Fully portable low-cost motion capture system with real-time feedback for rehabilitation treatment

Jacob Kritikos  
Biomedical Engineering  
Laboratory of Electrical and Computer Engineering dept.  
National Technical University of Athens, Greece  
jkritikos@biomed.ntua.gr

Anxhelino Mehmeti  
Informatics and Telecommunications dept.  
National Kapodistrian University of Athens, Greece  
jinomehmeti@gmail.com

George Nikolaou  
Informatics and Telecommunications dept.  
National Kapodistrian University of Athens, Greece  
gs.nikolaoy@gmail.com

Prof. Dimitris Koutsouris  
Biomedical Engineering  
Laboratory of Electrical and Computer Engineering dept.  
National Technical University of Athens, Greece  
dkoutsou@biomed.ntua.gr

Abstract—To date, technologically-based rehabilitation methods have been widely used for treating disabilities. The evolution of new technologies utilizing motion capture systems or wearable tracking sensors have further enhanced the standalone self-treatments which benefit both the patients and the physicians. However, current systems have not yet proved to be truly mobile or low-cost, since they do not only need significant processing power to operate or tech-savvy operators, but they also have patients visiting the clinic regularly, more often than expected for a home-based system, in order to receive feedback on their performance. This study presents and proposes a fully portable, low-cost motion capture system that supervises the progress of patients whilst each exercise is being executed; thereby, it provides physicians a more mathematically precise way of evaluating patients’ performance and progress through reports generated by the mobile application. For the purposes of this study, we conducted two separate experiments: one regarding accuracy and another regarding the efficacy of the system.

Keywords—Rehabilitation Treatment, Mobile System, Physiology, Disabilities, Motion Capture Camera, Low Cost, Real Time Supervision.

I. INTRODUCTION

Physical Medicine and Rehabilitation is a branch of ability and medicine that aims to enhance and restore function and improve the quality of life of those suffering from physical or disabilities caused by various conditions, such as injury, amputation, spinal cord injury, stroke, traumatic brain injuries, pain syndromes, to the extent of invasive procedures or aging [1]. According to the World Health Organization (WHO) [2], approximately 15% of the world’s population (which billion people) lives with some form of disability, 2-4% (between 110 and 190 million people) experience process significant difficulties in functioning. The treatment can occur either in a clinic or in an outpatient setting, and does not only involve an interdisciplinary team of physical, occupational, recreational, and speech therapists as well as nurses, psychologists, and social workers [3], [4].

For patients with reversible conditions, physical medicine and rehabilitation can be significantly beneficial during and after hospitalization, since it helps avoid muscle atrophy and could lead to maximized functional outcomes [5]–[7].

For those not able to fully restore working function, such as in cases of disabling impairments or diseases for which there is currently no known cure, the major concern physical medicine and rehabilitation address is the ability of a person to function optimally within the limitations placed upon them by their condition so as to maintain maximal quality of life [8], [9].

In both cases, complimentary rehabilitation exercises after hospitalization may be required for a short period of time for further improvement; in more severe cases, assignment of post-hospital discharge therapies can last throughout the course of the patient’s condition for months or even years on end [10]–[13]. However, most formal rehabilitation facilities are located in hospitals or care centers, which may not always be conveniently accessible for patients, especially those in geographically isolated areas [14]. Even in cases where distance is not an issue, patients may still not have the required time to repeatedly visit the facility, may lack transportation, or may not be able to afford frequent appointments with the clinic. This is merely a short list of evidenced reasons why a large number of patients drop out of their treatments [15], [16].

Figure 1: System flow of the proposed mobile rehabilitation system.
The aforementioned issues necessitate the development of a more economically-viable, home-based treatment program without the presence of a healthcare practitioner, which would potentially offer greater accessibility, and thus increase consistency in adherence to the regimen on the patient’s end while maintaining the level of efficacy [17]–[19]. Consequently, technologically-assisted rehabilitation through video capture of the patient's movements has emerged as one of the most useful tools in improving adherence to an exercise regimen from an outpatient setting [20], [21]. According to the Rehabilitation Devices Equipment Market Analysis By Product Type [15], “the global rehabilitation equipment and devices market size was valued at USD 10.53 billion in 2016 and is expected to grow at a CAGR of 6.0% during the forecast period”, implying that a variety of additional low-cost and accessible tools will come out.

The most widely used technology for video and motion capture in this field is the Kinect device, which up to now has been considered the most portable and easy-to-use solution for home-based rehabilitation [22]–[28]. However, even with the use of this technology in a home setting, there are still a lot of limitations. The primary limitation concerns equipment. Specifically, current motion capture systems and applications like Kinect require processing power to operate signifying the need to be connected to a computer with certain specifications regarding its processor, RAM and GPU [29]. Consequently, it cannot be considered an entirely portable device or a low-cost system. Additionally, it requires one to be familiar with technology in order to set it up making its use too complicated for the average user, especially in cases of rehabilitation in geriatrics [3]. The second main limitation concerns the treatment procedure. Up until now, current systems primarily focus on the patient’s engagement in the treatment rather than their performance throughout it. In particular, current motion capture systems provide a gamified experience by creating assorted virtual environments during the session, in order to show patients the completed movements via monitors or virtual reality tools [30]–[32]. However, commonly patients do not receive information about their mistakes until the end of their treatment, or after a big part of their rehabilitation has already been completed [22], [33].

So, in the present study, we aim to emphasize the importance of real-time feedback during the session, instead of feedback provided at the end of the session or the whole program, while also propose an easy-to-use, low-cost set-up equipment to affect real-time monitoring feedback. For this purpose, we created a fully mobile motion-capture system for home-based rehabilitation. The system uses a Motion Recognition Camera (MRC) which does not require a computer or a monitor to operate; since it has an embedded processor, it does not require an additional processing unit such as a computer to process the users’ data, meaning it is completely portable, thus the total cost of the system is just about $250. Also, the proposed system provides constant supervision and patients receive real-time feedback through their smartphone, which operates as the interface between the patient and the motion-capture system. The feedback received concerns the exact mistake they have made while performing the exercises, so they can correct their posture or exercise performance during their practice sessions.

Consequently, based on this proposed system, we aim to validate two hypotheses: [a] to determine the performance of our system by comparing its results to the ones of a professional physician, and [b] to show that home-based real-time supervision treatment and the synchronous feedback the proposed system offers are more beneficial to the patient’s progress in the long run than home-based treatment with asynchronous feedback usually provided by professional physicians through telemonitoring.

II. SYSTEM DESCRIPTION

A. System setup

In the current study, the system flow (according to Figure 1) is as follows: The patient selects the rehabilitation exercise they want to execute from the mobile application. Then, the patient reads the exercise instructions displayed on their screen and stands in front of the MRC in order to start the exercise. The MRC tracks the patient’s movements, dispatches the data to the mobile phone, and then informs the patient whether the exercise was executed appropriately. In case the performed exercise is assessed by the system as incorrect, the application informs the patient by displaying the mistake in the screen. At the same time, every piece of data from the patient’s practice is saved, dispatched, and stored on a cloud server. Thereby, doctors can access their patients’ data derived from their home-based practice sessions through their computer, and keep up with their patients’ progress. The system report for each patient does not consist of footage generated whilst the exercise is performed, as it is in current systems, since that would take a considerable amount of time for the clinician to assess. Instead, once the system has completed evaluating the patient’s performance, the physician receives a report about every attempt each patient made during each session, and is able to view the specific mistakes they have made. Therefore, the clinician can inform the patient of their overall progress more precisely and direct their attention to correcting their mistakes individually by changing the system factors or informing the patient on exercise modifications. Additionally, they can change how strict system
variables are for each patient; i.e., if a patient is unable to raise their arm so that it is completely horizontal to their body, the physician can alter the uppermost position the patient’s arm should reach, in order for the exercise to be assessed as correct by the system.

B. Hardware

The proposed system consists of the following hardware: [a] an Orbbec Persee MRC with an embedded processor; the system does not require an external processing unit to operate. The motion tracking accuracy has an error range of ±1-3mm from a 1m distance, whereas at a 3m distance it is estimated at approximately ±12.7mm. The maximum recognition range is about 6m (Figure 2). The Persee model consists of two cameras, a Depth Camera and an RGB Camera, which offer a 60° hort. x 49.5° vert. field of view; [b] a Galaxy S7 Samsung smartphone.

C. Software

The Software tools used are: [a] a Linux Operating System with specific drivers installed, in order for the ARM processor to recognize the Motion Recognition Camera; [b] a C++ compiler, so the tracking program can properly operate and dispatch the data of each user; [c] a Bluetooth database to transfer data from the MRC to the mobile.

D. Body Recognition

The Orbbec Persee MRC can recognize 19 joints of the human body. Each joint is essentially a point in 3D space represented by 3 coordinates: x, y and z, where the y-axis is the height axis and the x-z plain is the floor on which the user moves. This topology can be seen in Figure 3. The MRC is placed across the user on the -z axis. Therefore, the user can walk on the x-z plain, constantly remaining within the tracking field of the MRC while still facing it.

E. Data Dispatch

The Body MRC establishes a connection with the mobile device via Bluetooth Low Energy (BLE). As far as the mobile is concerned, we have created an android application which receives the patient’s position and processes those data. In particular, the MRC recognizes the coordinates of each joint every 7.4 ms; after gathering the coordinates of all eight of them, it transmits them to the Java application approximately every 60ms. Thereby, the mobile device receives input about the location of each joint approximately 17 times per second.

F. Exercise Evaluation

For the purposes of this study, we conducted our experiment focusing on an upper limb exercise and, in particular, the right hand-side ‘Lateral Raise’ (Raise your arm 90° out to the side until your upper arm is parallel to the floor). The joints used to track the ‘Lateral Raise’ are: the collar (C), the shoulder (S), the elbow (E) and the wrist (W), where every joint encompasses the (x,y,z) coordinates (Figure 4). In order to identify whether the exercise is executed correctly or not, we set the following parameters:
• Depth: \( \{C_x \approx S_x \approx E_x \approx W_x\} \) The \( \{z\} \) coordination concerns the anterior or posterior movement; consequently, with this condition we oblige the user to stay straight in front of the camera and move their arm only upwards or downwards (Figure 5). This condition is implemented throughout the entire duration of the exercise; if, at any given moment, this condition is false, then the system informs the user that the exercise is incorrect and encourages them to stay straight and not rotate.

• Loose-Arm: \( |SE| + |EW| \approx |SW| \) With this condition, we obligate the arm to a straight position and not bent on the elbow (Figure 6). This condition is implemented throughout the entire duration of the exercise; if, at any given moment, this condition is false, then the system informs the user that the exercise is incorrect and encourages them not to bend their arm.

• Position: In order to establish the initial conditions and check whether the whole exercise is executed properly, we used two equations. The \( S_x \approx W_x \) through which we examine whether the user has their arm parallel to their body or not. Additionally, the \( S_y \approx W_y \) enables us to check whether the user keeps their arm at a 90° angle out to the sides or not. To identify an exercise as correct, these two equations must be sequentially true (Figure 7 – a). If, at any point during the process, we attain the \( S_x \approx W_x \) equation sequentially twice without the \( S_y \approx W_y \) equation to be true between them, then the arm does not reach 90° out to the sides (Figure 7 – b); likewise, if at any point during the process, we get the \( S_y \approx W_y \) equation sequentially twice without the \( S_x \approx W_x \) equation to be true between them, then the arm is not parallel to the body.

• Velocity: \( \alpha \approx \omega_R = \frac{l}{|SW|} \leq \beta \) The velocity of the arm \( (\omega_R) \) must not exceed the \( [\alpha, \beta] \) range; if, at any given moment this condition is false, then the system informs the user that the exercise is incorrect and has to move their arm at a slower or quicker pace respectively. This calculation was measured by two successive frames of the joints: the \( W = (x, y) \) and the \( W' = (x + dx, y + dy) \). Then, we define the \( I \) vector as \( I = W' - W \) and subsequently \( |I| = \sqrt{dx^2 + dy^2} \). Since the \( SW \) vector (the shoulder wrist vector) performs a circular to center movement, the \( S \) remains stable throughout the whole movement. Therefore, the radius of the movement \( R \) is \( |SW| \), and consequently we conclude that \( \omega_R = \frac{l}{|SW|} \).

As far as those parameters are concerned, we have to take into consideration some assumptions: a) how to measure the asymptotically equal factor \([\approx]\), and b) which parameters we ought to set for \([\alpha, \beta] \). So, from experimental data we defined \([\alpha, \beta] \) as \([\alpha = 10, \beta = 30] \) and the asymptotically equal factor \([\approx] \) as the variable \( k \), which tends to small numbers, so the values are not far from \( k \). In this study, specifically during the ‘Lateral Raise’, the \( k \) is at approximately \([0,5] \). However, the variable \( k \) as well as the \([\alpha, \beta] \) depend on the desired system accuracy.

Figure 7: smartphone screenshots (a): left - correct exercise (b): right – “you did not reach 90°” notification.

A video concerning the exercise evaluations is available here: https://www.youtube.com/watch?v=GjP_SHF2QIM

III. METHOD

Currently used techniques involve telemonitoring guidance systems [20], [21], which record the patient’s sessions and provide either videos or reports of their performance to the supervising physician. The physician, upon assessing the patient’s performance during their sessions, communicates with the patient in whichever form, and provides feedback every few sessions, i.e. on a weekly or bi-weekly basis. Systems like these offer asynchronous supervision and feedback. In this study, we aim to suggest ways of improving this stand-alone, home-based rehabilitation via our system by conducting two successive experiments.

In the first experiment, we investigated the differences between the results of the proposed system and the results of a professional physician regarding the performance of the aforementioned exercise and how much the doctor's opinion is in alignment with the system. Seven people (3 men and 4 women) participated as system users. Each one of them participated in 9 sessions, during a period of 3 weeks. Each session lasted approximately 2 minutes. During each session, participants had to perform the aforementioned ‘Lateral Raise’ exercise with one hand and hold the smartphone on their other hand. While performing the exercise, the system supervised their performance and provided real-time feedback to the user through the user interface of the smartphone. For each correct attempt, a high-pitched sound was transmitted from the smartphone. For each incorrect attempt, the system produced no sound, and a message was displayed on the screen of the smartphone informing the user of what they are doing wrong in relation to the following parameters: Speed (Too Fast, Too Slow), Depth (Too Forward, Too Backward), Position (Did not reach 90°, Did not reach 0°) or Loose Arm. The session was
simply executed the same ‘Lateral Raise’ exercise alone as they, nothing else as concerns their mistakes. So, participants stay straight in front of the camera, so the camera can monitor feedback through the smartphone except to inform the patient to was that, in this group, the proposed system was not providing experiment above. However, the only difference between them do this, we formed a new group of 7 participants (4 men and 3 women) who executed the same procedure as in the first experiment. From sessions 1-5, the participants received no feedback about their performance. In Session 5, a clinician was physically present, in order to assist the participants; at the end of the session, each participant received feedback from the professional so as to correct their mistakes. From Session 6, and up until the end of all sessions (9th session), no feedback was offered.

It should be noted that before the first session, all participants from both groups were informed about the study’s purpose. Participants were also informed about how to perform the exercise properly and were given a description about when an exercise is considered incorrect.

All participants were recruited through an advertisement in the campus of the National Technical University of Athens. All the aforementioned sessions took place on the premises of the Biomedical Engineering Laboratory of the National Technical University of Athens on Mondays, Wednesdays and Fridays. These trials were approved by the Ethics Committee of the National Technical University with protocol number #7239.

### IV. RESULTS

#### A. Experiment 1 - System performance

As mentioned above, a physician graded users using the same criteria as the proposed system, i.e. Speed, Depth, Position and possible Loose-Arm. After both, the system and the physician, witnessed 1522 repetitions in total (7 participants, in 9 sessions, over the course of 3 weeks), we concluded that the physician and the system agreed on the accuracy of the exercise by 75.2% with the system assessing more repetitions as incorrect (Figure 8). Out of the 1522 exercise repetitions, the physician marked a total of 276 as incorrect, while the system detected 367 repetitions as incorrect. From the total of the repetitions (as Figure 9 shows), incorrect repetitions relating to parameters “Too Fast” (Physician:18, System: 19, Similarity in opinion: 94.73%), “Too Slow” (Physician:7, System: 8, Similarity in opinion: 87.5%) and “Loose Arm” (Physician:14, System: 15, Similarity in opinion: 93.3%) were detected almost equally by the physician and the system. Additionally, the parameter concerning the angle of the arm “Did not reach 0o” (Physician: 111, System: 118, Similarity in opinion: 94.06%) and “Did not reach 90o” (Physician: 96, System: 101, Similarity in opinion: 95.04%) were detected almost equally, as well. However, those were the most common mistakes participants made. The only parameters for which we observed a significant difference in the incorrect repetitions detected by the system compared to those of the physician were: Depth parameter “Too Forward” (Physician: 21, System: 59, Similarity in opinion: 35.5%) or “Too Backward” (Physician: 9, System: 47, Similarity in opinion: 19.1%). This can be justified by the fact that the MRC has a depth laser sensor which can identify the position of the arm in relation to the body. Therefore, the MRC detected even the smallest of differences in depth, undetectable by the physician who was observing the participants from the front angle only.
B. Experiment 2 - System effectiveness

In this experiment, we assembled two groups; Group A consists of all the system’s measured data from the participants of the first experiment who completed their sessions using the proposed system that provides real-time supervision and feedback; Group B consists of all of the system’s measured data from the second, new group of participants, who completed their sessions receiving asynchronous supervision and feedback only after Session 5. As can be seen in Figure 10, the amount of incorrect repetitions in Group B were higher than those in Group A in all of the sessions, even after the physician’s feedback (Session 5). In Session 1, which was right after the users received the initial instructions on the exercise, the incorrect repetitions percentage was almost identical in both groups.

During sessions 2-5, since users in Group B did not receive any feedback, we witnessed a gradual increase of incorrect repetitions resulting to 32.14% more incorrect repetitions, compared to the beginning of trial 1 where it was 26.42%. In Session 6, upon receiving feedback by the physician, we witnessed an immense drop in incorrect repetitions resulting to 22.14% from users in Group B (less incorrect repetitions than in the initial session); since the physician explained their mistakes, participants were more aware of their errors during Session 6 and focused much more on performing the exercise correctly. However, in Sessions 7-9, false attempts increased leading to the same percentage of incorrect repetitions, up to 25.71%. Overall, by the end of Session 9 and the completion of the trial, users in Group B showed a little less incorrect repetitions from 26.42% to 25.71%, which means they did not make any progress on how to perform the exercise correctly.

Contrary to that, we witnessed a decrease of incorrect repetitions in Group A during sessions 2-3 resulting to 19.81% incorrect repetitions by the end of the first week (Session 3). In Session 4, users seemed to have not improved at all since the beginning of the trial. Yet, by the end of the second week (Session 6), we witnessed a drop up to 14.35% of incorrect repetitions. The same pattern was followed in the third week by the end of Session 9 with 8.41% of incorrect repetitions. Overall, by the end of Session 9 and the completion of the trial, users in Group A showed a 90% or bigger (from 19.81% to 8.41% on average) improvement of their incorrect repetitions since the beginning of the trial, which leads us to the conclusion that the proposed system would respond to other rehabilitation exercises.

B. Participants Limitations

Another limitation to our study is that the sample of our participants consisted only of a young group of people (18-28 years old); this could have potentially affected the results since participants did not essentially have any physical disabilities that required rehabilitation and could, therefore, perform the exercises with ease. Had they suffered from a disability that hindered the execution of the exercise, they would have presumably presented more failed attempts. Moreover, participants were asked to perform only one, low-complexity exercise. In case of extended and more complex exercises with more repetitions, i.e. an entire routine of exercises, the number of incorrect repetitions could have altered due to confusion and fatigue that occur in long rehabilitation sessions.

C. Technological Limitations

The MRC used in this system can track 19 joints of the human body when the user stands in front of it. However, when the position of 2 different joints coincide on the x,z axis (e.g. arm located behind the user’s chest), the MRC will recognize only the anterior joint —which in this case happens to be the chest. This could pose an issue in exercises that require a joint movement behind the main body. The solution could be the addition of more MRCs that track users from assorted angles, which would however complicate the system’s setup. It is important to remember that this system is proposed for home-based rehabilitation meaning the system ought to be set up by the patient themselves. Another significant limitation is the parameter setting. It is of high importance that the clinician sets the parameters according to each patient’s limitations, otherwise the system will recognize a large number of their efforts as incorrect. For example, in cases where the arm must be extended 90° in relation to the body when standing up for the exercise to be executed correctly, patients with shoulder issues could fail; therefore, it is critical regarding their motivation and progress for the physician to configure the parameters appropriately.
VI. DISCUSSION

Our purpose in this study was to examine the efficacy of real-time feedback so as to enable patients to correct themselves during the rehabilitation session. We thus created a system which can monitor patients and provides information on how to successfully perform the task in hand through their smartphones (i.e., if their arm is bent on the elbow, or it did not reach a 90° angle). All 14 participants from both groups responded immediately to the task assigned, and the information gathered from their results confirms our hypothesis. The synchronous feedback that the 7 participants from Group A received during sessions assisted them in reducing the number of failed attempts throughout the trials and in improving their progress throughout the rehabilitation treatment; thus, it took participants less time to improve and observe tangible results from their sessions compared to the other 7 from Group B.

As indicated by the results of the first experiment, the physician’s opinions were in alignment with the system’s reports by 75.2%, with the physicians detecting less incorrect repetitions than the system. The fact that we observe a difference in conclusions between the physician and the system regarding the arm’s depth, which was not entirely visible to the clinician, led us to the conclusion that the MRC can offer additional advisory information to the physician, beyond what they can perceive. At the same time, through the proposed system, we provide an easier method to evaluate the patient’s progress; more specifically, the clinician is capable of reviewing anytime not only whether the patient is executing each exercise correctly, but also the exact mistake they have made.

In the second experiment, we observed and concluded that real-time feedback leads to a gradual decrease of incorrect attempts compared to asynchronous feedback; in particular, in Group A, incorrect attempts decreased three times more compared to Group B. So, we conclude that without real-time feedback the participants are more relaxed, they do not focus and consequently make more mistakes than if they had someone to observe them and correct them all the time. Therefore, it is crucial for patients to be informed on their mistakes regularly, so as to immediately correct them.

Another issue worth discussing is our choice to use the Motion Recognition Camera instead of Wearable Body Tracking Sensors like wristbands or suits with gyroscope trackers or accelerometer trackers. MRCs have certain disadvantages; their primary disadvantage is their inability to recognize patients’ movements when they accidentally ‘hide’ parts of their body (or their whole body) from the camera’s recognition range. Wearable Body Tracking Sensors do not pose such an issue, but they still present other disadvantages; mainly, they consist of wearable sensors that have to be placed in multiple parts of the body so as to recognize different joints and, consequently, form limbs. In contrast, MRCs only need a single camera tracker. Moreover, wearable sensors could cause patients to feel uncomfortable, and this might end up hindering their movements or reactions during rehabilitation. Hence, we preferred using a non-wearable Body Tracking Sensor like the Motion Recognition Camera, which achieves immersion without adding equipment to the user, and allows them to move comfortably and naturally, just like in real life.

VII. CONCLUSION

Many patients suffering from disabilities rely on home-based rehabilitation methods, in order to overcome their condition. These rehabilitation methods usually include sets of exercises that patients must execute in the space of their own home [34], [35]. Nonetheless, the absence of an actual expert when they perform the aforementioned exercises restrains them from comprehending the instructions given. Moreover, they often forget the specific instructions the physician has given them on how to execute the exercise properly and accurately. Consequently, the vast majority of patients end up performing the exercise incorrectly and are unaware they are doing so until their next scheduled physiotherapy appointment. Incorrect posture or speed of motion as well as poor movement quality can thus hinder the benefits of the rehabilitation process.

Due to all that, a large variety of interactive feedback technologies capable of supporting, monitoring and improving the quality of the rehabilitation have recently emerged [36]–[38] These new technologies could potentially improve rehabilitation techniques in the future by assisting patients in executing the exercises accurately, thus enhancing their performance. Nonetheless, despite the possible benefits mentioned above, they have generally not been practically implemented, and their usage remains within the confines of specialized rehabilitation clinics.

Since home-based rehabilitation methods are fundamental for many rehabilitation clinics, the necessity of developing groundbreaking, original techniques to instruct, monitor and encourage patients throughout the process of their rehabilitation is essential. This study outlines the suggested approach, as far as the design of an interactive system is concerned, which can provide patients with synchronous feedback so as to assist them in understanding and correcting their mistakes on the spot.

ACKNOWLEDGMENT

The 3D Models from Figures 3, 4, 5, 6, 7 are from Make-Human, an open source tool for making 3D characters. The doctor’s photo from the Figure 1 is a purchased photo from the StoryBlocks website. All the participants recordings were sent to the professional physician through USB and after the trials all those recordings and personal data were permanently deleted. Finally, we would like to thank our physiotherapist Michael Stavrianos from ΙΑΣΙΣ Physio who assisted us in this project.

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