A Customizable Upper Limb Stroke Rehabilitation Tool

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October 2022

Abstract

With the increasing emergence of interactive rehabilitation systems, some technologies target specific rehabilitation fields. Stroke rehabilitation is one of those fields and a rather important one, considering stroke has affected 1.1 million people each year in Europe alone at the beginning of the 21st century. The biggest obstacle in stroke rehabilitation systems is that stroke patients' symptoms include hemiparesis, causing motor and cognitive impairments that differ from patient to patient. With this in mind, we developed an intuitively interactable system with the ability to record and review any movement desired by a patient. The system also features the capability for a therapist to set the compensatory movement thresholds considered ideal for any actuating body segment in said movement, according to patient need, the means for the patient to practice said movement, with the help of dynamic feedback, and review it alongside the clinician, with access to data metrics, captured during motion execution. Additionally, we conducted a user study where physical therapists interacted with our system, where results suggest that the adaptability to both patient's needs and therapist intervention methodology diversity are imperative for the validity of any neurological therapy interactive tool. Moreover, we concluded that, due to the predominance of stroke victims of an older age group, stroke rehabilitation tools should focus on the simplicity of interface and equipment used and that an exercise review feature, including performance and error metrics, can improve the quality of exercise analysis and consequently treatment quality.
Keywords: Rehabilitation, Stroke, Motion Capture, Compensatory Movements, User Interface, HTC Vive

1. Introduction

A stroke is a common form of brain injury, generally caused by cerebral infarction (ischemic stroke), a nontraumatic intracerebral haemorrhage or an intraventricular haemorrhage [35]. Stroke is a leading cause of disability, affecting approximately 1.1 million people in Europe each year at the beginning of the 21st century [4].

Rehabilitation is a crucial part of muscular dysfunction or motor disability recovery, and it usually implicates muscular stimulation and reinforcement through exercise. However, since the most common and widely recognized impairment caused by stroke is motor impairment, which can be regarded as a loss or limitation of function in muscle control or movement or a limitation in mobility, much of the focus of stroke rehabilitation. In particular, the work of physiotherapists and occupational therapists is on the recovery of impaired movement and the associated functions [16].

This specific approach of rehabilitation, due to its subjective nature, requires the analysis of compensatory movements as these are frequent when someone is re-learning limb function-associated motions. While these compensatory movements help patients to achieve their tasks, they can also obstruct recovery progress and induce new orthopaedic problems. In light of this, detecting and preventing compensatory movements warrants particular consideration [34].

On another note, one of the most disabling motor conditions following stroke-related brain damage is the loss of arm function. Following a stroke, up to 85% of patients have a sensorimotor deficit in the arm [9]. Whilst hemiparesis (a common symptom of stroke-related brain damage consistent with the weakness of one side of the body) is evident in both the lower and upper body, initial rehabilitation is generally focused on the lower body rather than the upper limbs. Only 17% of stroke survivors discharged from hospitals felt that they received good arm and hand therapy and approximately 80% of stroke survivors never recover fully from motor impairments in their upper limbs [15]. This said, upper-body rehabilitation of stroke-related motor impairments is an area that currently requires unique focus.

The exponential emergence of interactive solutions has a very positive impact on the field of rehabilitation, and a lot of these solutions are becoming specialized, targeting specific conditions/disabilities, one of them being stroke-related dysfunctions. However, the current solutions do not allow for enough personalization to cover the specifications of stroke rehabilitation, not considering the diversity of impairments caused by a stroke and, consequently, the subjectivity of the rehabilitation process that each patient should go through [10][12]. Instead, the existing solutions rely on preset exercises/motions/games that limit stroke patients' movements. Moreover, most systems do not consider compensatory movements - an important aspect to monitor when re-learning motor function - and are user-focused, not considering therapists' needs to properly take advantage of interactive and feedback technologies to improve treatment.

The main objective of this project is to develop a user-centered user interface that allows for enough exercise personalization to allow the proper monitorization and execution of any pre-recorded exercise/motion, taking into account compensatory movements, using an affordable movement tracking technology that is accurate enough to capture these, as well as any motion required.

To do this, we sought to use the combined information collected from studying the current state of the art, leveraging the work and findings of a former IST student project, the ARCADE[11], and some expertise from experienced professionals on our team, to design a prototype concept. We would then present that concept to practising physical therapists, which would give us enough feedback and general direction to build a tangible system, that would achieve our aforementioned goals, while simultaneously meeting clinicians technical needs, in order to improve the quality and efficiency of their daily work.

The main contributions of this paper are: (1) create a system that can detect and measure compensatory movements with different set thresholds of compliance, (2) create an interface that allows stroke patients to record and practice their subjective motor impairments, (3) create an interface that allows stroke patients to record and practice their subjective motor impairments, (4) create an interface that allows stroke patients to record and practice their subjective motor impairments, (5) to make the HTC Vive viable as an accurate and affordable movement tracking system to use interactive rehabilitation systems and (6) validation of the usability and utility of the developed interface.

2. Related Work

The related work is discussed along the topics of compensatory movements, interactive rehabilitation, user-centred interactive rehabilitation focus, movement tracking technologies, the effect of motivation in rehabilitation and the physical focus of stroke rehabilitation.

2.1. Compensatory Movements

Traditionally, the choice between rehabilitation strategies has been based on the phase of stroke recovery. Thus, in the acute stages, therapy focuses on preventing maladaptive compensatory strategies while promoting the healing of normal function. In chronic phases, the emphasis is placed on maximizing function, often through the teaching of compensatory strategies. Today, observations suggest that such a clear division between function vs criteria treatment approaches may not be justified [21].

Michaelsen et al. investigated the effects of the suppression of shoulder and trunk compensatory movements and concluded that compensatory movement restraint allowed patients to decrease compensations and improve range and coordination of upper-body motions [20] while the unrestrained movement showed to limit the potential recovery of normal movements [20].

Even with evidence defending the restriction of compensatory movements in stroke recovery [34], some studies still find that task-specific and purely outcome-oriented training are both viable, depending on the severity of the motor impairments displayed by the patients [9].

This split view between the importance of compensatory movement restriction is still a reality and, to be easily adaptable and viable to clinic use, a system where compensatory movements can be measured and detected (with compensation movements as an input [1]), with variable compensation thresholds would give them the freedom to accommodate any rehabilitation practice, according to each practitioner's compensation restriction criteria.

2.2. Interactive Rehabilitation

With the incremental appearance of new technology-based rehabilitation systems, some areas in the rehabilitation process were immediately improved. These areas include data capture and storage, previously existing only in therapist/doctor notes, exercise feedback and visual movement guidance.

Interactive rehabilitation systems are revolutionizing the way physical and psychological recovery can be achieved using new technology to capture and display data in different ways. Feedback in physical recovery is imperative to sustainable rehabilitation. It ensures the patient can recover physical functioning and avoid re-aggravating their injury. In addition, the feedback can contribute to the patient's motivation [30].

Even though interactive guidance has been a reality for decades now, in the form of informative videos, the dynamic potential of new feedback visualization approaches can have big benefits in patient recovery, specially compared to these old formats [2].

As we mentioned previously, Faria et al. [11] developed a tool to evaluate if a context-aware system can be helpful in a rehabilitation environment called ARCADE. This tool captures exercises performed by a patient, giving immediate feedback to both patient and therapist in the form of skeletal models of the patient demonstrating the success rate of the performed exercises and other valuable metrics.

Still, with the amount of data captured when performing physical therapy exercises, feedback visualization can have negative effects if shown in excess [30].

Some projects were successful in finding a balance in feedback format that improved rehabilitation, such as Saraee et al. [27], who evaluated the progress made toward a more comprehensive analysis of the performance of patients in therapy sessions and the feedback given to both patients and physical therapists and found that the quantitative feedback after each trial and the playback of a reference exercise while performing a practice exercise are beneficial to motor recovery.

2.3. User-Centered Focus in Interactive Rehabilitation

Most interactive software developers adopt a user-centred approach since the result is usually more usable and acceptable applications [3]. The problem with this approach is that some of these applications usually disregard the role of the therapist in the rehabilitation process, considering the patient only as the user, even though it has been shown that accurate assessment, evaluation and comparison of the patients' motion patterns over time can improve their motor recovery, when therapists can make more informed decisions [23].

A common example of patient-centred rehabilitation technologies that are not suitable for stroke patients is Exergames (games that are also a form of exercise), such as the set of home-based games developed by Alankus et al. [1], to improve stroke rehabilitation performance by helping with motivation in the practice of recovery exercises. Although they were successful in motivating patients, they realized that games only suit a narrow range of motions a stroke patient could need to work on, as impaired motions vary so much from patient to patient.

On another perspective, Nicolau et al. [23] presented a computer-assisted virtual rehabilitation platform developed with a focus on therapist priorities, mainly concerning themselves with the platform's usefulness to therapists. This led to results indicating that therapists found their platform a valuable addition to current rehabilitation procedures.

2.4. Movement Tracking Technologies

Motion tracking technologies come in three primary forms: magnetic motion capture, mechanical motion capture and, arguably most used nowadays, optical motion capture. Most modern interactive rehabilitation systems usually use one of two optical motion capture methods: depth cameras or marker-based tracking.

2.4.1 Microsoft Kinect.

The Microsoft Kinect depth camera is the most widely used motion tracking technology in interactive rehabilitation systems because of its affordable price, good performance and general ease to set up and use.

However, the Kinect has shown limitations in precision, especially in skeletal tracking, where the system has difficulty tracking movements that cause large amounts of occlusions [2] [33].

Although it proved to be very accurate in tracking coarse movements when limbs were pointed directly at the camera or occluded by the body, the overall tracking was severely penalized. The tracking of extremities needed to be more accurate to identify mistakes made by participants. Another limitation identified was the lack of support for detecting rotations such as pronation and supination of the wrist [30][31]. Due to these limitations, a wide variety of movements can't be tracked by the Kinect.

2.4.2 Nintendo Wii

The Nintendo Wii game console has garnered considerable attention, mainly due to its controller, the Wii Remote, and its motion-tracking capabilities. This remote is considered a versatile way to collect abundant, high-quality data since it communicates with the console over a standard wireless Bluetooth interface, making it quite simple to use. Its price is typically a fraction of dedicated, commercial data acquisition tools [32].

Despite some studies showing the validity of this technology in interactive rehabilitation systems [33][14], due to the nature of this system and remote dependency, full limb tracking capabilities are limited, as this remains a single point of measurement on ample space of motion possibilities [29].

2.4.3 Marker-Based Motion Tracking.

Marker-based motion tracking is another optical motion-capturing method that uses cameras and a set of markers mounted on joints and other predetermined spots on a person's body to computationally render a simulation of that person's body in a specific software. Methods of motion capture of this nature, usually designated by MBS systems,are arguably the most accurate optical motion capture method available [8], being de-facto standard for high-precision applications, including biomechanics research and clinical gait analysis [6].

The issue with these technologies is, compared to a Microsoft Kinect, they are much more expensive, and their set-up is more time-consuming [25][22], making their deployment in most physical therapy clinics unlivable[13].

2.4.4 HTC Vive.

A newer form of motion tracking hardware is HMD (Head-Mounted Display) Virtual Reality devices, such as Oculus Rift, PlayStation VR and HTC Vive. These devices, amongst other features, are capable of positional and rotational tracking. While Oculus Rift and HTC Vive HMDs offer exceptional tracking through an embedded infrared system, the feature that distinguishes HTC Vive from the others is the Vive Tracker, which allows people to bring any real-world object into the virtual environment by simply attaching the Tracker to it. The position and orientation of this device are then tracked by two base stations based on infrared signals. Studies showed that this technology could track both joint rotation and position with elevated levels of accuracy[7][5].

2.5. The Role of Motivation in Rehabilitation

One of the biggest, but sometimes overlooked, obstacles in rehabilitation is the patient's state of mind. The human mind can quickly go to a state of lack of motivation and disbelief in recovery when faced with a challenge like motor impairment.

Motivation is a subject of great importance in physical therapy, even considered by some *the most important, yet the most difficult part of the work of the therapeutic professions* [24].

This motivation can be affected by factors external to the clinical environment [18], which can lead to adverse effects on exercise performance [28]. This said, clinical awareness of all the factors impinging on motivation for rehabilitation could only have positive effects on patient care [17].

2.6. Physical focus of stroke rehabilitation

Presently, in stroke rehabilitation, focus on lower-limb recovery is predominant, as mobility issues are usually considered more restrictive. Despite this convention, only 20% of stroke survivors fully regain their ability to use their impaired upper limb[15]. This reality remains, primarily due to upper-limb exercise neglection, since studies have determined that early intensive practice of active functional tasks can lead to more positive outcomes for upper limb rehabilitation [19].

Kytö et al.'s [15] study provided insight into the importance of upper-limb interactive rehabilitation technologies in order to increase stroke survivors' independence in their daily lives.

3. Building an Interactive Stroke Rehabilitation Concept Design

To understand the practical side of the concepts that stand as a foundation of the development of our system, Stroke Rehabilitation and Interactive Rehabilitation, and taking into consideration the contributions we aimed to achieve, we concluded that no other work had enough similarities to our personalization requirements. Bearing this in mind, feedback from active professional physiotherapists was a priority, especially considering the need to have a user-centred approach to developing our system due to the nature and profession of our end users.

In order to prepare ourselves to present our idea and to get the best and most appropriate information, we decided to make a Low-Functionality prototype representing our main ideas and design guidelines. To build this first iteration of a prototype we used, as a baseline, information gathered from the professional expertise of our supervisor, Prof. Marlene Rosa, as an experienced physical therapist, and followed the previous work of a former IST student, Afonso Faria, utilizing important information and feedback from therapists, gathered during the development of his proposed upper-limb biofeedback physical therapy system called ARCADE[11].

3.1. ARCADE

ARCADE is a proximity-based context-aware biofeedback system that aims to improve clinicians' situational awareness and facilitate communication with the patients, aiming to improve the therapists' work quality.

The study of information and metrics in the development stages of the ARCADE system provided some of the most valuable insights we could leverage. Since information was one of the pillars of their work, it was essential to understand the information needs of physical therapists and adapt them to their workstation structure. To comprehend this, they designed a workshop activity with several professional therapists. At the end of some exercises, having discussed multiple metrics, adding some and discarding others, they reached a list of metrics, ordered by the importance given by experienced clinicians, from which they based their visual development. They considered the list, represented in the following table, to be *an optimal baseline for someone trying to develop a tool that can assess the performance of an individual while doing upper-body exercises*, which is exactly what we intend to use it for.

Importance Level					
1	2	3	4	5	6
• Movement quality • Muscular tonus • Motor objective and efficiency of the gesture • Movement trajectory • Compensatory movements • Head and torso movement in relation to the superior limb • Multigesture and head synchronization / Movement coordination • Scapular movement relation with the shoulder	• Functional movements	• Exercise velocity • Angular amplitudes and translation for the articulations • High speed movements	• Cerebral function • Rotation movements • Muscular activation	• Physiotherapist's hand pressure	• Number of performed sessions • Weight / Load • Complete repetitions • Number of repetitions inside the path • Structure resistance during the movement • Session time • Pain during the movement

Table 1: List of optimal metrics for upper-body exercise performance assessment, in order from most important (1) to least important (6)

3.2. Design Guidelines

By studying the state of the art, it was abundantly apparent that physical therapists have routines in current physical therapy that translate into specific needs that software that they would need to interact with on a daily basis would have to meet.

Therefore, it was evident that the development of our system should be accompanied by experienced professionals in order to design features that are actually useful and usable by the intended end users, who's work has a very technical foundation and, therefore, very technical requirements. This process also ensures no time is wasted on unwanted features we might not, at a first glance, predict.

With this in mind, and with the orientation and experience in our team, we formulated a set of guidelines from which we based the first iteration of a prototype of our application: (1) Design a system that could handle different patients and therapists; (2) Design a system that understands the needs of professional clinicians; (3) Design a system that allows enough exercise personalization to let patients practice any upper-body exercise they need; (4) Design a system that allows enough set-up personalization so that therapists can track any compensatory movement made and control those compensations limitations; (5) Design an easy to use interface with easy to set up equipment; (6) Design a system that allows for a patient, while assisted, to record any exercise needed in order to repeat it and receive appropriate feedback; (7) Design a system that lets therapists define which compensatory movements to focus and set physical limits for each compensation, depending on what their movement restriction preferences; (8) Design a technical but easy to understand visualization for setting compensatory movement thresholds; (9) Design a biofeedback visualization to help patients when preforming rehabilitation exercises; (10) Design a exercise review visualization to facilitate therapist and patient exercise reflection and analysis; (11) Design a system that could promote better efficacy, quality and efficiency in stroke victims' rehabilitation.

3.3. First Prototype: Low-Functionality Prototype

In order to make sure we developed a system that met the guidelines previously established and did not spend time and resources aimlessly developing an application and features from scratch, we decided to make a low-functionality prototype, representing our vision to embody the design concept. This first prototype iteration aimed to present this vision to professional physical therapists and get feedback and direction to better plan each feature devised. The interface we intended to develop followed the following user flow:

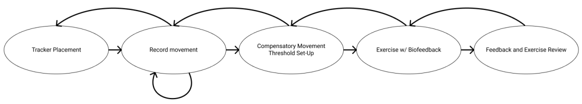


Figure 1: User Flow of our system

The interfaces illustrated in the flow are: (1) a tracker position selection, so the system could know where trackers were placed, (2) an interface allowing for a patient to record a chosen movement, followed by (3) an exercise review interface, (4) an interface allowing the therapist to set the ideal compensatory movement thresholds for said movement, (5) an interface where the user could practice the chosen movement, while receiving dynamic feedback and (6) a final interface where the users can review that practice, having access to information like performance and error metrics.

In the spirit of providing a more complete picture of how this system would fit in a standard physical therapy appointment, we designed a storyboard representing the flow of a therapy session and how our system would insert itself into it.

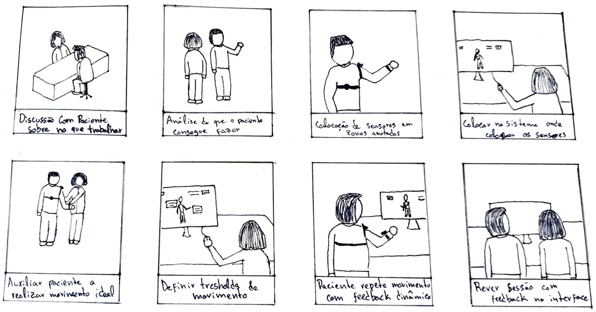


Figure 2: Therapy Session Flow Storyboard

3.4. Feedback Sessions

On separate occasions, we conducted sessions with professional physical therapists to receive feedback on our concept, and to define what designed features would be kept, removed, or altered.

To maximize our time with the therapists, we decided on the following structure: A brief introduction where we establish our proposition, the motivation behind it and how we want to resolve it. Following that, we presented the **the Storyboard** where we demonstrated how the system would fit in a standard physical therapy recovery. Lastly, we exhibited the **Low-Functionality Prototype**, representing our main ideas and features.

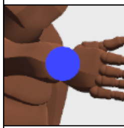
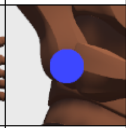
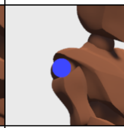
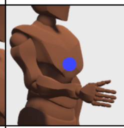
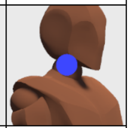
WRIST	ELBOW	SHOULDER	CHEST	NECK
				
. Flexion/Extension . Radial Deviation/ Ulnar Deviation . Supination/Pronation	. Flexion/Extension	. Flexion/Extension . Abduction/Adduction . Lateral Rotation/Medial Rotation . Horizontal Flexion/ Horizontal Extension . Circumduction	. Flexion/Extension . Lateral Flexion (Left)/ Lateral Flexion(Right) . Rotation (Left)/Rotation (Right)	. Flexion/Extension . Lateral Flexion (Left)/ Lateral Flexion(Right) . Rotation (Left)/Rotation (Right)

Table 2: List of Proposed Compensatory Movements

3.5. Discussion

With the feedback given in these sessions, we were able to validate our concept design, and its potential, gaining insight into the factors to consider when developing the final prototype.

Utilizing a personalizable tool allows patients to record any movement and review their exercise practice on it, permitting them to understand better their movement and errors associated with it and, possibly, accelerate its correction and enable faster rehabilitation progress.

The personalization of compensatory movement restrictions was also well-received in our study. Learning how important the ability of a program to adapt to different methodologies of intervention can be corroborated by the significance of this component.

Besides verifying these aspects of our approach, in the first phase of the feedback sessions, we also identified a key obstacle for interactive rehabilitation systems. This factor was the frequent unwillingness of people from older age groups to work with modern and technology-based rehabilitation systems, being regularly overwhelmed either by the interface or by the equipment used to run it. Considering most strokes occur in older people, being age one of the most prominently associated factors with stroke incidence [26], we needed to dedicate development time to ensure we achieve a simple and perceptive interface with easy-to-use equipment.

Compensatory movement restriction should be associated with a specific list of compensatory movements. The proposed compensatory movement list we managed to verify in these sessions was the following:

These sessions also brought a new concept of dynamic feedback, where the user was presented with a guide, where the patient would have an indication of where to move its arm next to achieve ideal movement.

The last contribution from these sessions was the suggestion of including the compensatory movements associated with an error in the error description in the final exercise review visualization.

4. System Overview

The chosen development environment for the development of our software was Unity3D as it is a heavily supported development environment, and it was the environment used in the development of ARCADE [11], and its predecessor application.

The HTC Vive system, using the Vive trackers, was the motion tracking technology chosen, as it is an optimal solution since it allows for position and rotation tracking and is available at an affordable price when considering clinic adoption viability.

4.1. System Architecture Vive Trackers Integration

After gaining some understanding of how the HTC Vive communication functions, we concluded that the fact that HTC Vive is a system built for Virtual Reality (VR) interactive applications makes it so that tracked devices connected to the system have to transmit their position information to the Head Mounted Display (HMD), so it can display in real-time, a manifestation of those devices. All information is then transmitted from the HMD to the connected computer.

After some experimentation, we discovered that there is a dependency of the HTC Vive system on running information through the HMD. In order to make the Vive Trackers work without having to use an HMD, and after experimenting with several setups, we arrived at a functional architecture:

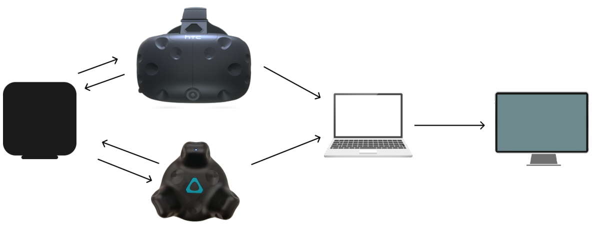


Figure 3: Ideal System Architecture

In this architecture, we set up our system in a way that is connected to the HMD, just like it would if we were planning on using it for a VR application. To deceive the HMD into considering it is being used, we utilized rubber bands to put pressure on the pressure sensor at all times. Additionally, the Base Stations are connected just as they usually would, sending pulses of Infrared signals to be detected by sensors on tracked devices (in this case, the Trackers), and the trackers are then free to communicate and send their position directly to the system.

4.2. Body Movement Tracking

After choosing an appropriate avatar, to emulate the movements a user would perform while utilizing our program, we had to set up the Vive Tracker in a way we could represent movements in all body segments that could possibly intervene in a chosen movement.

To track the positions of so many segments, we needed to infer the positions of some of them using the tracked positions of other segments. For this to be possible and to avoid getting an overwhelming amount of trackers on a patient, we had to resort to Inverse Kinematics (IK).

For the system to make the transition from input position data to moving the avatar, according to that data, we implemented a 3-layer animation process, where the avatar visualized mesh segments would follow the IK calculations, which in turn would use its target object to follow an object updating with the tracked positions of the Vive Trackers.

We observed that the avatar would show irregular arm and shoulder positions when adding the representation for the shoulder tracking, along with the IK constraints it came with. We suspect this is because both IK scripts partially affect the same bones, having the shoulder tracker IK intercepting with both wrist and neck IK scripts.

As a result, we decided to remove the visualization of the shoulder tracking, achieving full one-arm upper-body movement representation, with the exception of some elbow and shoulder elevation motions. This imperfect visualization was a compromise to keep the program's functionality, as the shoulder tracker still gave the position data necessary to detect movement errors and general compensatory movements later on.

4.3. Movement Recording and Visualization

To make sure the avatar moves according to the position of the trackers attached to the patient's body, considering the possible differences in size and position, we developed a calibration algorithm that adjusts the size of the avatar according to the patient's height and its position in the applications X and Z axis, moving the interface's camera accordingly.

To record the movement made by the patient, we used a UnityEditor class called GameObjectRecorder, which usually works as an animation-creating tool in an application development environment. This tool populates an empty animation with an animation curve obtained by reconstructing the changes of all the elements of a GameObject, taking snapshots of these positions in every frame.

The User Interface (UI) for the recording visualization features a simple record button that allows the user to start and stop recording the chosen movement. After recording a movement, the user is greeted with an interface visualization scene, with a UI constituted by a fully functional media player we scripted, giving the users the freedom to visualize the recording in an intuitive way allowing the patient and therapist the option of reviewing the movement recorded, before advancing to the next visualization scene.

4.4. Compensatory Movement Configuration and Monitorization

The most significant factor that makes our system adaptable to different intervention methodologies is the configuration visualization scene, where therapists can set compensatory movement thresholds for the previously recorded movement.

The UI, the user, is greeted with is a selection interface with the five segment options of compensatory movement origin. These segments are the Wrist, the Elbow, the Shoulder, the Chest and the Neck. When selecting one of the segments, the visualization changes to a set of sliders associated with each of the possible movements for that particular segment2.

The threshold limit is represented by a transparent dummy body segment corresponding to the movement associated with each slider. To animate the thresholds, we associated a rotation axis from an avatar joint to each pair of *opposite movements*, where the rotation direction specifies the pair's movement.

4.5. Exercise Repetition and Biofeedback

Following the Compensatory Movement Configuration Interface, the system is ready for the patient to start exercising. This System has a similar UI to the Record Movement Interface, with a similar avatar calibration routine.

To verify any errors during the exercise, the system uses stored position lists created in the ideal movement recording as a resource to compare the saved positions to the newly tracked ones. Every time the tracked positions enter a pre-defined radius around one of the stored positions, the program checks if the tracker skipped any precedent positions in the exercise timeline. If there is a skip, the system creates an error data object, populating it with information about this occurrence.

Considering the fact we store a sequence of positions to be intercepted in a certain order, the implementation of Dynamic feedback in the form of a Guide, one of the concepts of biofeedback we had planned on implementing, was very straightforward, and thus, we created small sphere objects, where the positions to intercept were. These spheres change colour depending on the user's actions.

While the exercise is repeated, the program also checks for the existence of compensatory movements. To achieve this, every time there is an interception, the system compares the rotation values of the Trackers with the rotation values stored, going through the list of set compensation thresholds.

4.6. Feedback and Exercise Review

The last Interface in our program is an exercise review visualization, where the therapist and the patient can review the preciously practised exercise. This visualization scene is composed of a media player UI, similar to the Recorded Movement Review Interface, with the addition of error-related information display and a representation of metrics linked with exercise performance.

Figure 4: Final Exercise Review Configuration Interface

The errors are represented as markers in the player's progress bar. Upon clicking on these markers, a window containing the error description appears, with the information stored in the error object created while exercising.

The last feature introduced in this interface is a collapsible window, labelled *Performance Index*, where performance-related metrics are displayed. These metrics, conceived by the ARCADE project [11], are collected in the previous interface while the patient practices the exercise motion. In addition to metrics like session time, the number of repetitions and number of errors, we represented a *success* metric. This system metric was designed by Faria et al., describing the general quality of the movement repetitions.

$$\frac{correct\ repetitions}{total\ repetitions} * 100 = success\ percentage$$

Figure 5: Formula for the Success Percentage

5. User Study

To validate this capability we ran a user study, with professional therapists to assess the usability of our system and it's adaptability to both therapists and stroke victims.

5.0.1 Research Questions

With this study, we aim to corroborate the potential of our program. In order to reach the conclusions that would allow us to do that, with this activity, we wanted to answer the following questions: (1) Can the program give enough personalization to adapt to stroke's patients upper- body recover? (2) Is the compensatory movement threshold feature technically intuitive for professional use? (3) Does the program represent a way to improve therapists' daily work?

5.1. Procedure

For the activity structure, our intent was to, in a firs phase, briefly present the motivation and proposal behind our project. In a second phase, we planned on having therapists individually try interacting with our system. In a third and last phase, therapists were presented with a questionnaire, to try and collect feedback of a **quantitative** nature.

5.2. Participants

For our participants we went to the Health and Neurology clinic *Saúdis* a clinic that specializes in neurological physical therapy and neuropsychology services. Due to unpredictable situation by part of the clinic, the study was postponed to a date where only 2 participants could attend. These participants both had more than 20 years experience in the field of neurological physical therapy and both exercise functions of both therapist and physical therapy professors.

5.3. Apparatus

To be able to run our system in the clinic, we had to bring all the movement tracking equipment there. So, essentially, to conduct the study, we used the HTC Vive system, including the HMD and two Base Stations, three Vive Trackers and 3 straps to attach them with. In the second phase of the study, a monitor display provided by the clinic was also utilized.

5.4. Questionnaires

With the intent of getting a quantitative set of information, we designed user questionnaire, to present the user with, at the end of the individual system interaction. Having this in mind we separated the form in 5 parts. The 3 first parts addressed the characterization of the answering population. These included identity, physical therapy experience and former experience with interactive rehabilitation solutions. We then proceeded to make questions concerning their previously made interaction user testing. In this section, we ask standard and identical usability questions, concerning each interface they interacted with. In addition, in most interface's subsections, we added questions about features or visualization elements specific to those visualization scenes. Lastly we closed with a section that discusses general observations about the interactive tool and its viability, limitations and potential on a clinical level.

5.5. Results

To analyse the results of this user study, we separated the information obtained and revised into different thematic categories, seen in both therapists participation.

5.5.1 Movement

Considering that users start the interaction with our system utilizing the movement recording interface, there were immediate observations about the movement tracking system:

(1) Both therapists considered that plenty of postural compensations would arise on the opposite side of the affected limbs and that lower-body limbs, connected to upper-body limbs, frequently originated posture changes, (2) The imperfect representation of elbow and arm segments, due to the removal of the shoulder tracker IK calculations, can have consequences in exercise performance, as some patients could have difficulties in performing exercise motions correctly; (4) Both clinicians were very pleased on how smooth and satisfying the real-time representation of their movements was. This was due to the increased tracking precision of the Vive Trackers, comparing to other motion tracking technologies they both used in the past. (5) Most stroke rehabilitation interventions prioritize the individual necessities of the patient, focusing on functional exercises. This means regular arm movements are not common or even recommended as exercises usually revolve around task oriented motions.

5.5.2 Visualization

Regarding the multiple visualizations throughout the usability flow of our program, the therapists were in general very impressed: (1) The exercise review interface represented a very easy to use feature, something that interactive solutions generally lack. (2) The compensatory movement threshold configuration was very straight forward and complete. The proposed compensatory movements were all relevant and in general sufficient and the motion limit visualization was easy to interpret and visualize. (3) The dynamic feedback approach composed by the visualization of guide targets let's the patient plan out his motions, helping towards earlier exercise success. The sphere solution was perceived as a helpful tool but cannot always represent the motion to be achieved by the patient. (4) The final exercise review visualization are really helpful to support exercise analysis.

5.5.3 Adaptability

Both professionals commented that the adaptability of the system was twofold: It allows for exercise personalization, something essential in most neurological rehabilitation practices, and it allowed for a lot of adaptability tint the therapist's choice of chosen intervention methodologies, considering the customization present in the monitorization of compensatory movements.

Moreover, both therapists reported they had never seen a interactive rehabilitation tool that approached motor rehabilitation while segmenting the characteristics of a movement in such detail. They also recognized the potential of this system being versatile enough to warrant the consideration of it being used in other types of physical rehabilitation.

5.5.4 Questionnaire Review

The number of participants did not allow for any statistical analysis of the quantitative data provided by the questionnaire. Even so, it is worth noting that, for the most part, the professionals found the visualizations simple, intuitive and useful. Furthermore, they both recognized potential in the way this system could improve movement analysis, provide enough personalization to adequately contribute to stoke rehabilitation.

5.6. Discussion

Our user study needed a significant number of participants to warrant sizable importance in its quantitative part. However, due to the qualifications of both participants and the insight that came with it, its qualitative phase was still of importance.

Patients utilizing motion-tracking technology need an accurate representation of their movements. Our approach of prioritizing functionality over visualization regarding the avatar animation could be better in an actual physical therapy session environment.

The precision of the motion tracking technology utilized, the Vive Tracker, was considered superior to other technologies participants used in the past. Despite these advantages, an uncovered dependency of a Vive HMD to properly work still complicates the system's setup.

There is also the apparent reality that, in stroke victims, lower-body limbs can have a frequent and substantial effect on a patient's movements. Being this the case, not monitoring lower-body limbs can lead to deceiving results.

Task-oriented exercises are usually the norm in stroke rehabilitation. Even though our program allows for enough personalization to adapt some exercises to simulate regular tasks, task-oriented exercise support, such as in application interactable objects to simulate pick-up and hand fingers motion tracking, would make for valid tools to help with patient intervention reception and motivation.

Visualization in this program was, in general, well received. It was apparent that some essential UI elements needed to be included or optimized. These optimizations could include implementing a notification where the user has started recording or exercising, loaders during avatar calibration and updating the dynamic feedback to have the targets be dummy transparent body segments instead of spheres.

By observing the professionals interact with our system, even if they overlooked it, we were capable of identifying two main problems with error checking: the routine was not correctly verifying rotation-only motions and movements that share the same spacial positions due to the storage of the unique positions.

Nevertheless, throughout the user study, the participants considered our project to be working in the correct direction to tackle the biggest obstacle impeding most interactive rehabilitation tools from being viable to utilize in neurological physical therapy, which is the lack of system adaptability to patient's particular needs (confirming the **first research question**).

Furthermore, the compensatory movement configuration interface was considered technically intuitive from a physical therapist's perspective, allowing the therapist to adapt their intervention methodologies (confirming the **second research question**).

This project was also perceived as the basis of what had the potential to be an extremely useful rehabilitation tool that was adaptable enough to be potentially used for other types of physical therapy, such as musculoskeletal physical therapy (confirming the **third research question**).

6. Conclusions

In this project, we propose and develop an intuitive interactable program with the ability to record and review any movement desired by a patient, the capability for a therapist to set the compensatory movement thresholds he deduces are ideal for any actuating body segment, the practice of the recorded movement, the means for the patient to practice said movement, with the help of dynamic feedback in the form of a motion guide, and review it alongside the clinician, with access to data metrics captured during motion execution. Our findings suggest that the adaptability of both patients, through their need for exercise personalization, and therapists, through the importance of the possibility of using different intervention methodologies, considering the variety in patient characteristics and limitations, is imperative for an interactive system's viability in neurological therapy. Furthermore, rehabilitation solutions, due to the age group most stroke victims are included in, there is a need for simple and intuitive interfaces, which is a challenge due to the complexity of the previously established requirements for a stroke rehabilitation tool. If these conditions are met, the already overly consensual contribution, of motion-tracking technology-based solutions, in physical therapy, the automated data collection, analysis and visualization, can be attained and utilized to improve clinical examination and improve motor recovery. Last but not least, the motion capture utilized in this system, the Vive Trackers, proved to be a cost-effective solution for precise and reliable body tracking.

Future work involves improving the dynamic feedback feature, correcting the avatar representation, and the error verification. Moreover, this project could be seen as a modular basis for a more complex solution, including full upper-body or even full-body tracking, as it seems to be an essential step, specifically for stroke patient rehabilitation. A more complete set of user studies, including more participants and clinical trials involving stroke victim patients, would also be crucial for this program's better usability validation. Finally, this solution should be viable to use in other physical therapy areas that could benefit from its exercise personalization features, even if this personalization is less crucial in those areas.

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