.5 ± 3.0
Pressure/Tension	6.4 ± 3.1	7.3 ± 3.6	7.4 ± 3.3

TABLE III

Mean root-mean-square (RMS) value of hand velocity and other game parameters for all three game variants. DF = default value as seen in Fig. 2.

Game Parameters	Type of difficulty adaptation		
	<i>No adaptation</i>	<i>Manual adaptation</i>	<i>Automatic adaptation</i>
RMS of hand velocity	0.030 ± 0.010	0.040 ± 0.014	0.038 ± 0.018
Mean end score difference	5.95	8.05	3.22
Mean end ball speed	2.0	4.25	3.875
Mean end paddle size – Bimeo player	DF	112% of DF	89% of DF
Mean end paddle size – joystick player	DF	138% of DF	111% of DF

TABLE IV

Mean values for the four Intrinsic Motivation Inventory (IMI) scales across all 5 impaired participants.

IMI scale	Type of difficulty adaptation	
	<i>Manual adaptation</i>	<i>Automatic adaptation</i>
Enjoyment/Interest	12.4	12.2
Effort/Importance	11.8	12.6
Perceived Competence	9.8	10.0
Pressure/Tension	7.8	7.2

TABLE V

Root Mean Square (RMS) values of hand velocity for impaired participants. Underlined values indicate participant's preferred game variant.

Impaired participant	RMS for type of difficulty adaptation	
	<i>RMS – manual adaptation</i>	<i>RMS – automatic adaptation</i>
1	<u>0.0251</u>	0.0175
2	0.0253	<u>0.0298</u>
3	0.1084	<u>0.1141</u>
4	0.0405	<u>0.0412</u>
5	0.0292	<u>0.0200</u>
Mean	0.0457	0.0445