Journal of Biomedical Informatics 108 (2020) 103501

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Winning compensations: Adaptable gaming approach for upper limb rehabilitation sessions based on compensatory movements

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ARTICLE INFO

Keywords:
Rehabilitation strategies
Difficulty adjustment
Compensatory behaviors
Upper-limb
User studies
Usability testing

ABSTRACT

Recent research has been using automatic difficulty adjustment techniques as an effective channel to improve the quality of physical rehabilitation. Notably, these approaches often incorporate adaptation metrics such as emotions and performance. Nonetheless, compensatory movements, which hinder movement correctness and are considered as a core quality evaluation criterion of rehabilitation, have not been considered as an adaptation metric. Weighting how visual feedback interfaces increase patient engagement, we leverage an interactive system with a compensatory movements-based difficulty adjustment framework to enhance the upper-limb physical rehabilitation process. We conducted user tests with professionals (N = 15), which included observation sessions, co-design workshops, semi-structured interviews, and usability testing, to evaluate our prototype. Results showed that our interactive system achieved scores of perceived usability between 74 and 78.17, along with participants praising both the dynamic and manual customization of difficulty parameters. Our findings empower physical therapists and health professionals by reducing their burden on physical rehabilitation monitorization.

1. Introduction

Conventional physical rehabilitation methods adjust the difficulty of exercises based solely on observation. In particular, the subjective assessment of the patient's performance leads to changes in certain parameters such as amplitude in order to increase the difficulty of an exercise. While this type of methods allows for a closer relationship with the patient, its micromanagement nature restricts practical applications [1]. In addition, this approach is not scalable, restricting the number of patients each physiotherapist can assess [2]. Both these effects may lead to a decrease in the quality of the rehabilitation process, regarding both patient's performance, as they have a weaker quality assessment along time, and engagement, since their efforts reflect in worst results throughout rehabilitation sessions. Therefore, there is a need for more automatic, quantitative and precise methodologies of adjusting the difficulty of the physical exercises, while also enhancing the engagement of patients in the rehabilitation process, keeping them motivated improve their condition from session to session.

Dynamic difficulty adjustment carries many benefits regarding player experience in digital games and exergames [3–6]. There are several metrics to use as a basis of the conditions that trigger an adjustment of difficulty such as emotions [4,5], performance [6], or mental states [6]. However, there is a lack of research regarding the use compensatory movements as metrics to adjust difficulty during the physiotherapy process. Compensatory movements (e.g. [7–10]) occur whenever patients manifest alternative muscle activation patterns when trying to compensate for motor function deficits, which, in turn, leads to exercises that do not follow the right motor patterns to achieve the desired postures. Since compensatory movements ultimately result in pain and inhibition of motor recovery [11], we consider that it is of utmost importance to study the inclusion of compensatory movements as a metric for difficulty adjustment in physiotherapy sessions. Weighting how visual feedback interfaces increase patient engagement [12,13] and how harmful compensatory movements are [14], we propose an interactive system with a compensatory movements-based difficulty adjustment framework to enhance the physical rehabilitation process. Specifically, we extend prior state-of-the-art research focused on upper-limb rehabilitation [15,16,13].

Our research started with the development of an inexpensive solution built with commercial off-the-shelf hardware to promote upper-limb rehabilitation and collaboration between stroke patients and physiotherapists [15]. We continued our project by enhancing our

Abbreviations: **CI**, Confidence Interval; **ISCSEM**, Instituto Superior de Ciécias da Saúde Egas Moniz; **M**, Mean; **SD**, Standard Deviation; **SUS**, System Usability Scale

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https://doi.org/10.1016/j.jbi.2020.103501
Received 27 February 2020; Received in revised form 14 June 2020; Accepted 29 June 2020
Available online 18 July 2020
1532-0464/

system with a proximity-based context-aware component, that aims to improve the situational awareness of the clinicians and to facilitate communication with the patients, with the intent of improving the therapists work quality [16]. Next, we focused on the impact of compensatory movements on upper-limb rehabilitation by studying how different visual biofeedback techniques can leverage motion analysis by representing upper-limb compensatory movements in real-time [13]. In the present study, we continue our line of research by applying dynamic difficulty adjustment techniques to the execution of upper-limb physical rehabilitation. In particular, we include observation sessions, co-design workshops, semi-structured interviews, and usability testing with professionals to create and evaluate our prototype.

We contribute to the state-of-the-art with a novel difficulty adjustment framework based on compensatory movements for physiological upper-limb rehabilitation. Additionally, our user testing yielded strong results showing that our interactive system achieved scores of perceived usability between 74 and 78.17. Participants claimed that the greatest value of the system lies in the customization possibilities that both dynamic and manual adjustment of difficulty parameters can bring to the effectiveness of prescribed upper-limb physical rehabilitation treatments. In addition, all participants expressed their will to implement the system into their own patients treatment in the near future.

2. Observation sessions and co-design workshops

To properly design an interactive system that could provide adaptable visual bio-feedback for upper-limb rehabilitation based on compensatory movements, we collaborated with eight professionals in the physical rehabilitation sector from a private clinic Ciências da Saúde Egas Moniz. Several observation sessions were conducted that included semi-structured interviews and follow-up co-design workshops to understand physiotherapists' needs. First, participants were asked a set of standard questions and then observed and inquired while working on their own environments. The questions focused on which metrics should be monitored during upper-limb rehabilitation sessions and some standard exercises the therapists usually prompt in the clinic. In addition, we addressed the main compensatory movements that affect the correct performance of those exercises.

The professionals focused on two types of movements: upper-limb abduction/adduction and flexion/extension. They often pair physical exercises with cognitive challenges to promote functional tasks, such as picking up a glass from a cabinet. These exercises are usually divided in three levels of difficulty, which are achieved through variations in speed, range of motion, resting time, equilibrium, and adding new apparatus, such as an elastic band. Regarding compensatory movements, professionals pointed two behaviors that should be detected: (i) **shoulder lift** (exaggeration of abduction or flexion movements by lifting the shoulder above the coronal plane); and (ii) **lateral flexion of the trunk** (leaning of the trunk when performing upper body movements beyond the users' range of motion capabilities). These compensatory movements are corrected through direct intervention of the physiotherapist by lowering the effort patients have to make or by changing exercises.

Co-design sessions included all eight physiotherapists that criticized a preliminary prototype from Lopes et al. [13], providing limitations and suggestions of eventual improvements. This process resulted in the following set of requirements: (R1) the system must be engaging and interesting for the patient so that they keep their motivation throughout sessions; (R2) it must be adaptable to people that may have cognitive as well as the musculoskeletal impairments; (R3) it should provide accurate, quantitative information on compensatory movements; (R4) real-time feedback framework to motivate the fast correction of those movements; (R5) a simple, natural or familiar graphical user interface; (R6) clear objectives in the exercises for the patients to accomplish; (R7) it must output clear and valuable data to the physiotherapists; and (R8) both automatic and manual difficulty adjustment to allow customization.

3. System development

Based on the set of requirements, we designed and implemented *Winning Compensations*, an interactive system with a compensatory movements-based difficulty adjustment framework to enhance upper-limb physical rehabilitation. Similar to Lopes et al. [13], our interactive system consists of a Kinect One,[1] a computer to run the application, and a screen to display information to both physiotherapist and patient (Fig. 1). The avatar that represents the patient is a normalized skeleton that keeps the same relative distance for each segment independently of the user. Additionally, compensatory movements are detected by measuring the slope of the line segment that connects both shoulders to calculate the unevenness of the shoulder girdle, and relative inclination of the trunk with respect to the vertical line [13]. The Kinect One was chosen as the preferred motion capture device as it has been shown as a clinically valid method for objectively measuring active shoulder motion (e.g. [17]). In addition, it stands as a low-cost and easy to set up system, thus supporting new professionals and researchers working on physical rehabilitation by allowing them to use methods that are usually out of their scope and may ease their work [15]. Finally, the system provides quantitative data for the physiotherapist on the number and types of compensatory movements executed by the users, the number of correct, wrong and total repetitions for each exercise, as well as a correctness value for each exercise which is the ratio between the correct and total repetitions.

3.1. Type of exercises

Inline with the physiotherapists requirements, we considered typical upper-limb physical rehabilitation exercises such as abduction, adduction, flexion, and extension. Accordingly, a set of three different exercises were implemented: *Target Reach*, *Line Draw*, and *Shape Draw*. In particular, we take inspiration from the conventional methods as a means to create a sense of familiarity to both patients and physiotherapists. In order to detect whenever a patient performed a compensatory movement, we decided to include a cross overlaid with the avatar and represented by two green lines, in the coronal and median planes (horizontal and vertical, respectively). In case there is a compensatory movement, the green lines will change their color to yellow (tolerable movement) or red (incorrect movement), prompting the patient to return to a correct posture. Moreover, the physiotherapist can toggle the visibility of both these lines.

3.1.1. Target reach

Patients have to move their limbs on *Target Reach* in order to touch a sphere that is being displayed in colored areas on a grid (Fig. 2). We used an image of the grid that the physiotherapists typically use on their rehabilitation sessions as a background map to provide a familiar setting to both patients and physiotherapists. *Target Reach* includes four different variables that can be customized accordingly. **Amplitude/Range of motion** has been described as a strong metric for the effectiveness of physical therapy exercises and the quality of movement [18]. Therefore, we included it the range of motion in our exercise. In particular, it dictates at which angle the spheres should be instantiated.

Distance to the center controls the distance between the targets and the center of the circular grid. The closest from the center, the easier the exercise is, since the movement is done much closer to the user's trunk. The interface depicts a light-blue semi-circle which serves as an indicator of how far from the center-point targets are instantiated. In addition, we added a **reaction timer** to each target that progressively changes its color from green to red as time passes. If the target becomes red before the user can activate it, it will disappear and

[1] https://developer.microsoft.com/en-us/windows/kinect/ (accessed in 16/Feb/2020).

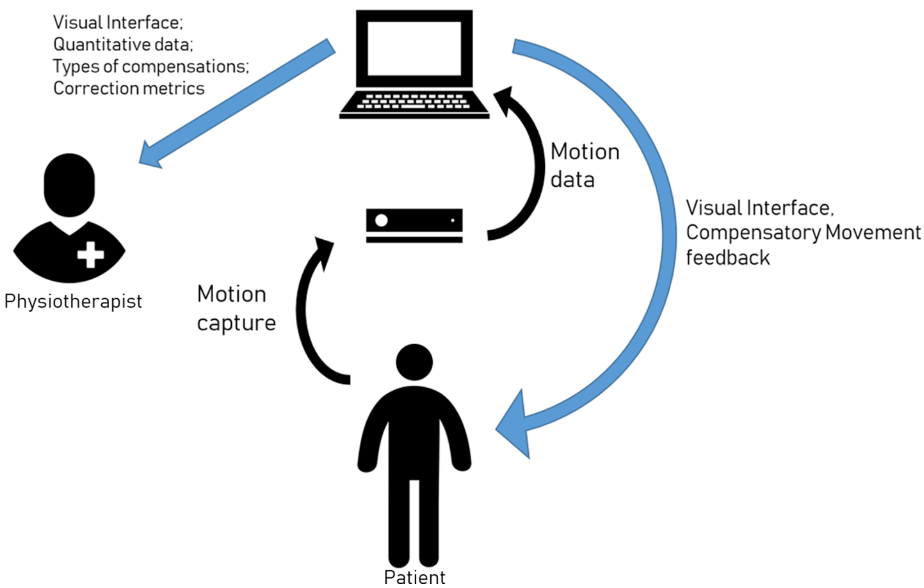


Fig. 1. System overview for Winning Compensations. The Kinect One acquires motion data from the patients' movements and sends it into the system. This data is shown in the interface for both the physiotherapist and the patient to see. The physiotherapist analyzes the quantitative and performance-assessment data while the patient can focus on the qualitative feedback and compensatory movements detected by the system.

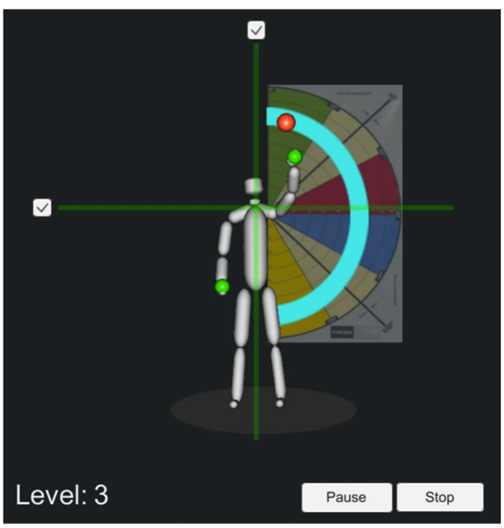


Fig. 2. Patient's graphical user interface for *Target Reach* while performing exercises for the left arm. The sphere in red represents the ongoing objective. The colored areas on the grid represent the different amplitudes where spheres are instantiated according to the difficulty of the exercise. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

another one will be instantiated following the current difficulty level in a different point on the grid. Finally, we decided to include a cognitive challenge through the instantiation of **obstacles** as purple spheres, which the patient has to avoid touching. This feature was designed to stimulate patients with cognitive impairments as it was required by the physiotherapists present in our first user sessions. Touching an obstacle sphere increases the number of tries the patient has to perform, while decreasing the correctness of the exercise. These spheres spawn on the circumference produced by the line of the **distance to the center** variable.

3.1.2. Line draw

Next, *Line Draw* was inspired based on feedback gathered at one of the collaborative sessions we had with professionals at Ciências da Saúde Egas Moniz. As the health professionals mentioned, they ask their patients to perform several repetitions of consecutive flexion/extension movements using a marker against a whiteboard, hence, drawing a series of straight lines. Therefore, our graphical user interface displays a path of targets that patients have to complete sequentially starting at a blue sphere and ending in a green one (Fig. 3). After completing one extension movement, an inverted path instantiates to allow participants to complete their mobilization of the joint with an opposite flexion movement, thus performing a full range of motion. *Line Draw* allows vertical and horizontal movements following the following variables: (i) **distance to the center** – dictates how far away from the center of the circular grid the middle point of the path instantiates –, and (ii) **length** – as the name implies, the physiotherapist can control the number of targets that form the path.

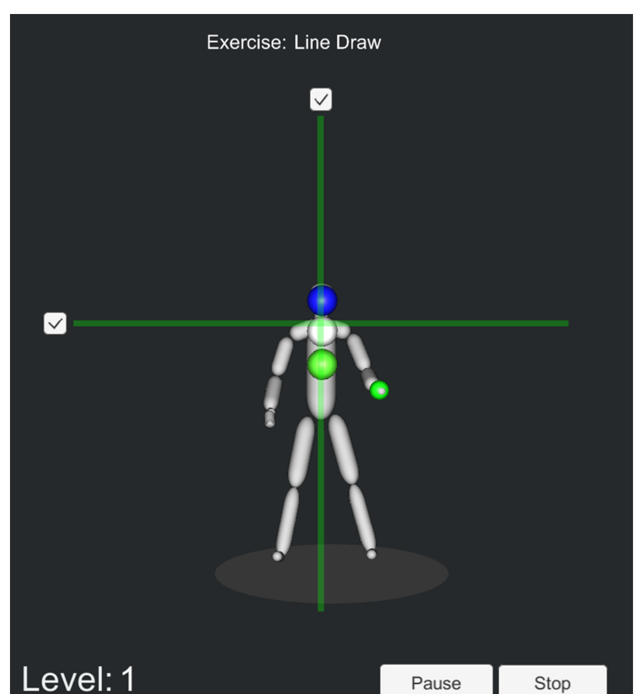
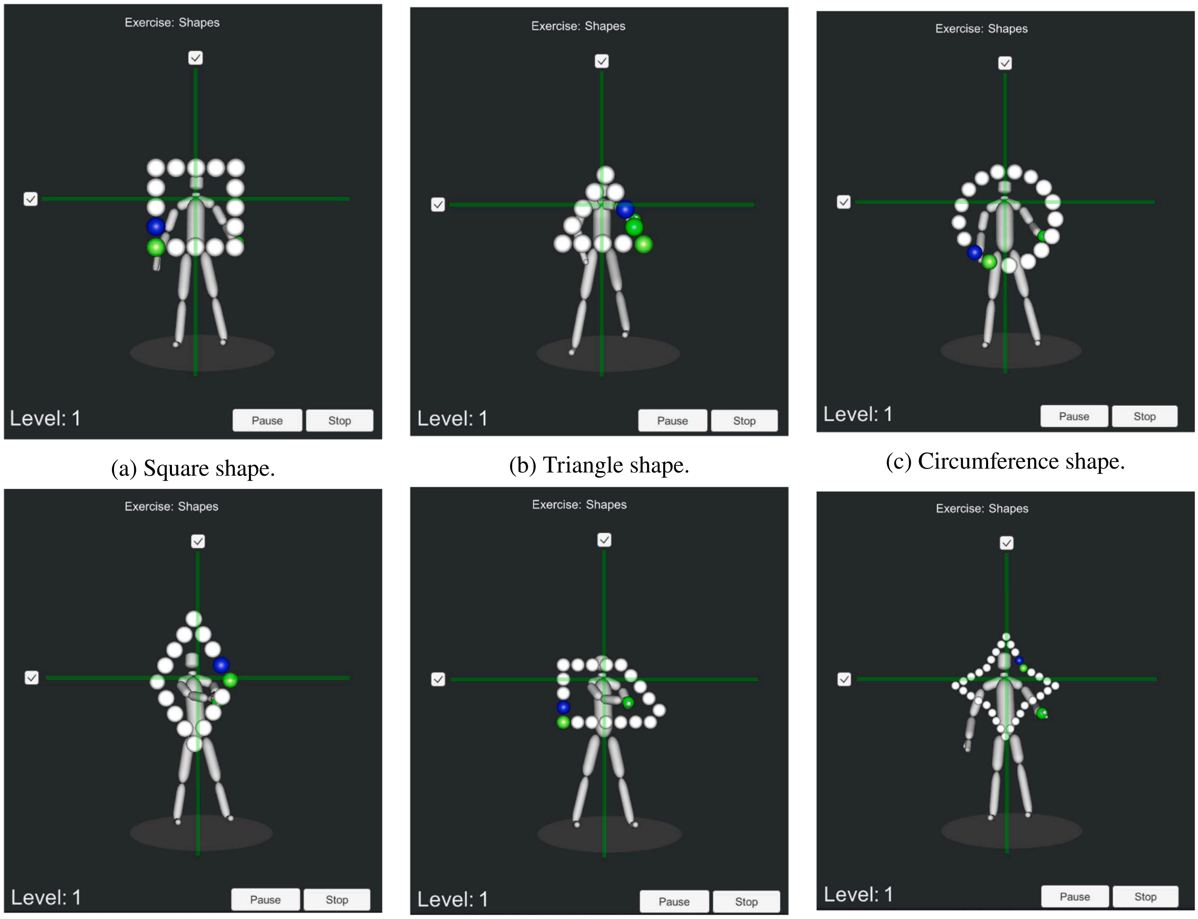


Fig. 3. Patient's graphical user interface for *Line Draw* while performing exercises for the left arm in a vertical motion. Flexion and extension movements are being assessed through a sequential activation of set of targets starting at the blue one and finishing in the green sphere.



(a) Square shape. (b) Triangle shape. (c) Circumference shape.

(d) Diamond shape. (e) Trapeze shape. (f) Star shape.

Fig. 4. Patient's graphical user interface for *Shape Draw* while performing exercises for the left arm. The objective in this exercise is to activate the targets from blue to green following the suggested shapes.

3.1.3. Shape draw

Finally, *Shape Draw* extends *Line Draw* by considering an additional spatial dimension. Notably, the exercise requires fine movements and a good sense of proprioception, i.e. kinaesthesia [19], which is the self-notion of the location and precision of the movement of the several body segments. It allows the physiotherapist to select which **shapes** the patient will have to draw throughout the session, since it was stressed during the co-design sessions that, as different shapes lead to distinct difficulty levels, professional should be able to choose the difficulty limits according to the condition of specific patients. The default run includes an incremental difficulty by drawing a square, a triangle, a circumference, a diamond, a trapeze, and then a star (Fig. 4), but it is possible to make any number of runs.

3.2. Difficulty adjustment

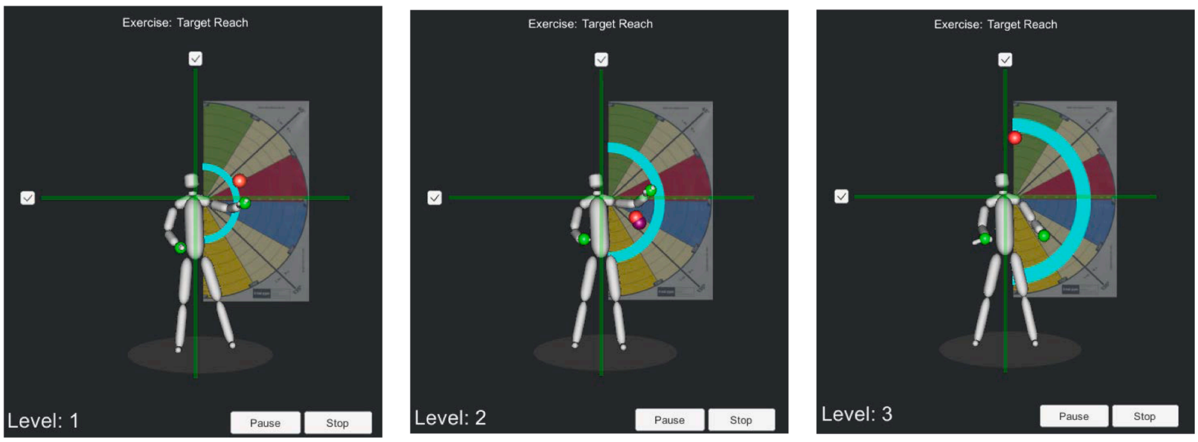
After developing the exercises and allowing certain parameters to be customized depending on the patient, we focused on how the automatic customization should be defined. For example, [4] used both boredom and frustration to balance the in-game difficulty. While high boredom and low frustration indicated that the challenge is too low and there is a need to increase difficulty, low boredom and high frustration led to a symmetric approach. Regarding parameters, the authors changed the number of obstacles, and the horizontal movement and speed of the game platforms between difficulty levels. [6] also addressed dynamic difficulty adjustment in a first-person shooter game. They implemented two state machines with three states to control the difficulty level, which transitions were meant to keep the participant in a flow state [20] based on mental states, or make the game harder as the performance of the player increased and vice versa. Each level varied the speed, spawn time, and health of the enemies in order to vary difficulty. In our approach, compensatory movements dictate whether the difficulty level should be varied. In particular, if the patient is performing the exercises accordingly, the level of difficulty increases, thus, reinforcing a correct rehabilitation behaviour. When any shoulder lift or leaning compensatory movement is detected, the level of difficulty is decreased. Similar to what physiotherapists already perform during their practice, we decided to use three difficulty stages on both *Target Reach* and *Line Draw*. Addressing each exercise at a time, the different *Target Reach* levels are presented in Table 1 and depicted in Fig. 5. The spawning of obstacle spheres can be disabled at any time. Regarding the reaction time, as the user successfully activates all targets, the reaction timer will be shorter for an increased difficulty level, making the exercise harder. After some attempts, if the user cannot activate the targets on a certain level, the system will adapt and reduce the difficulty level, which makes the timer longer.

Since *Line Draw* has fewer parameters, the difference between levels can only be varied in the distance to the center – short, medium, and long – and the length – three, four, or five spheres –, respectively (Fig. 6). Finally, *Shape Draw* is distinct from the other exercises, as it has six different levels, which increase in the following order: square, triangle, circumference, diamond, trapeze, and star (Fig. 4). When the patient takes too much time to complete the path of a shape, the system returns to the shape that has a difficulty level immediately lower to the one presented.

Besides the automatic difficulty adaptation, physiotherapists are

Table 1
Level differences for each variable of *Target Reach*.

	Level		
Variable	1	2	3
Range of motion	[−30°, +30°] (blue and red areas)	[−60°, −30°[∪] + 30°, +60°] (white areas)	[−90°, −60°[∪] + 60°, +90°] (yellow and green areas)
Distance to the center	Short	Medium	Long
Reaction time (pace)	Slow	Medium	Fast
Obstacles (spawn time)	10 s	8 s	6 s



(a) Level 1. (b) Level 2. (c) Level 3.

Fig. 5. Representation of all three levels of difficulty for the *Target Reach* exercise.

able to vary several parameters of the rehabilitation sessions. Particularly, this adjustment can be performed in real time while the patient is doing their exercises. In addition to the ones we presented for each exercise, the physiotherapist is prompted to define a set of specific parameters for the performance of the exercises, as depicted in Table 2.

4. Evaluation

We performed usability tests with the think-aloud protocol followed by semi-structured interviews with health professionals. This approach allows us to first verify with the professional community whether our technology may be useful in their work environment and rehabilitation process. In particular, we consider perceived usability a strong metric to evaluate the quality of *Winning Compensations*.[2]

4.1. Participants

Subjects were recruited through standard convenience sampling procedures including direct contact. Each participant was asked to sign a consent form. There were no potential risks and no anticipated benefits to individual participants. We conducted a total of 15 tests (six males, nine females) between 18 and 45 years old. In particular, there were four (26.7%) professional physiotherapists with three, eight, 15, and 18 years of experience, and the remaining eleven (73.3%) were finalist students of the physiotherapy course at Ciências da Saúde Egas Moniz. Moreover, only four (26.7%) had already used motion capture technology in their sessions and 14 (93.3%) stated that they frequently use difficulty adjustment in their treatment sessions. Finally, all participants reported that they felt the need to customize the exercises to the individual capabilities of their patients.

[2] https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en (accessed in 18/Feb/2020).

4.2. Apparatus

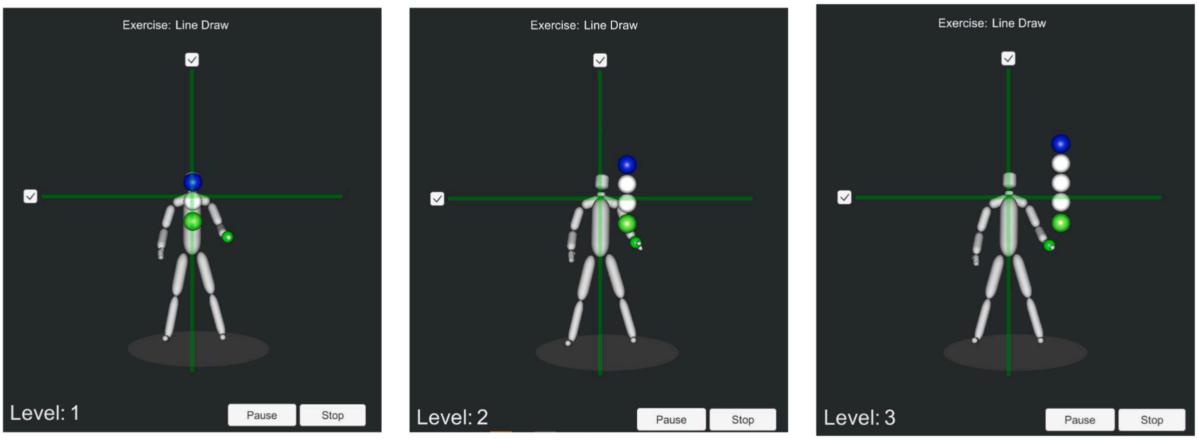
The System Usability Scale [21] is a subjective measure of usability that should be used right after the respondent interacts with a system. It is composed of ten items scored on a five-point Likert scale from *strongly disagree* to *strongly agree*. In our study, we used the Portuguese version of the System Usability ScaleSUS [22]. The experimental setup included additional material, namely (i) a computer to run the system, (ii) a computer mouse for the initial configuration of the system, (iii) a Microsoft Kinect One (V2) for motion capture, (iv) a screen to display the interactive system, (v) an audio recorder for the semi-structured interviews, and (vi) paper and pen to write down observations.

4.3. Tasks

In order to evaluate our system, we defined a set of tasks that users had to perform to configure Winning Compensations and then execute the exercises. First, participants had to select the ”Dynamic Difficulty Adjustment” category, followed by which arm the participant will execute the exercises with. Next, it is necessary to define the parameters of the session as (i) 15 repetitions for the maximum amount of repetitions per set, (ii) 3 sets for the maximum number of sets per type of exercise, (iii) 2 min duration for each set, (iv) 15 s rest period, and (v) an instance of each exercise type to be included in the session.

Then, we outlined a set of tasks to perform in each exercise. Regarding *Target Reach*, the first two sets were run with the automatic difficulty adjustments. While performing both sets, participants had to assess the correctness in each set, and keep track of the number and type of compensatory movements detected by the matrix (shoulder misalignment and trunk tilt). In the third set the participant switches the adjustment mode to ”manual” and proceeds to (i) set both ”Difficulty Range” and ”Distance” parameters to their maximum values, (ii) decrease the reaction time, and (iii) disable the cognitive spheres.

For the *Line Draw*, the participant performs (i) the first set in the vertical variant focusing on flexion and extension movements, (ii) the



(a) Level 1. (b) Level 2. (c) Level 3.

Fig. 6. Representation of all three levels of difficulty for the *Line Draw* exercise.

Table 2
Level differences for each variable of *Target Reach*.

Variable	Description
Side of the arm	Which arm is going to be focused on the rehabilitation session.
Maximum repetitions	The maximum number of correct repetitions the user has to perform so they can advance to the next exercise. The default value is 10 repetitions.
Time per set	The total maximum duration of each set of repetitions. The default value is 60 s.
Number of sets	The total number of sets the user has to accomplish in each exercise. The default value is set to 3 sets.
Rest duration	The time the user has to rest between two sets. The default value for this parameter is set to 60 s as well.
Exercise selection	The set of exercises that the patient will perform throughout the session.

second set in the horizontal variant targeting abduction and adduction movements which cross the median line, and (iii) the third set in the horizontal variant after increasing the time-limit to execute each repetition to 15 s. Finally, for *Shape Draw* the participant selects and performs the first three shapes, the last three shapes, and any number of shapes in the first, second, and third sets, respectively.

4.4. Procedure

Before the experiment, participants were informed about the experience and invited to sign a compulsory consent form. They were also informed that they could stop the experiment at any time. After receiving consent, participants were asked to stand at two meters in front of the screen and received a tutorial regarding mechanics and possible actions to perform. Additionally, we allowed participants to interact with the interface in order to support the development of a minimal mental model. When the participants felt comfortable with the system mechanics, they performed the three exercises in a random order, as seen in Fig. 7. After executing each exercise, we invited the participant to fill-in the System Usability Scale regarding that exercise. Finally, we conducted a semi-structured interview with each participant to gather additional in-depth insights and then thanked them for their collaboration.

5. Results and discussion

We started by calculating the scores that each participant reported. Results showed that *Line Draw* scored higher ($M = 78.17; SD = 13.14; 95\%CI = [71.51; 84.82]$) on perceived usability, followed by *Target Reach* ($M = 74.83; SD = 13.58; 95\%CI = [67.96; 81.70]$) and *Shape Draw* ($M = 74.00; SD = 15.64; 95\%CI = [66.09; 81.91]$). Since System Usability Scale scores have a range of 0 to 100 with an average System Usability Scale score around 70 [23], all our exercises have a mean perceived usability above average. Nevertheless, there is room for improvement in all exercises, as all values are very close to the reported average System Usability Scale score.

Regarding the semi-structured interview, our main focus was to collect more in-depth feedback from the physiotherapists and physiotherapy students, as to whether our system would be viable and applicable in a practical clinical context, and, in either case, what would the implications be. We also wanted to know what the participants liked and disliked the most in Winning Compensations.

When asked whether our prototype would have practical usability in the daily work of physiotherapists, all participants answered positively and gave different examples of situations where they would use Winning Compensations. In particular, they stated that the system could be easily implemented in both clinical and hospital settings, although some adjustments to the setup would have to be made, such as the size of the display in which the exercises would be shown. Participants also reported that Winning Compensations provided good real-time feedback to the patients, giving them something much more objective to guide themselves through the process and keeping them more engaged during the exercises. A possible application in a gym setting was also mentioned by one of the physiotherapists, who said that it would allow a much better perception of smaller, less evident, compensatory movements, that can be harder to detect conventionally and ”with the naked eye”. Furthermore, most participants (66.7%) also indicated that the prototype would have great potential in many other scenarios independent of musculoskeletal ones such as helping physiotherapists with patients with neurological and cognitive limitations correcting compensatory movements more effectively in different environments and helping patients regain functional movement capabilities through the exercises that can be similar to daily activities. In addition, conditions such as post-surgery, shoulder dislocations, and fractures were examples of clinical conditions where Winning Compensations could help patients greatly regain quality of movement, with its interactive approach and quantitative assessment capabilities.

All participants undoubtedly believed that the quantification of compensatory movements throughout the sessions brings great value to the physiotherapists' daily task of helping patients correct and regain

(a) Physiotherapist performing tasks for the *Shape Draw* exercise. (b) Finalist physiotherapy student performing tasks for the *Line Draw* exercise.

Fig. 7. Participants executing scripted tasks for the exercises.

their movement functionality, since it is only natural that compensatory movements occur when the patients are executing the movements by themselves. Participants also said that, with our interactive system, it is possible for patients to autonomously correct their performance without needing permanent supervision and attention from the physiotherapists.

Another important topic brought to light during the interviews was the necessity to understand whether a certain degree of compensation is acceptable or not, due to physical limitations that a certain patient might already have. Such situations require even greater customization in terms of the tolerance of the matrix to detect compensatory movements, which we addressed by allowing practitioners to manually adjust the tolerance of the system's compensation matrix. The different adjustable parameters were considered very useful overall, mainly the adjustment of the amplitude and speed in the *Target Reach* exercise, and the high customization and variability possible in the *Shape Draw* exercise. Notably, the majority of the participants emphasized at a stronger degree the importance of manually adjusting the parameters compared to the dynamic adjustment. Nevertheless, they also praised the dynamic difficulty adjustment as a very useful technique in many situations as well, mainly for regaining normal movement functions in a controlled, progressive approach. In addition, it allows on-the-fly customization of the challenges to different patients with specific necessities. The constant feedback on the posture of the patient was another very strong feature pointed out by the physiotherapists.

Concerning the graphical user interface, all participants said the interface was well implemented and easy to interpret by the physiotherapists, with little to no issue at all. One participant also suggested that a short tutorial showing the patient the correct way to execute the exercises would greatly help them understand not only the exercises, but the interface as well. Another suggestion focused on how the completion of the goal of both *Line Draw* and *Shape Draw* exercises was not being completely evident in each set of targets. We believe that this effect is due to the last target having the same color than all the other activated targets, making it hard to detect if it has already been activated or not. Although we already provide an audio cue that plays once the final target is activated, additional changes in color of the target would make it more clear. Another approach, as pointed out by one physiotherapist, was to ”hide” some of the information available in the interface so that it doesn't confuse patients while performing the exercises. Nevertheless, all participants found that data regarding the tracking of the repetitions and sets, the amplitudes shown in real time, and the monitoring and quantification of the compensatory movements executed is highly relevant. Finally, when asked whether something was missing on the interface, all participants said it was already very complete and the information available was the most useful. Regarding what other parameters could be dynamically tweaked with patient performance, only the physiotherapists made suggestions. For example, they said that it could be interesting to implement a parameter which randomized the duration for each set, according to the difficulty level the patient is in. This could be interesting, mainly in the *Line Draw* and *Shape Draw* exercises, since some of the objectives require more time, while others require less and part of the challenge can be to try and accomplish them according to varying time limits. This feature also increases variability in the exercise, which is one of the key points of an adaptable rehabilitation process, according to the physiotherapists we interviewed.

5.1. Study limitations

There are some important factors that may explain some of our results. First, the number of participants in this experience could have been larger. In particular, a larger number of physiotherapists would allow conclusions with a stronger impact. Second, as pointed out by the participants, the interface was in English, which may have led to translation errors from our participants, despite the terms used in the graphical user interface being popular among practitioners. Third, the graphical user interface was projected on a 17 inches laptop screen. Such a small screen led participants to often come closer to the screen to read the information that was being displayed. Finally, our study did not include patients, which are also part of the end-user stakeholders. The lack of input from patients may hinder some graphical user interface adjustments that must be applied in order to conform to this type of users' interactions, as they differ from the physiotherapists' ones. Although we are firstly trying to assess from the physiotherapists point of view whether Winning Compensations would be viable in their workplace, it would be interesting to find if patients could effectively and efficiently interact with our system. In addition, the participants knew that a member of the development team conducted the usability tests, which may have led to a bias by hindering their critical responses. Nevertheless, participants were informed that it was the system that was being tested and not themselves, as a way to counter this bias.

6. Conclusions and future work

The aim of our work was to access the potential of an interactive system with compensatory movements-based difficulty adjustment for the practice of upper-limb rehabilitation. In order to study the value of our interactive system, we conducted observation sessions, co-design workshops, semi-structured interviews, and usability testing with professionals to understand whether practitioners assessed our prototype with a high level of perceived usability, user satisfaction and preference. The results presented in this work contribute to advancing the state of the art of knowledge in several aspects. In particular, we extend prior state-of-the-art research focused on upper-limb rehabilitation [15,16,13]. *Winning Compensations* empowers physical rehabilitation practitioners with a new easy to set-up, cost-effective interactive system that shows promise as a means to improve the quality of upper-limb rehabilitation. All three proposed exercises scored above average System Usability Scale scores, with participants praising both automatic and manual dynamic difficulty adjustment. In particular, the physiotherapists emphasized the possibilities the system offered to manually change and manipulate the parameters of the several exercises. Some even chose one of the exercises as their favorite and, among all participants, the *Shape Draw* exercise was the one that generated the most discussion. Moreover, most participants enjoyed it a lot and described it as the most attractive, challenging and engaging from the three, as well as the most adaptable and similar to functional exercises that the physiotherapists already implement in their sessions. Thus, our system can bring positive aspects to the physical therapy paradigm.

Future work includes integrating real patients in the design process. Notably, we aim at conducting an user testing phase through several upper-limb rehabilitation sessions where we study how patients assess the usability of Winning Compensations and whether the physical rehabilitation process is improved. In addition, future work comprises a new version of the system where we implement feedback from our participants and use a larger screen size to display the system. We also believe that studying the effect of Winning Compensations on the physical process as well is a relevant direction for our study such as the trajectory of the upper-limb while patients perform the exercises. Among relevant changes in the graphical user interface, we can include the detection of more compensatory movements or individual differences such as personality [24] to make for a more complete user-based adaptation.

Finally, Winning Compensations empowers physical rehabilitation practitioners with a new cost-effective interactive system that shows promise as a means to improve the quality of upper-limb rehabilitation. As a motion capture-based approach, Winning Compensations is not bounded by wearable that are usually recalled as intrusive by patients, thus limiting the patient's movements. Furthermore, it takes a short time to setup. Additionally, compensatory movements are the most common, subjective performance indicator that physiotherapists observe to progressively achieve better results in their patients' recovery, since these compensations can be exaggerations or deficiencies of correct movements. Therefore, Winning Compensations provides therapists the required objective information about their patients' adherence to rehabilitation exercises, which is often not present [11].

CRediT authorship contribution statement

M.S. Tomás Alves: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **M.S. Daniel Simões Henrique Carvalho Lopes:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - review & editing, Visualization, Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Daniel Simões Lopes:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by national funds through Fundação para a Ciência e a Tecnologia (FCT) with references UIDB/50021/2020, SFRH/BD/144798/2019, and STREACKER UTAP-EXPL/CA/0065/2017.

References

[1] J.D. Smeddinck, M. Herrlich, R. Malaka, "Exergames for physiotherapy and rehabilitation: a medium-term situated study of motivational aspects and impact on functional reach," in, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM, 2015, pp. 4143–4146.
[2] S. Siegel, J. Smeddinck, Adaptive difficulty with dynamic range of motion adjustments in exergames for parkinson's disease patients, International Conference on Entertainment Computing, Springer, 2012, pp. 429–432.
[3] J.A.G. Marin, K.F. Navarro, and E. Lawrence, Serious games to improve the physical health of the elderly: a categorization scheme, in: CENTRIC 2011 The Fourth International Conference on Advances in Human-Oriented and Personalized Mechanisms, Technologies, and Services, 2011, pp. 64–71.
[4] J. Frommel, F. Fischbach, K. Rogers, M. Weber, "Emotion-based dynamic difficulty adjustment using parameterized difficulty and self-reports of emotion," in, Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play, ACM, 2018, pp. 163–171.
[5] G. Chanel, C. Rebetez, M. Bétrancourt, T. Pun, Emotion assessment from physiological signals for adaptation of game difficulty, IEEE Trans. Syst. Man Cybernet.-Part A: Syst. Hum. 41 (6) (2011) 1052–1063.
[6] T. Alves, S. Gama, F.S. Melo, "Flow adaptation in serious games for health," May, 2018 IEEE 6th International Conference on Serious Games and Applications for Health (SeGAH), 2018, pp. 1–8.
[7] D. Hamacher, D. Bertram, C. Fölsch, L. Schega, Evaluation of a visual feedback system in gait retraining: a pilot study, Gait Post. 36 (2) (2012) 182–186.
[8] S. Caudron, M. Guerraz, A. Eusebio, J.-P. Gros, J.-P. Azulay, M. Vaugoyeau, Evaluation of a visual biofeedback on the postural control in parkinson's disease, Neurophysiologie Clinique/Clin. Neurophysiol. 44 (1) (2014) 77–86.
[9] D. Hamacher, D. Hamacher, L. Schega, Does visual augmented feedback reduce local dynamic stability while walking? Gait Post. 42 (4) (2015) 415–418.
[10] E.R. Walker, A.S. Hyngstrom, B.D. Schmit, Influence of visual feedback on dynamic balance control in chronic stroke survivors, J. Biomech. 49 (5) (2016) 698–703.
[11] C.C. Bassile, S.M. Hayes, Gait awareness, Stroke Rehabilitation, Elsevier, 2016, pp. 194–223.
[12] A.E. Boone, M.H. Foreman, J.R. Engsberg, Development of a novel virtual reality gait intervention, Gait Post. 52 (2017) 202–204.
[13] D. Lopes, A. Faria, A. Barriga, S. Caneira, F. Baptista, C. Matos, A. Neves, L. Prates, A. Pereira, H. Nicolau, Visual biofeedback for upper limb compensatory movements: A preliminary study next to rehabilitation professionals, Proceedings of the 21st EG/VGTC Conference on Visualization, 2019.
[14] D. Rado, A. Sankaran, J. Plasek, D. Nuckley, D.F. Keefe, A real-time physical therapy visualization strategy to improve unsupervised patient rehabilitation, IEEE Visual. (2009).
[15] A. Domingues, J. Jorge, D.S. Lopes, Kinect-based biofeedback interfaces to improve upper limb rehabilitation, in: Annals of Medicine, vol. 50, pp. S110–S111, TAYLOR & FRANCIS LTD 2–4 PARK SQUARE, MILTON PARK, ABINGDON OR14 4RN, OXON, ENGLAND: TAYLOR & FRANCIS LTD., 2018.
[16] A.V. Faria, Arcade: Augmenting rehabilitation centres to assist physiotherapists through digital environments. MSc dissertation, Instituto Superior Técnico, University of Lisbon, 2018.
[17] F.A. Matsen III, A. Lauder, K. Rector, P. Keeling, A.L. Cherones, Measurement of active shoulder motion using the kinect, a commercially available infrared position detection system, J. Shoulder Elbow Surg. 25 (2) (2016) 216–223.
[18] A. Peretti, F. Amenta, S. Tayebati, G. Nittari, S. Mahdi, T. Stütz, G. Emsenhuber, D. Huber, M. Domhardt, M. Tiefengrabner, et al., Jmir rehabilitation and assistive technologies, JMIR 4 (2) (2017).
[19] A. Alvemalm, A. Furness, L. Wellington, Measurement of shoulder joint kinaesthesia, Manual Therapy 1 (3) (1996) 140–145.
[20] M. Csikszentmihalyi, Finding Flow: The Psychology of Engagement with Everyday Life, Basic Books, 1997.
[21] J. Brooke, et al., Sus-a quick and dirty usability scale, Usability Eval. Indust. 189 (194) (1996) 4–7.
[22] A.I. Martins, A.F. Rosa, A. Queirós, A. Silva, N.P. Rocha, European portuguese validation of the system usability scale (sus), Procedia Comput. Sci. 67 (2015) 293–300.
[23] A. Bangor, P. Kortum, J. Miller, Determining what individual sus scores mean: Adding an adjective rating scale, J. Usability Stud. 4 (3) (2009) 114–123.
[24] T. Alves, C. Martinho, R. Prada, incorporating personality in serious games for health, in: 2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games), 2019, pp. 1–4.