applied sciences

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Prevention and Rehabilitation Gaming Support for Ankle Injuries Usable by Semi-Professional Athletes Using Commercial Off-the-Shelf Sensors

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Abstract: Ankle injuries are amongst the most common musculoskeletal injuries. The necessity of prevention measurements before or an early rehabilitation start after an injury, is essential for (semi-) professional sports like soccer to decrease healing duration. Sensor-supported serious games could complement a therapeutic program to support resilience and motivation during the prevention or rehabilitation process. Therefore, the aim of this study is to develop and evaluate a user-centered prototype of a serious game using a commercial Off-The-Shelf MetaMotion IMU sensor. A semi-structured interview with a soccer club therapist, followed by an online questionnaire containing 48 questions ($n = 91$), was performed to ensure a user-centered approach. Based on this, a prototype, including five identified functional requirements and seven exercises (comprising: horizontal/vertical in- and eversion, dorsi- and plantarflexion, knee bend and squat, and toe and heel rise), was developed in an iterative process and evaluated by two participants with an acute ankle injury. The questionnaire outcomes showed averages of 3.3 ankle injuries per participant and 40 absence days per incident. Additionally, 85% of the participants reported needing more prevention time for such injuries. The evaluation phase (total training duration: 2 h 52 min) consisted of playing two different game types (1 and 2 degrees of freedom) and three different levels, where an avatar needs to be controlled while running and avoiding obstacles or collecting trophies. Both range of motion (ROM) and scores, which are directly measured by the game, showed significant improvements (ROM: $t = 5.71$; $p < 0.01$; Score: $t = 3.98$; $p < 0.01$) between the first and last session in both participants (P1: ROM +3.56°; Score +7.00%, P2: ROM +6.59°; Score +9.53%), indicating high effectiveness, despite a short training period (1 and 2 weeks). ROM improvement results and athlete feedback coincide in that the sensor-assisted serious game might be beneficial for ankle prevention and rehabilitation. At the same time, the increased scores indicate substantial motivation over several training sessions.

Keywords: serious games; prevention; rehabilitation; soccer; ankle injury

Citation: Galli, J.; Baranyi, R.; Hoelbling, D.; Pinter, K.; Aigner, C.; Hörner, W.; Grechenig, T. Prevention and Rehabilitation Gaming Support for Ankle Injuries Usable by Semi-Professional Athletes Using Commercial Off-the-Shelf Sensors. *Appl. Sci.* **2023**, *13*, 9193. https://doi.org/10.3390/app13169193

Academic Editor: Alessandro Ruggiero

Received: 19 July 2023
Revised: 9 August 2023
Accepted: 11 August 2023
Published: 12 August 2023

1. Introduction

Ankle sprains are a prominent and common type of musculoskeletal injury that affect a wide range of individuals, from professional athletes to the general population. These injuries occur when one of the ligaments in the ankle is stretched beyond its limit, leading to tearing. Ligaments play a crucial role in connecting bones and providing support to the ankle [1]. The occurrence of ankle sprains has been the subject of numerous studies, which have explored their prevalence in various sports and among different groups of people.

1.1. Athletes/Sports

Globally, the incidence of ankle sprains is approximately one per 10,000 person-days, with an estimated two million acute ankle sprains occurring annually in the United States alone [2]. Ankle injuries can occur in everyday life, but they are particularly prevalent among athletes participating in various sports. Findings from a systematic review focusing on ankle injuries and ankle sprains in sports [3] reveal that the ankle is the most frequently injured area in 24 out of the 70 sports included in the study.

1.2. Awareness

Despite the high incidence of ankle sprains in both sports and everyday life, preventive measures and awareness remain lacking. In the context of soccer, ankle injuries comprise approximately 13–20% of all reported injuries, with ankle sprains accounting for a substantial portion, ranging from 51% to 81% of these injuries [4,5]. Another good way to prevent injuries is balance training, which reduces the risk of ankle injuries by 42% [6].

1.3. Related Work

As-needed rehabilitation exercises tend to be repetitive and resilience and motivation tend to decline over time. However, this issue can be addressed by incorporating serious games [7]. Rehabilitation focuses on mitigating the influence of a medical condition on an individual's daily existence, enhancing their capabilities, and minimizing the extent of their impairment [8]. In conventional terms, functional rehabilitation encompasses counselling for therapy, along with engagement in physical exercises and tasks, either with or without professional guidance [9]. Serious games refer to applications that not only provide entertainment factors but also utilize interactive mechanics commonly found in video games, offering additional benefits to the users [10]. Meijer et al. [11] examine the impact of serious games and wearable technology on the rehabilitation of patients with bone and soft tissue injuries. The authors examined 12 studies in this topic area. As a result, promising effects were found, among others, through adherence to therapy. The application range of serious games is wide and diverse, encompassing various fields such as training and simulation, education, human performance engineering, strategic communication, and healthcare [12]. It has been asserted and concluded within a meta-study in [13] that the utilization of serious games and virtual reality has demonstrated the ability to encourage patients to meet their therapeutic needs, enhance their physical fitness, and alleviate symptoms of diseases.

From the problems described above, it is clear that prevention and rehabilitation in the context of ankle injuries should be supported by the development of a new serious game using commercial off-the-shelf (COTS) sensor-tracking ankle exercises. State-of-the-art examples suggest that there are only a few serious games for ankle rehabilitation incorporating different movements, needing specific hardware, and complex setup, but none of them use the MetaMotion sensor within a customizable and easy setup. There are no solutions specifically designed also for preventional use. The possibility to play the games with different configurable movements is also lacking exploration in current research. Furthermore, the focus of other solutions is often not clearly stated and aims at rehabilitation after an injury, rather than preventing one.

Pino et al. [14] engage in the development of a visual and interactive user interface for the therapy of people with ankle dysfunctions using an exoskeleton capturing dorsi-plantarflexion movements to control an avatar within a jump-and-run serious game. The system has been well received in their evaluation of participating healthy subjects. Another study by Salazar et al. [15] presented a system based on three components. On the one hand, it is a robot, on the other hand, it is a serious game that supports rehabilitation. The third component is a facial expression recognition system to collect feedback from patients in order to adapt to the game's difficulty. The serious game contains mobility, force, and a combination of both as objectives. Testing their system with six healthy participants showed that the game entertains them while doing exercises.

Ibarra et al. [16] focuses on adaptive control strategies to increase patient participation and support during strength training using the Anklebot. Patient stiffness is used as a measure of patient participation. Two approaches are studied. The results show that both adaptive control strategies were able to improve patient participation and performance. Another study by Pasqual et al. [17] deals with the development of a serious game for ankle rehabilitation also using an already established hardware (Anklebot). They developed a serious game similar to pong. One additional publication relying on the Anklebot by Michmizos [18] describes the development of three serious games for motor therapy in children with cerebral palsy aged between 5 and 8 years. Motor impairments such as coordination problems, reduced speed or accuracy, as well as cognitive or perceptual impairments should be addressed and improved by the games. Gonçalves et al. [19] investigated serious games for the assessment and rehabilitation of patients after a stroke based on a platform to support ankle rehabilitation to support dorsiflexion movements and muscle strength. Within one of their games, moving food items need to be collected. The results showed that their proposed platform can be used for the rehabilitation of ankle movements. Within another research study by Pino et al. [20], a therapy strategy that uses a combination of mirror therapy and robot-assisted training with a serious game where a plane needs to be flown through rings in the air was shown. After six sessions with one healthy participant, the results of the method favored active ankle plantarflexion range of motion (ROM) and muscle activation, also increasing the ROM.

Garcia et al. [21] developed a mobile RehApp application that uses augmented reality (AR) to stimulate movement exercises and is intended to provide therapeutic support during ankle sprain rehabilitation. Its primary objective is to aid both physiotherapists and patients in their rehabilitation process. A custom-made AR marker is placed on the foot enabling the camera of a tablet to capture the movements.

Within another research study by de Oliveira Andrade et al. [22], serious games in robotic ankle rehabilitation were researched. To do so, an active ankle-foot orthosis was used, which can be configured to perform exercises to improve patient skeletal muscle strength regarding two ankle movements (dorsiflexion and plantarflexion); e.g., within one of their games, small creatures emerge on the screen and the user, controlling a foot, must eliminate them by meeting the specified strength requirements set for the patient. The outcomes indicate that the suggested games can be successfully employed in robotic rehabilitation. A similar target was researched by Ferreira et al. [23] in the field of clubfoot rehabilitation using a serious game (moving a car and avoiding obstacles). The game is controlled by a self-developed device to capture foot movement patterns for dorsiflexion and plantarflexion. The results showed good acceptance by the two involved children.

One approach for knee rehabilitation is the serious game called “Fun-Knee” [24], which was specifically designed to aid the rehabilitation of patients who have undergone knee prosthesis implantation. The game incorporates a fishing task, known as the heel slip exercise, to make the therapeutic exercise more enjoyable and engaging. This exercise is commonly prescribed during knee prosthesis rehabilitation to enhance knee joint flexion movements. To capture the required movements, the patients wear a knee sleeve equipped with various sensors. The captured data is then transmitted to a smartphone via Bluetooth, and the serious game is displayed on the smartphone screen for the patients to interact with. An exergame called “MoveYourFeet” [25], a mobile application specifically developed for performing ankle joint exercises that target dorsi-extension and plantar flexion, was researched. The system is composed of two wireless inertial measurement units and a mobile device. The game itself is designed as a side-scrolling game that responds to the user’s ankle joint movements, allowing them to control the game by stretching and bending both ankle joints. Duarte et al. used MetaMotion in a study to assess posture adjustment [26], showing that such a solution is comparable with a video-motion-capture system and can therefore be carried out in a more accessible, portable, and cost-effective way.

1.4. Proposed Solution

The solution presented here offers novel approaches to developing a serious game supporting ankle-injury prevention for (semi-professional) athletes in the example of soccer players. The here-proposed solution also focuses on prevention, which is a drawback among other solutions for this problem. Therefore, the aim of the study is to investigate the possibility of an easy-to-use serious game for the prevention and rehabilitation of ankle injuries, with potential increases in motivation and resilience in soccer players, which leads to the research question: Can the requirements defined by therapists and soccer players for a digital training module be met in the development of a serious game and also be incorporated with the usage of a COTS sensor?

2. Materials and Methods

The methodology contained different steps, including engineering requirements based on qualitative and quantitative aspects, an iterative prototyping process, and an additional evaluation phase—this was also part of an over graduate thesis [27], on which the presented data was based. For the overall process, participants from two different soccer clubs (first and second league) were included to support the different steps. These participants were gathered through peers knowing that people there currently suffer from ankle problems. The overall process was based on a user-centered design (UCD) approach (see [28] for a more detailed description), involving both visual review and hands-on gaming in later stages. New requirements were defined and implemented containing five iterations and additional field tests.

2.1. Requirements Identification

In the first step (Iteration 1), a semi-structured interview was conducted with the therapist to extract framework conditions for a serious game for successful ankle injury prevention and rehabilitation. To utilize this, an interview guide was developed beforehand. The interview guide contained questions about current rehabilitation interventions as well as status quo of ankle injuries in the context of soccer, as well as serious gaming in that context (e.g., "do you think that it would be possible to recreate conventional exercises within a Serious Game?"). Using qualitative content analysis [29,30], requirements were extracted, based on significant key-phrases and descriptions in the transcript. Afterward, a group brainstorming session with therapists and soccer players of one soccer club was conducted (Iteration 2) to strengthen the requirements and also refine gaming ideas, also showing the sensor and discussing ideas. In addition, a specific questionnaire was designed targeted at people partaking in a lot of sports (independent of the area) in a competitive field to find out additional aspects about ankle injuries, in general, to get to know the problem space and additional information for the serious game better (Iteration 3). This questionnaire was created with SurveyHero [31] and distributed among different peers (e.g., participating soccer players from one soccer club), selected therapists, and other sport-related people, also asking them to distribute it further. The questionnaire contained 48 questions grouped into three major sections (personal history with ankle injuries, rehabilitation process of ankle injuries, utilization of serious games) and had different types of questions and scales, e.g., "would a game increase the motivation to perform rehabilitation exercises?" with yes/no/do not know as the answer, or "how much time is spent during training specifically for exercises to prevent ankle injuries"? with a scale from 1 to 7 (from no time to much time).The results of the online questionnaire were analyzed in the context of descriptive statistics (e.g., mean practiced years), and a context analysis within the free text fields was also done.

2.2. Prototype Development

After the baseline was established, the implementation began (Iteration 4). Based on the requirements (gathered and refined in Iterations 1–3), technical feasability, and its easy integration possibility, the MetaMotion sensor [32] was identified as optimal data source for the game. It is a wearable device that offers real-time and continuous monitoring of motion and environmental sensor data containing a gyroscope, accelerometer, and magnetometer. The sensor data was integrated into a desktop application comprising the implemented serious game, which was developed with Unity [33]. Different game and level ideas were implemented and discussed internally and together with the therapist (Iteration 5). Ultimately, two different game types were selected to proceed and refine further. Based on the previous results, exercises could quickly be carried out with such a sensor and deliver the identification and measurement of the ROM paired with the most common exercises within this setup and setting. The data are transferred from the MetaMotion sensor to one laptop running Linux, which sends these data to another laptop running Windows with Unity and the game itself. This setup was necessary because support for the sensor using Windows and C# was no longer available, and it was decided to stick with the easiest solution to run the serious game. The MetaMotion Sensor is attached with a flexible band either on the feet or the lower leg, dependent on the exercise. See Figure 1 for an overview of the setup, architecture, and possible exercises.

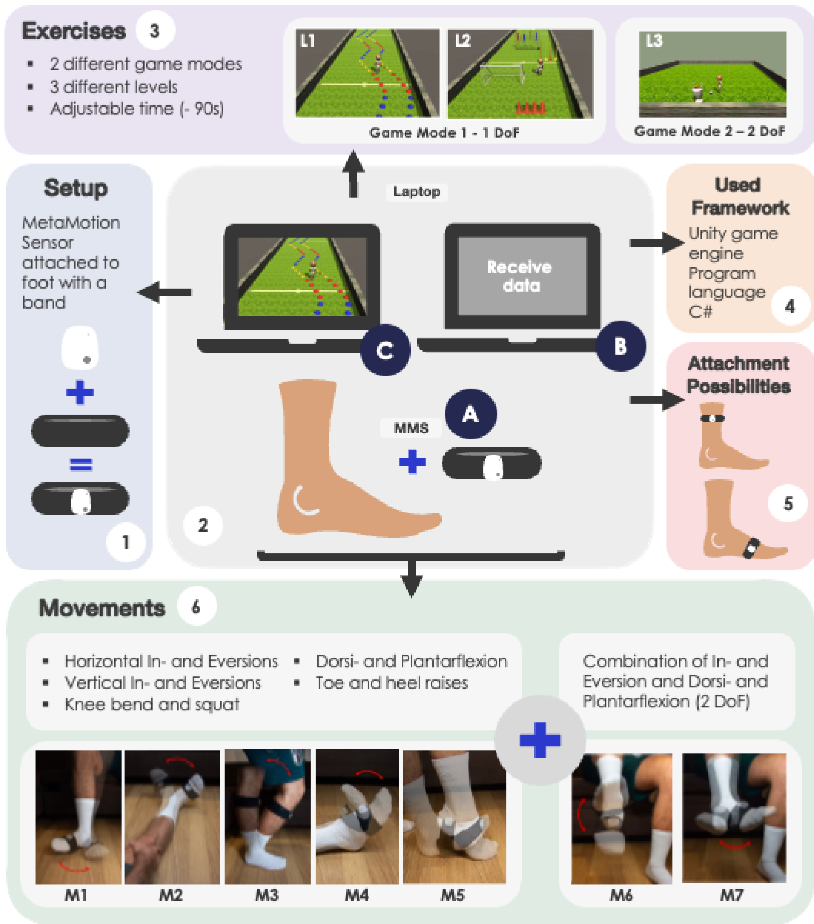

Figure 1. Overview of the setup, architecture, and possible exercises.

2.3. Field Test

Due to the iterative nature of prototype development, it was decided to conduct the field test in a case study format. Active healthy athletes (n = 2), despite a current ankle joint injury, from two participating soccer clubs, aged between 18 and 30 years, were included in this study. See Table 1 for a demographic overview. During the evaluation period (on-site experiments), the participants were individually monitored for durations of one week (P1) and two weeks (P2) to assess the system's usability and acceptance as well as preliminary indications for improvements (i.e., ROM). The evaluation process involved setting up the sensor (see if it is correctly attached and the signal is received on the PC), conducting the calibration and observing the athletes' exertion levels during exercises, collecting their feedback after each session and after the testing period, gathering insights and comments from the accompanying physiotherapist as well as analyzing the outcomes achieved through the serious game. Both participants played different selected game modes. To increase difficulty, participant 2 also used adapted exercises (using a rubber band for increased force), which was recommended by the therapist. Due to the small number of participants in the evaluation, only preliminary statistical analysis could be conducted. During each session of P1 and P2, a protocol was prepared beforehand and written containing all results as well as the date, start time, end time, conducted exercises, ROM (collected after calibration), and game results (displayed after a level is finished within the serious game); also total number of exercises as well as playing time were recorded individually and afterward combined within Figures A1 and A2.

Table 1. Evaluation participants.

ID	Age	Gender	Duration (Weeks)	Sessions	Repetitions/Exercise	Ex. Time/Session (min)	Total Time (min)
P01	23	M	1	3	3	20	60
P02	21	M	2	4	3	27	112

2.4. Statistical Analysis

The field experiment data were quantified directly in the system and exported into MS Excel 2021. Further descriptive statistics and inferential statistics were calculated using IBM SPSS 28 software. All variables were checked for normal distribution using a Shapiro–Wilk test. Variables differing from normal distribution are shown as median and interquartile range, while all others are displayed as mean and standard deviation. To analyse differences in ROM (as a measure of physiological adaption) and game scores (as a measure of motivation), a dependent t-test between the first and last session was performed.

3. Results

The following sections contain the gathered results based on the previously explained methodology. Overall a serious game was developed, which is controlled based on selectable movements.

3.1. Online Questionnaire

Within the questionnaire, 48 questions in three different categories were covered (personal history regarding ankle injuries, rehabilitation process after ankle injuries, and the utilization of a serious game during rehabilitation). Overall, 91 people participated in the questionnaire with a completion rate of 71% (65 participants) (answering all questions and finalizing it) and an average completion time of around 15 min with an average age of 27.4 years, including 11 different sports and an average of 11.1 years of sports activity. On average, the participants stated 3.3 ankle injuries during their sports career and life, including severe ones. Asking how they judge the risk of suffering an ankle injury, they judged 5.1 on average (on a scale from 1—associated with no risk—to 7—associated with high risk). The median of absence days after an injury was 40 days per injury and 90 days in total. The majority (85% of 77 participants) of participants think more time should be spent during training for specific exercises to prevent ankle injuries. In addition, 57% (52) think that serious games would be possible to increase this time. See Table 2 for an overview of the participants, where the respective data were entered. These results indicate a lack of prevention and a big problem associated with ankle injuries that seem to be tolerated, and there is indeed the need for a supporting serious game.

Table 2. Online questionnaire participants.

Sport	Sum	Male	Female	Practised Years (Mean)	Age (Mean)
American Football	2	2	0	11.0	27.0
Basketball	8	7	1	10.0	27.5
Soccer	18	18	0	13.2	28.3
Crossfit	5	3	2	4.7	28.6
Judo	1	1	0	10.0	18.0
Volleyball	6	1	5	7.1	23.1
Rugby	45	45	0	11.8	27.7
Swimming	1	1	0	N/A	30.0
Horseback Riding	1	0	1	8.0	24.0
Mountainbike	1	1	0	N/A	37.0
Nordic-Ski	1	0	1	10.0	26.0

3.2. Requirements

Throughout the different phases of the research, different requirements were identified. An overview of the five proposed requirements can be seen in Table A1. These were all included within the serious game's concept, design, and implementation. Within the serious game, there should be the possibility to include conventional exercises and movements, i.e., movements carried out during classic rehabilitation must also be used within the game (see R01). Seven different exercises were identified based on classic rehabilitation and prevention exercises—see Figure 1. Individualization is important. Therefore, the serious game should also be adaptable/configurable for each participant in measuring and using the range of motion to adapt to the difficulty (see R02). To fulfill this, the game was designed so that the needed exercise (movement) can be chosen—e.g., participant A requires only a specific exercise and can play the game just with this one. In addition, the time limit for a game can also be individually set. Before a game starts, calibration needs to be carried out to determine the current range of motion and adapt the game accordingly. For some indications for the therapists and patients, visualization and progress tracking should also be included (see R03). This should also be used for motivation and further therapeutical indications. To do so, this was implemented by giving feedback on the progress (score). For the specific case of the setting (soccer), the serious game should also reflect this by adding a familiar setting within the game environment (see R04). This was incorporated by delivering a familiar game scenario on a football field and controlling soccer players to identify themselves. To be used easily at home and integrated into daily processes, a quick setup time and good portability was also an additional requirement (see R05). By using laptops, this setup was performed quickly during the evaluation.

3.3. Prototype

For the here-presented serious game, different exercises were identified and selected, which were incorporated in a game using the MetaMotion sensor.

Before starting each game, the duration, game scene, and required movement can be selected based on the degrees of freedom (DoF) of an exercise. The total number of movements included horizontal (M1) and vertical (M2) inversion and eversion of the foot, dorsal and plantar flexion (M4) of the foot, toe and heel raising (M5), knee flexion and squatting (M3), and a combination of inversion and eversion (M7) and dorsal and plantar flexion (M6) of the foot. Movements M1 to M5 can be used freely for game mode 1, which includes levels 1 (L1) and 2 (L2). In level 1, the player must follow and stay within the path of a pair of cones by moving left or right. In level 2, the player must avoid obstacles by moving left or right and collect trophies. The avatar moves forward automatically in both levels. A combined movement M6 and M7 (2 DoF) can be used for game mode 2 (containing one level (L3)): the player has to collect a randomly appearing trophy. When it is caught, a new one spawns on the screen). The movements, game modes, and levels can be seen in Figure 1. These exercises are all designed to be feasible for both prevention and rehabilitation.

Before starting the chosen game, calibration must be carried out (for each DoF). The player must pose for a short time (5 s) in each position where the maximum and minimum angles of the exercise are defined, representing the extreme positions within the game. The values of the calibrated maximum angles are then used to calculate the length of the edge that extends from an anchor point to the furthest point within the range. This must be carried out for one axis (1 DoF) or two axes (2 DoF). These positions are increased to make the game more challenging. Depending on the game selected (game mode 1 or 2), the player can play the game until it is finished. The score is then displayed in the form of correctly passed pairs of cones for game mode 1 or the number of trophies caught for game mode 2 (or level 2). In addition, the range on the characteristic angle of the selected exercise is displayed (game 1) or the average of the two ranges (game 2). The user can also choose between restarting the game with the same choices, returning to the menu and changing the game scenario, the exercise or the game duration, or quitting the game and closing the application.

As an example of gameplay, game mode 1 (1 DoF) and level 2 (obstacle avoidance) are chosen, together with horizontal inversion and eversion. The sensor is attached to the foot with a strap. After calibration, the game starts and the foot must be moved left and right in a sitting position while the avatar moves forward continuously. When an obstacle appears (on either side), the player must move the foot in the other direction before it is hit. If the obstacle is hit, the avatar will slow down. At the end of the selected time, points are awarded based on the player's progress (percentage of the maximum level without hitting obstacles).

3.4. Evaluation

To evaluate the developed serious game, two participants (see Table 1) from two different football clubs were involved in playing and testing the serious game. Both players had suffered a non-severe ankle injury three weeks previously and were already familiar with conventional rehabilitation.

Participant 1, from a local football club, had three sessions in one week, with three repetitions per exercise (30 s, 45 s, and 60 s), for 20 min of active exercise time per session, for a total of 60 min per week. Participant 2, from another professional third-division football club, had an initial meeting with a therapist and four training sessions spread over two weeks. Three repetitions per exercise were performed (every 90 s), for a total of 27 min of active exercise per session, for a total duration of 1 h and 52 min. The evaluation results of participant 1 (P1) are shown in Figure A1 and those of participant 2 (P2) in Figure A2. The scores for the second game are abbreviated with T (Trophies). The measured ROM with the sensor is shown in the corresponding column (range) and the corresponding scores in the column score. Both participating soccer players gave positive feedback on the developed serious game. They also found the time spent playing the game to be enjoyable and entertaining. They would have continued to use the serious game and noted that they probably spent more time with the serious game than with classic rehabilitation or prevention exercises. The authors think that the participants also tried to increase their score and ROM over time. See Table 2 for an overview. On average P1 improved the ROM by 3.56° and scores by 7.00%, while P2 gained 6.59° and 9.53%, respectively.

No variables showed significant differences to normal distribution; therefore, a paired sample *t*-test was performed to compare both performance indicators between the first and last session. Both the ROM (t = 5.71) and the Score (t = 3.98) showed positive, highly significant ($p < 0.01$) differences between the sessions.

4. Discussion

This research aims to introduce a novel and engaging strategy to motivate patients to perform preventive and rehabilitative exercises, leading to pain reduction and improved therapy outcomes. This was achieved by incorporating a commercially available off-the-shelf sensor into a newly designed serious game for football players.

4.1. Key Findings

This paper suggests a solution for aiding ankle injury prevention and rehabilitation therapy by creating a serious game with different levels that is controlled by the MetaMotion sensor, which comprises diverse movement patterns. The commercial off-the-shelf sensor was robust enough to collect similar data for these movements. The possible usage of a MetaMotion sensor was also already stated in [34] within the domain of cycling and as a replacement for motion capturing. Combining individual soccer exercise choices in the same gameplay with the possibility for one or two degrees of freedom (DoF) movements has not been carried out before. This is supported by conducting state-of-the-art research. Previously developed solutions do not integrate a MetaMotion sensor in combination with soccer athletes as a target audience in the context of ankle injury prevention and rehabilitation.

Due to the collaboration of a therapist in the development process and two patients within an evaluation, the feasibility of the solution was also given—classic rehabilitation exercises can be transferred into game-relevant movements with a COTS. In addition, an online questionnaire gathered insights from semi-professional athletes, backing up the importance and need for support (with a serious game). The questionnaire results indicate that ankle injuries pose a significant risk and problem; currently, there is not enough prevention against it. A serious game may pose a good possibility to support this setting. Within a study by Herne et al. [35], the positive impact of a virtual reality-based serious game on upper limb rehabilitation following a stroke increased enjoyment and motivation to engage in therapeutic exercises for rehabilitation, which was already shown for this domain. It can be stated that the significant improvements in ROM and score equally indicate the physical and mental (motivation) functionality of the system. The feedback of the evaluation participants also indicates that with such a serious game, the time spent on prevention and rehabilitation might be increased (which was articulated by them as well). These results also indicate that users were becoming more and more engaged and ambitious, trying to improve ROM and scores, and generally getting better at using the system. This was also subjectively noted when watching them perform the exercises.

All participating stakeholders gave positive feedback to the developed serious game, the setting, and the used sensor. The perceived time while playing the game was also considered joyful and entertaining. All participants would have continued to use the serious game. Such a solution incorporated into the training, especially for prevention, might also avoid getting injured. This was also supported during the online questionnaire by needing to spend more time on such exercises.

The initial question of requirements for a digital training module was met in developing a serious game using a COTS sensor. It was shown that this is feasible and possible. The identified requirements could be implemented, and from a technical point of view, it was also shown that our setup could be used during rehabilitation.

4.2. Limitations

Although the proposed solution seems promising, further research is needed to address the following limitations. A larger and more diverse sample and a longer evaluation period is needed to gain more insights on the capacity of training with this system. In particular, the evaluation period lasted only one and two weeks, which is a rather short time frame. In addition the demographics of the two participants are also limiting the results. The setting was evaluated within the context of soccer and not within other domains. Although the results seem promising and to be moving in a positive direction for using a serious game with a COTS sensor, further research is necessary to counter these limitations. In the context of available data, it is unclear if such a solution really can support the rehabilitation and prevention of ankle injuries. The integration of the COTS sensor into the serious game allows us to measure the ROM but was also limited to testing with two participants. Feedback and the gathered requirements are also only subjective measures and should be backed up with further analysis during a larger evaluation.

5. Outlook

Although this is very promising, some additional future work should be carried out. A more extensive evaluation and more participants should deliver significant results. Additionally, some information to be shown to the therapists should be considered (e.g., an overview of played games, performance, etc.). This might also include a pain scale for additional references. Although the setup does not require many components, this process and usage should be investigated further. For more extended usage, the comparison and storage of data should also be included, as well as dedicated training programs for each individual. Additional exercises (movement patterns) might also be included to emphasize this further. For additional exercises, the possibility of correctly measuring the ROM and using them within such a setting must also be looked into.

From within a gaming context, many additional aspects could be included. It might be possible to define specific levels by therapists with an editor to even more individually create these levels. In addition, the levels might also be created using Artificial Intelligence based on previous levels as well. For long-term motivation, different gamification aspects could also be included (e.g., high scores, achievements, or badges).

In addition, the here-presented serious game might be integrated into the rehabilitation of other domains, e.g., of stroke sufferers, and could be combined within other solutions like [36,37], or also in combination with balance boards to support the training of lower limbs. It is further noted that this serious game could be incorporated in a more extensive leg-injury-prevention training program, also involving knee and hip joint [38–40] games and devices, to stabilize the lower extremities comprehensively.

Overall this publication should pose a good starting point for further advancements and additional research. The proposed solution holds promise in enhancing the efficiency and cost-effectiveness of healthcare, delivering an easy-to-setup solution.

Author Contributions: Topic selection, R.B.; initial game idea, J.G.; conceptualization, J.G. and R.B.; methodology, J.G., R.B., C.A. and T.G.; software, J.G.; validation, J.G., R.B., D.H., W.H., T.G. and K.P.; formal analysis, J.G. and R.B.; investigation, J.G. and R.B.; data curation, J.G., R.B., K.P., C.A. and D.H.; writing—original draft preparation, R.B. and J.G.; writing—review and editing, D.H., C.A., K.P., W.H. and T.G.; visualization, J.G. and R.B.; supervision, T.G. and R.B.; project administration, R.B. All authors have read and agreed to the published version of the manuscript.

Funding: Open Access Funding by TU Wien.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the RISE PREC Ethics Committee (approval code RD_2021/11/COPA001).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Raw data are not publicly available.

Acknowledgments: First and foremost we would like to thank all participants of the online survey, as well as therapists and soccer players. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme for this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
COTS	Commercial Off-The-Shelf
DoF	Degree of Freedom
L*	Level
M*	Movement-Pattern
Rep	Repetition
ROM	Range of Motion
T	Trophies
UCD	User-Centered Design

Appendix A

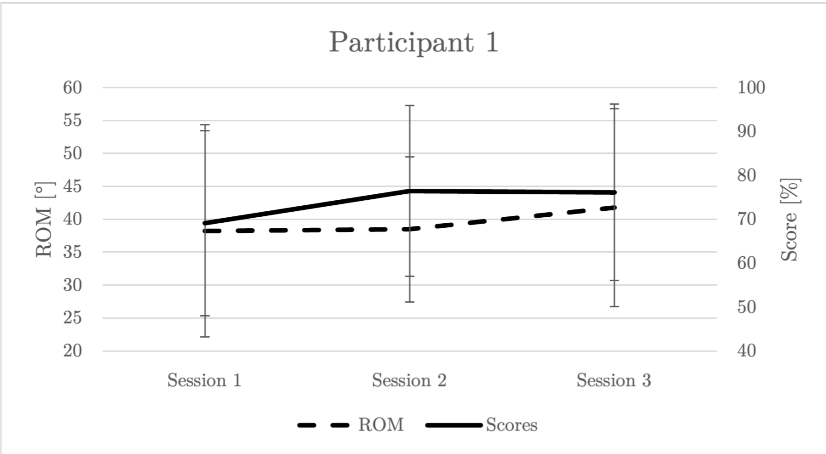

Figure A1. Participant 1.

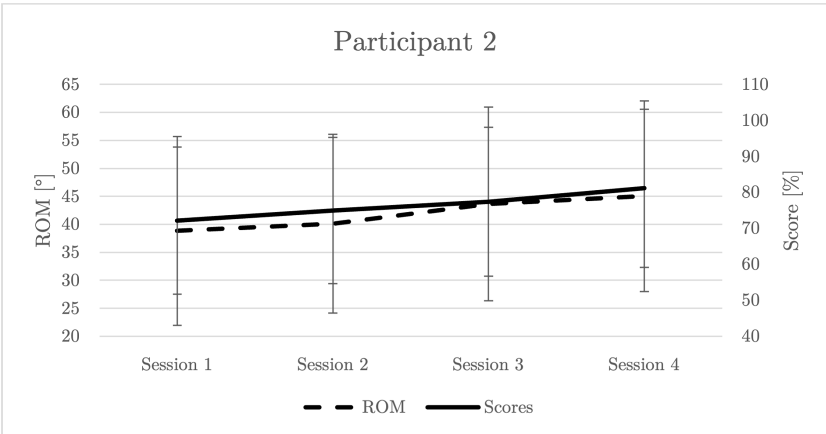

Figure A2. Participant 2.

Table A1. Identified requirements.

ID	Description
R01	Recreation of multiple conventional rehabilitation exercises
R02	Individual adjustment of difficulty and Range of Motion (ROM)
R03	Visualization of scores and tracking of progress
R04	Maximization of user acceptance by creating a soccer-familiar game environment
R05	Portability and quick setup

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