Informatics

# Analyse, Design und prototypische Entwicklung eines Serious Games für Rehabilitation und Prävention von Verletzungen am Knöchel

DIPLOMARBEIT

zur Erlangung des akademischen Grades

Diplom-Ingenieur

im Rahmen des Studiums

Medizinische Informatik

eingereicht von

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an der Fakultät für Informatik
der Technischen Universität Wien

Betreuer: Thomas Grechenig

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Informatics

# Analysis, Design and prototypic Implementation of a Serious Game for Rehabilitation and Prevention of ankle injuries

MASTER'S THESIS

submitted in partial fulfilment of the requirements for the degree of

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in

Medical Informatics

by

Jonas Galli
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to the Faculty of Informatics
at the Vienna University of Technology

Advisor: Thomas Grechenig

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ausgeführt am
Institut für Information Systems Engineering
Forschungsbereich Business Informatics
Forschungsgruppe Industrielle Software
der Fakultät für Informatik der Technischen Universität Wien

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# Kurzfassung

Untersuchungsgegenstand dieser Diplomarbeit ist der Themenkomplex der Knöchelverletzungen sowie deren Rehabilitationsprozess und wie dieser erweitert werden kann. Zunächst werden die theoretischen und medizinischen Grundlagen der Verletzungsmechanismen, die Inzidenzen sowohl weltweit als auch im Bereich des Leistungssportes, sowie die gängigen Rehabilitationsmethoden und -Übungen vorgestellt. In einem zweiten Schritt, werden diese Aussagen durch Gespräche mit den beteiligten Akteuren und mit einer hierfür konzipierten Umfrage auf ihre Aussagekraft hin überprüft. Alle Beteiligten bestätigen die kritische Situation bei solchen Verletzungen: die kurz- und langfristigen Auswirkungen werden oft unterschätzt und Physiotherapie wird meistens nicht mit dem nötigen Ausmaß an Engagement betrieben. Der Belastungsdruck auf den Patienten und die subjektiven Betrachtungen der Situation führen oft zu einer erzwungenen und zu schnellen Rückkehr zum Sport. Um diesem Trend entgegenzuwirken, haben Experten im Bereich der Medizin und Physiotherapie versucht, sowohl standardisierte Rehabilitationsmethoden zu identifizieren als auch Evidenzen und Parameter zu ermitteln, die den tatsächlichen Zustand des Knöchels selbst sowie den Stand im Rehabilitationsprozess wirklich zeigen, dies jedoch mit mäßigem Erfolg. Die zuverlässigste Einschätzung ist nach wie vor die Bewertung des gesamten Prozesses aus den Augen eines Physiotherapeuten. Jedoch können effektive und objektive Instrumente, welche Physiotherapeuten und Patienten während des gesamten Prozesses begleiten, Transparenz und Klarheit für alle Beteiligten schaffen.

Ein Beispiel hierfür ist die Anwendung von Serious Games. Ziel und Ansatz dieser Anwendungen ist es, die rehabilitativen Übung in einen unterhaltsamen und sogar angenehmen Vorgang zu verwandeln. Die Herausforderung besteht darin, positive Gefühle bei den Nutzern zu erreichen und auszulösen. Oftmals ohne, dass der Benutzer dies bemerkt, wird durch die Integration effizienter und nützlicher Übungen und die Darstellung einer vertrauten Situation eine Bindung zum Spiel hergestellt, welche automatisch die Bindung an die gesamte Therapie erhöht. Dies wird auch in dieser Diplomarbeit gezeigt, in der ein solches System prototypisch implementiert und evaluiert wird. Nach einer intensiven Untersuchung der Ausganslage und der Voraussetzungen wurden verschiedene Übungs- und Spielkonzepte idealisiert und in ein Serious Game integriert. Mit Hilfe von Mitgliedern aus einem professionellen Fußballverein wurde das System evaluiert und getestet. Die Ergebnisse zeigen deutlich die Wichtigkeit und die Steigerung des Engagements für die Übungen bei der Anwendung in einem spielähnlichen Szenario. Vor allem festzustellen ist eine Steigerung der Aktivierungszeit und das Erkenntnis, dass die Zeit, die theoretisch mit dem Spielen eines Videospiels verbracht wird, Zeit für Rehabilitationsübungen ist. Diese Diplomarbeit unterstreicht die wichtige Bedeutung von Serious Games, um die Adhärenz nicht nur für physiotherapeutische, sondern auch für Präventionsübungen zu erhöhen.

**Keywords**: *Knöchelverletzungen, Digitale Rehabilitation, Serious Game, IMU-Sensor, Fußball*

# Abstract

This diploma thesis explores the landscape regarding ankle injuries, their rehabilitation process and how this process can be enhanced. First, the theoretical and medical fundamentals of the injury mechanisms, the incidences worldwide and in the specific world of sport, and popular rehabilitation methods and exercises are elucidated. In a second moment, these findings are assessed of viridity by on-field observations, discussions with involved stakeholders and with the creation of a specifically designed survey. All the involved parties underline the critical situation with such injuries: the short- and long-term effects are often underestimated, physiotherapy is not done with the necessary dedication and different pressures, and subjective looks at the situation often lead to a forced and rushed return to activity or return to sports. To invert this negative trend, researchers in the fields of medicine and physiotherapy tried to identify standardized rehabilitation methods as well as evidence and parameters that show the actual state of the ankle itself and in the rehabilitation process. With moderate results. Because still, the best evaluation stems from the assessment of a physiotherapist of the whole process and no parameter or test result would succeed over the observation of the process. Nevertheless, effective and objective tools that accompany the physiotherapists and involved patients during this whole process will bring transparency and clearness to all the involved parties.

This is the point where new technologies come to play, represented, for the sake of this diploma thesis, by the application of serious games. The goal and approach of these applications, in this case, is to transform rehabilitative exercises into an entertaining and joyful moment, where the user would not even perceive to perform an exercise. The challenge is to achieve and trigger these feelings from the users. Therefore, the application needs to be well designed and adapted to each situation. By maximizing the attachment and adherence from the user towards the game, and by integrating efficient and useful exercise inside the game, automatically also the adherence towards the therapy increases, often without that the user even feeling or knowing it. This is also shown within this diploma thesis, where such a system is prototypically implemented and evaluated. After an intense pre-requisite and requirement engineering, different exercise and game concepts were idealized and integrated into a serious game. With the inclusion of members from a professional soccer club, it was possible to test and evaluate the system. The results clearly underline the importance and also the increment of the dedication towards the exercises within a game-like scenario. Furthermore, what really stands out is the increment of the activation time and the oversight that the time spent while playing a video game, in theory, was time spent with rehabilitation exercises. This diploma thesis furthermore evidences the important factor that serious games can have in increasing the adherence not only towards physiotherapeutic but also towards prevention exercises.


**Keywords**: *Ankle injuries, digital rehabilitation, serious game, IMU-sensor, soccer*

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# 1 Introduction

The very first part of this diploma thesis introduces the context and the conditions in which the following work and studies were conducted. From the presentation of the underlying problem, the motivation that led to the conceptualization of this diploma thesis and the consequently identified research objectives are elaborated and defined. Furthermore, the last part of this section, describes the structure of the thesis, the applied methodology and contains a graphic visualization of the various steps that were followed for the realization of this final work.

## 1.1 Problem Definition

Ankle injuries can happen in everyday's life scenarios but are even more frequent for athletes in every kind of sport. Results of a systematic review on ankle injury and ankle sprains in sports [1] show that the ankle is the most common injured body site in 24 of 70 included sports. In football, ankle injuries account for 13–20% of all injuries, with ankle sprains constituting between 51% and 81% of them [2] [3]. The missed playing time varies, depending on the involved ligaments and the severity of the tear, between one to two weeks and up to several months. What highly influences the return to play after a severe injury is the performance and the dedication towards the exercises in the first phase of the rehabilitation process where it is important not to overload the injured foot and allow the ligament fibres to heal. The process of rehabilitation after such an injury can be very long, tedious and annoying. The first exercises of the rehabilitation pathway are simple range of motion exercises to regain confidence and muscle mass in the sprained ankle. These exercises, composed of basic movements, contractions and rotations of the injured foot, can be very boring and frustrating but are essential for the continuation of the rest of the rehabilitation process.

The effect of physiotherapy highly depends on the adherence of the patient [4]. A low adherence by the patients to the given therapy can lead to negative outcomes and negative effects on healthcare costs. Therefore, new methods can be included in the rehabilitation process to increase the motivational aspect of the patients. For the purpose of this diploma thesis, these new methods are defined by Serious Games. For the application of serious games during the rehabilitation process, there are mainly two reasons: with the serious game it is possible to incorporate both, simulated and new types of rehabilitation exercises and second because the application of serious games can increase the motivation and adherence of the patients to the given therapy [5] [6].

## 1.2 Motivation

There already exist serious games that are used for exercises on an injured ankle and are used for rehabilitation purposes, but none of them puts the focus on the acceptance for protagonists from the world of sport. This diploma explores the requirements that physiotherapists and players put to a serious game application for rehabilitation purposes and implements a prototype of such a serious game with the identified requirements. The serious game should be able to recreate conventional exercises used during the rehabilitation process and combine them with the fighting spirit of professional athletes to increase the adherence to the given therapy and influence the mood of the players in a positive way.

## 1.3 Research Objectives

Nearby the elaboration of the requirements towards a serious game used for rehabilitation exercises, the diploma thesis should define if the serious game application finds its acceptance, especially in a younger target group when integrated into such a rehabilitation process. Here the serious game should be used as part of a training program to increase the amount of time spent with exercises focused on the increase of the stability and the balance of the ankles before and after an injury. The goal is to show that the serious game can increase the motivation of younger athletes to perform these exercises to strengthen their ankles and prevent future ankle injuries.

## 1.4 Methodology and Structure of the thesis

The work of this diploma thesis can mainly be divided into three phases (see Figure 1). The first phase aims to identify the requirements that are necessary to implement a serious game used for medical purposes and spans over Section 2, Section 3 and the first part of Section 4 of this thesis. It contains all the components of the so-called requirements engineering where the theoretical background, already presented systems and the specific context of the application are analysed and assessed.

The description of the theoretical background contains a physiological description of the involved body part, the ankle, a medical analysis of the different types of ankle injuries and an epidemiological analysis of the incidence of ankle sprains across the whole population and in the specific case of the world of sports. Then the rehabilitation process after such injuries is described, how it evolved in time and, with the example of published systems and projects, the utilization of serious games for rehabilitation purposes in general and in the particular case of rehabilitations after ankle sprains is presented. All these findings are then assessed with on-field observations and with the

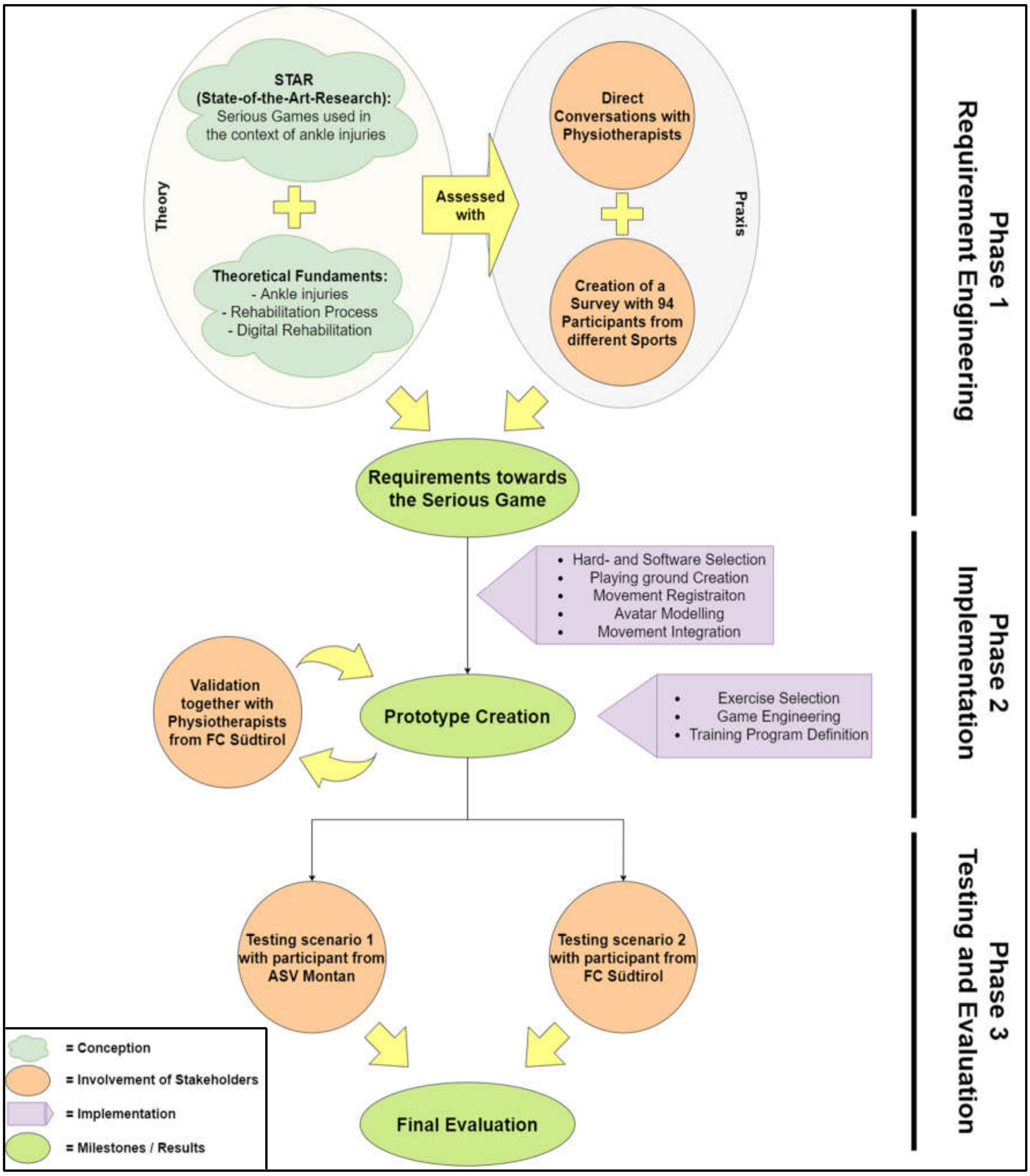



**Figure 1 Schematic visualization of the work of the diploma thesis**

creation of a specifically designed survey. With the start of the conceptualization of the diploma thesis, exponents of the F.C. Südtirol, a local soccer club playing in the third Italian league, were contacted and asked for a collaboration for the realization of the thesis. After a brief presentation of the content, a physiotherapist gave his availability to follow the process and to give his expertise in different steps of the diploma thesis. This connection was used, in a first moment for the assessment of the theory and in a second moment for the testing and the evaluation of the different prototypes of the implemented serious game. From the interview with the involved physiotherapist, from discussions with other experts and from the answers of 94 participants to the survey, it was possible to verify the different parts of the theoretical fundaments and to identify further requirements towards the implementation of the serious game. Based on these requirements the second phase aims to create a series of prototypes that are tested, evaluated and improved in order to end up with the definition of a set of exercises and playing scenarios implemented into the serious game. The second part of Section 4 of this thesis elucidates the iterative process that leads to the creation of the serious game itself. It contains a detailed description of the various steps that were followed for the implementation of the first prototype, the way it was further optimized and the features that were included into the final prototype that is furthermore tested and evaluated in the third and last phase of the diploma thesis. During the testing phase, two young athletes were followed respectively for one and for two weeks to determine the usability and the acceptance of the system. This testing phase takes as results the observation of the effort that is put in during the exercises by the involved athletes, their feedback at the end of the sessions and at the end of the testing period, the thoughts and comments of the involved physiotherapists that follow the process and finally the results achieved while playing the serious game. These results are collected and analysed in order to judge and value the final outcomes of the diploma thesis.

Lastly, a discussion of the achieved result is followed by a summary and the outlook towards future works.

# 2 Theoretical Background

In order to better understand the problems defined in Section 1.1 and to understand the consequences that the actual situation brings with it, this section explains all the theoretical fundamentals that are necessary to do so. Since all the gathered information run into the definition of the requirements towards the serious game, the section starts with the elucidation of the requirements engineering process. Then, the content of the further parts of the description of the theoretical background shows the importance and the influence of medical informatics on the work of this diploma thesis. In fact, the anatomical presentation of the ankle, the medical description and an epidemiological analysis of ankle injuries are followed by the description of the rehabilitative process after such injuries and the role of the digitalization of the medicine in general and the physiotherapy in particular. This last part opens the door to the definition of scenarios where serious games can be used to increase the effect of a therapy and to increase the motivation and the adherence of the patients towards the presented methods.

## 2.1 Requirements Engineering

Back in 1995 Frederick P. Brooks, former Professor of Computer Science at the University of North Carolina and known as the "father of the IBM System/360" wrote the following quote in his book The Mythical Man-Month [7]:

"*The hardest single part of building a software system is deciding precisely what to build. No other part of the conceptual work is so difficult as establishing the detailed technical requirements, including all the interfaces to people, to machines, and to other software systems. No other part of the work so cripples the resulting system if done wrong. No other part is more difficult to rectify later*"

More than 25 years later this concept is still at the basis of each and every project that involves the creation of a software system. This diploma thesis not excluded. Therefore, before starting with the implementation, the so-called Requirements Engineer process needs to be performed to address all the necessities of the involved stakeholders, to elucidate the context in which the system will be introduced and, more importantly, to define the problem that the system is going to resolve. This whole process should be characterized by this simple statement with three different implications: How and Why should the system do What. When all the three implications are addressed, reasonable answers can be given to each of them and functional and non-functional requirements towards the system were identified, the project can pass to a next phase where these requirements are integrated and implemented into the desired system. Answers to these questions are given by understanding the needs of users, customers, and other stakeholders; understanding the contexts in which the to-be-developed software will be used; modelling, analysing, negotiating, and documenting the stakeholders' requirements; validating that the documented requirements match the negotiated requirements; and managing requirements evolution [8].

For this diploma thesis the process of the requirements engineering, in order to assess the context, address the problem and define a possible solution to it, contains an intense theoretical background scanning where different aspects of ankle injuries are analysed and by identifying the needs and the problems seen by involved stakeholders such as physiotherapists and players with direct conversations and with the creation of a specific survey. The requirements engineering part spans over Sections 2, 3 and 4 and ends with the definition of the identified requirements towards the serious game in Section 4.3.

## 2.2 Physiology and anatomy of the ankle and ankle injuries

The ankle joint (Figure 2) is composed of different bones and maintained together by several ligaments, more precisely, the Tibia and Fibula (the two bones composing the lower part of the leg under the knee) are bend together by the Anterior and Posterior Tibiofibular ligaments and end on top of the Talus. The Posterior and Anterior Talofibular ligaments ensure this position and allow the dorsi- and plantarflexion (up and down movement) of the foot. These two ligaments, combined with the Calcaneofibular ligament, form the Lateral collateral ligament complex. The Calcaneofibular ligament connects the Fibula and the Calcaneus, positioned under the Talus. The anatomy of the ankle and the surrounding position of the Tibia and Fibula around the Talus allow the dorsi- and plantarflexion of the foot, but ensure the stability of the whole body while standing by limiting the inversion and eversion movements of the foot [9].

When it comes to ankle injuries, there is to distinguish between ankle contusions, ankle dislocations and, most commonly, ankle sprains [10]. Ankle contusions mainly happen while playing contact sport due to a hard-tackling by an opponent (see Figure 3a and b for example scenarios). In this case, the tissues and the muscles around the ankle start to swell and moving the foot really hurts. In most cases, the ligaments, the bones and the whole ankle joint are not damaged. The first thing that is done after such an injury is to put ice on the ankle in order to reduce inflammation and swelling. The therapy of the case will simply be the application of anti-inflammatory creams and the prescription of a short resting period [11].

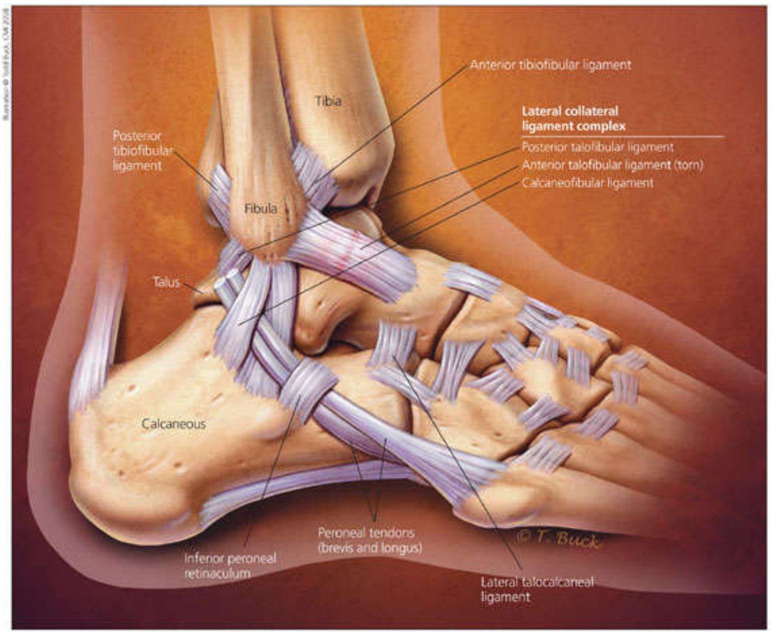



**Figure 2 Anatomy of the ankle with the ligamentous and bone structures [12]**

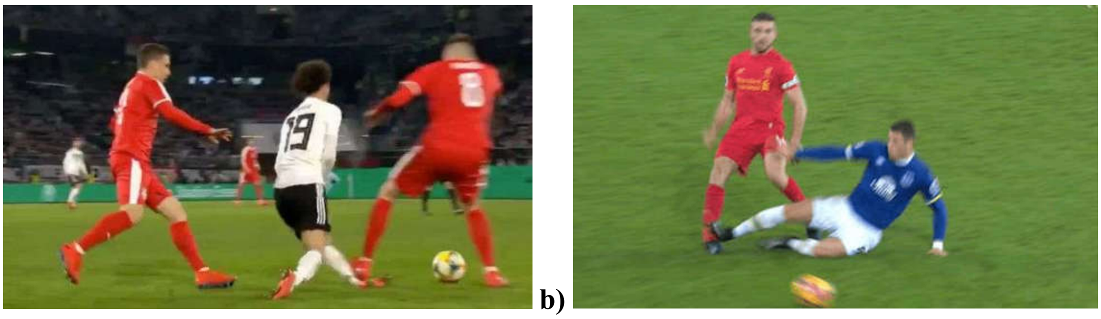
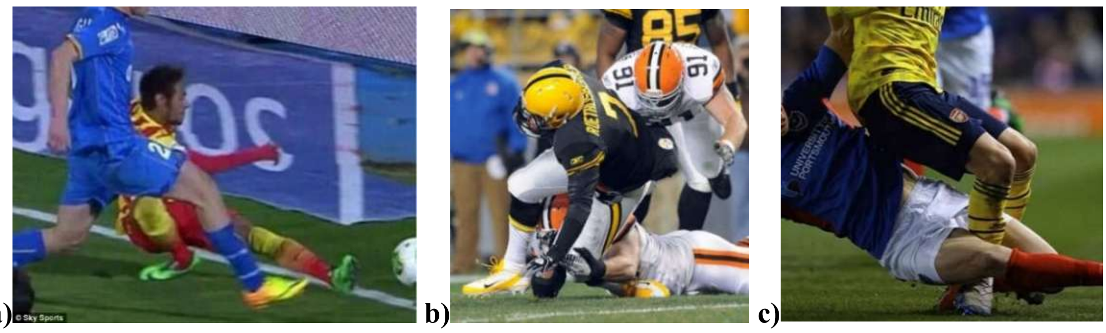
a)  b)

**Figure 3 Typical situations of ankle contusions in soccer games due to a hard-tackling by an opponent. a) Image taken from [13] b) Image taken from [14]**

When ankle contusions are a typical injury happening in soccer, ankle sprains can happen in quite every type of sport and also during everyday life. In sport, they can be caused by the contact or the tackling of other players, due to holes or a bad condition of the pitch or, like it can happen in everyday life situations, by simply planting the foot or while landing in the wrong way and putting too much load on the ankle joint from a wrong angle. In general, ankle sprains happen when the ankle joint is stretched to the outside (eversion) or to the inside (inversion) of the body. When this is happening, the bones that form the ankle joint are punt in unusual positions and the ligaments that ensure that this is not happening are stretched and can be damaged. The dynamic of the movement that leads to the injury determines the ligaments that can be damaged during these moments. There are mainly two types of ankle sprains, the high ankle sprain, also known as Syndesmosis and the low ankle sprain, also known as lateral ankle sprain [15].

The high ankle sprain is more severe than the low ankle sprain but is also less common. It only makes up about 10% of all ankle injuries [15]. The high ankle sprain is caused by an eversion of the foot (see Figure 4a-c for example scenarios) and the term high ankle sprain is given by the involved ligaments (anterior and posterior tibiofibular ligaments) that are positioned above the ankle joint (= 'higher'). This outside movement of the foot is mainly caused in collision and contact sport when a player is tackled and the foot remains stuck under the body of the tackling player. In other non-contact sports or in situations of everyday life this movement is less probable and such injuries didn't happen very often. The eversion of the foot forces the Talus, which is also part of the external rotating foot, to rotate laterally and consequentially to modify the position of the Fibula by pushing it away from the Tibia. This push causes the Posterior and Anterior Tibiofibular ligaments to hyper stretch and consequentially to tear these ligaments. In all three scenarios of Figure 4, the injured foot is pointed outside and stuck under the body of an opponent. In the case of Neymar's injury (Figure 4a), the foot is planted, but the whole body is falling backwards causing the ankle to be in this eversion position and putting too much load on the ankle joint. The rehabilitation process after high ankle sprains is longer than for lateral ankle sprains and the full recovery can take anywhere from six weeks to three or even more months. The duration of the rehabilitation depends on the severity of the tear in the ligament. For ankle sprains there are three grades that describe the tear in the involved ligament. Grade 1 sprains are sprains where the ligament tissue is stretched and some small tears appear inside the ligaments tissue. Grade 2 sprains already show a larger ongoing tear in the ligaments and range up to grade 3 sprains where a complete rupture of the ligaments is present [16].



a) b) c)

**Figure 4 Typical scenarios of high ankle sprain injuries where the foot is stuck under the own body weight or under an opponent. a) Image taken from [17], b) from [18] and c) from [19]**

The more common type of ankle injury is the lateral or low ankle sprain. The name is given by the position of the involved ligaments which are part of the lateral collateral ligament complex on the outside of the foot. Because of the dynamic that causes this type of ankle injury they can happen in quite every kind of sport, contact and non-contact, and in a lot of different situations during everyday life. The mechanism that leads to an injury is an inversion movement of the foot that stretches the ligaments of the lateral collateral ligament complex. The more common involved ligaments in low ankle sprains are the anterior talofibular ligament and the calcaneofibular ligament. There are several situations where this type of injury can happen. Examples are shown in Figure 5a-d and they illustrate situations without the influence of other participants and situations in contact-sport where an action of someone else causes or is part of the dynamic that causes the injury. As one can see, and probably as one has already felt at least once, this type of injury is very common and can happen very quickly, but, in most cases, it heals, or is perceived to heal very quickly. Also in this case the severity of the injury and consequentially the duration of the resting period and rehabilitation phase is depending on the severity of the tear of the involved ligament. Normally the injury is completely healed after just one to two weeks, but with a more severe tear in the ligament, the rehabilitation can last for several weeks [15].


**Figure 5 Scenarios of lateral ankle injuries. a) while walking, image taken from [20]; b) during a basketball match, image taken from [21]; c) while playing tennis, image taken from [22] and during a soccer match, image taken from [23]**

The most severe ankle injury is the ankle dislocation. Ankle dislocations can happen as a consequence of ankle sprains when the contrast or the tackle is very hard, but also as consequences of other types of incidents, such as motorcycle incidents. With this type of injury, the ligaments that compose and fix the ankle joints are completely torn and are not able to stabilize the bones of the joint. When this happens, the bones, especially the Talus, can pop out of the cave formed by the Tibia and the Fibula in order to cause an abnormal separation between two or more bones of the ankle joint. In most cases, the dislocation of the ankle is not only a consequence of the tear in the ligaments but also a consequence of the fracture of the distal ends of the Tibia and/or the Fibula [24]. In some rare cases, the dislocation can be reversed by doctors or physiotherapists that move the bones back in place without surgery immediately after the injury. This may cause a lot of pain but is important for the blood vessels and the nerves of the foot to not be damaged. In other cases, the dislocation and, if present also the fracture, need to be treated surgically to repair the ankle joint. The dislocation of the ankle can be assessed with X-ray imaging but normally it is understandable already by seeing the unusual position of the foot in respect to the rest of the leg (Figure 6a and b). The recovery after an ankle dislocation takes a much longer time than for ankle sprains and can have much more complications during the rehabilitation pathway. This, for example, was the case of the injury that happened to Alex Smith, Quarterback of the NFL-Football team Washington Redskins, who suffered a compound fracture that broke both the Tibia and Fibula with further complications in 2018 (injury in Figure 6b) due to an infection of flesh-eating bacteria after Smith's initial surgery. Following that first procedure to address the compound fracture, Smith needed 16 more surgeries before his leg could be fully recovered. The infection became septic and was that dangerous, that Smith not only had to fear for his leg but for his life. Fortunately, the medicals could bring the infection under control and save both Smith’s life and also his leg and almost miraculously he managed to work himself back to the pitch and was able to return to the field about 20 months after the initial injury [25].

a) b)


**Figure 6 Situations of ankle dislocations during football matches. a) Image taken from [26]; b) Image taken from [27]**

## 2.3 Incidence and epidemiology of ankle sprains

Ankle sprains are one of the most common musculoskeletal injuries and there are a lot of studies that assess their incidence across professional athletes and different sports and also the epidemiology across whole populations. Worldwide approximately one ankle sprain occurs per 10,000 person-day and an estimated two million acute ankle sprains occur each year in the United States alone [28]. The incidence rates calculated from the medical department vary between 2 to 7 acute ankle sprains per 1,000 person-year but are likely to be significantly underestimated. A study from the Netherlands [29] revealed that the incidence rates of all ankle injuries are around 5.5 times higher than those registered at emergency departments. This increase in the incidence is given by all the non-medically treated ankle sprains and give a much more complete picture of the landscape of ankle sprains. With these assumptions, the incidence is determined between 19.0 to 26.6 per 1,000 person-year and would result in an approximation of more than seven million cases a year in the United States.

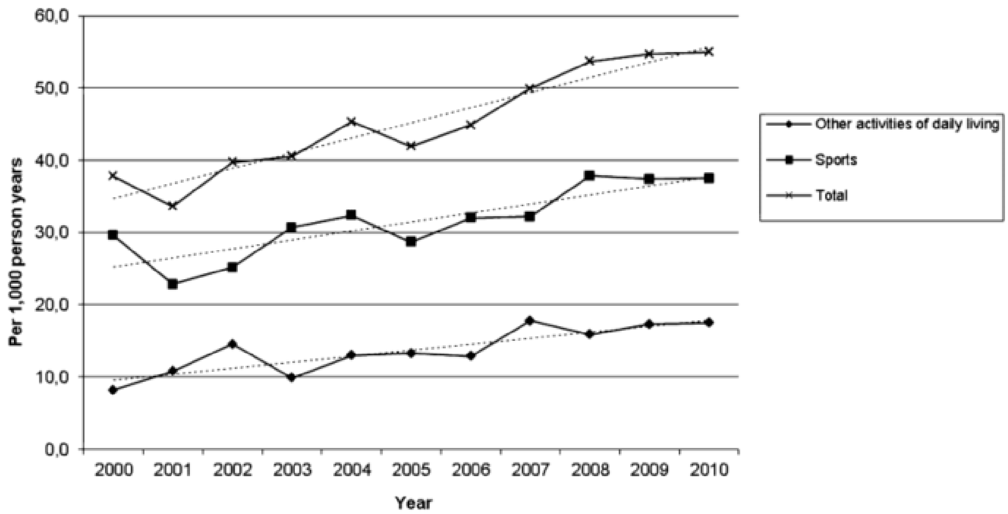



**Figure 7 Long term ankle injury trends. Ankle injuries during sport and other activities of daily living per 1000 person-years in the Netherlands, 2000-2010 [29]**

Figure 7 shows the trend of the incidence of ankle injuries in the Netherlands between 2000 and 2010. The collected data comes from two national surveys and contained both medically and non-medically treated injuries. The two Dutch surveys are *Injuries and Physical Activity in the Netherlands* (IPAN) [29] [30] and the *Dutch Injury Surveillance System* (DISS) [29]. The IPAN survey contacted around 11,000 people a year by online interviews and telephone and one randomly selected family member was interviewed and asked the following question: “Have you had any injuries in the past three months? Overuse injuries and less severe injuries should be taken into account.” Based on this question, questions about the body location of the injury and how the injury happened were asked. Injuries were classified as injuries resulting from other activities of daily living if they didn't occur while working or while doing sports and examples are injuries that occur in and around the house, in public buildings, while playing or walking on pavements and streets, and while spending leisure time. The second survey, DISS, has registered injuries at the Emergency Departments of a representative sample of all hospitals in the Netherlands with an average of 97,500 registered patients and contained therefore all the medically treated injuries. The overall results show an increase in ankle injuries from 600,000 cases in 2000 to a total of 910,000 ankle injuries in 2010 and result in a trend increase from 8.2 to 17.5 ankle injuries per 1,000 person-years for ankle injuries happened during activities of daily living and an increase from 28.6 to 37.5 ankle injuries related to sports per 1,000 person-years. From all the injuries resulting from the IPAN survey, around half of them were medically treated. These findings led the authors of the paper to conclude that the incidence of population-based ankle injuries increased considerably from 19.0 to 26.6 per 1,000 person-years and is significantly, around 5.5 times, higher than the incidence reported in other studies that considered only medically treated injuries in the United States [28] and in Europe [31] where the incidence rates were supposed to be respectively 2.2 sprained ankles per 1,000 person-year and 5.3-7.0 sprained ankles per 1,000 person-years. The previously cited American study registered a total of 3,140,132 ankle sprains at emergency departments between 2002 and 2006. During the study period, there were no significant differences in the incidence rate among males and females, accounting respectively for 50.3 and 49.7% of all cases. The mean age of the patients was 26.20 years and more than half (53.5%) of the injuries happened in individuals between 10 and 24 years. Here, a difference between males and females was found. In fact, males had the highest incidence rate of ankle sprain between the ages of 15 and 19 years, while the peak incidence rate in females occurred between the ages of 10 and 14 years. The most injuries occurred during athletic activity (49.3%) followed by falls from stairs (26.6%) and stumbles on ground-level surfaces which accounted for 6.7% of all ankle injuries. The majority of injuries occurred at home (47.9%), followed by a place of recreation or sports (28.5%), school (14.5%) and a street or highway (3.2%) [29].

When compared these findings with the results obtained from a systematic review and Meta-Analysis of Prospective Epidemiological studies [32] that included 181 prospective epidemiology studies from 144 separate papers, some differences were noted. The main findings of the review demonstrated a higher incidence of ankle sprain in females compared with males (13.6 vs 6.94 per 1,000 exposures), in children compared with adolescents (2.85 vs 1.94 per 1,000 exposures) and adolescents compared with adults (1.94 vs 0.72 per 1,000 exposures) and they concluded that the female sex, the lower age and athletes competing in indoor and court sports are the subgroups with the highest risk of ankle sprains [29].

### 2.3.1 Incidence in sports

As seen, ankle sprains are one of the most common musculoskeletal injuries in general, but they are also considered to be the most common injury registered across a multitude of sports [1]. This review included 70 different sports and in 24 of them, the ankle is the most common injured body site. The sports with the highest incidence per 1,000 person-hour were rugby, followed by soccer, volleyball, handball and basketball. In football, ankle injuries account for 13–20% of all injuries with ankle sprains constituting between 51% and 81% of them [2] [3]. A well designed and curated survey in collaboration with the Union of European Football Association (UEFA) evaluated the time-trends and circumstances surrounding ankle injuries in men’s professional European football following 27 clubs from 10 countries [2]. During the studied period, between 2001 and 2012, a total of 8,029 injuries were recorded during 1,057,201 exposure hours including 888,249 training and 168,952 match hours. Of all the injuries, 1,080 ankle injuries were detected and accounted for 13% of all injuries. Given these numbers, it can be predicted that a professional football club with a roster of 25 players will be faced with around seven ankle injuries each season. There were no statistically significant differences between the different parts of the season, but the injury rate resulted to be around 8 times higher during a match (3.8 injuries per 1,000 exposure hours) than during training (0.4 injuries per 1,000 exposure hours). Additionally, 40% of all match-related injuries were caused by a foul play. Of all the ankle injuries, 68.9% were ankle sprains and 75.7% of all ankle sprains affected the lateral ligament (=lateral ankle sprain) and only 5.2% resulted to be a high ankle sprain. Behind the joint and ligament sprains, contusions (16.9%) and fractures (2.0%) made up for the rest of ankle injuries. The average lay-off time per ankle injury was 16±27 days. For high ankle sprain, the lay-off time was significantly higher with 43±33 days and even higher was the lay-off time for ankle fractures with an average of 103±45 days. During the observation period of the survey, an average annual decrease in the ankle sprain rate of 3% was observed. This trend can, in part, be explained with the successful implementation of prevention strategies in the clubs with the introduction of balance board trainings and taping and bracing for preventing recurrent ankle sprains and it shows the importance and necessity of even more such training sessions and exercises. Another study [3] followed a Premier League club over a 4-season period and were able to observe also the recurrence rate of ankle injuries. They found that eleven players suffered a recurrence of the injury, which accounted for 26.8% of all cases and interestingly the mean absence time in these cases was 36.7 days, in contrast to the mean absence time for the players that had no reinjury which was 44.5 days. This contrast can have two underlying motivations and consequences, either smaller injuries were not taken seriously enough and not treated with the respect they would have needed, or simply that the recovery period was too short and the player, or because he felt ready or because he was forced by the team, returned to play even though the injury was not healed at 100%. The fact that the return-to-play time is higher than in the previously analysed study can be explained with the bias in the first study regarding the lay-off time, that in some cases can be given by the time until the reinstatement in training and in other cases the full time until the player came back in a game, as it is in this case.

In other sports, the trends and the numbers are similar to those seen in soccer. In the two nationally wide most popular sports in the United States basket and American Football, the National Basket Association (NBA) reported that lateral ankle sprains were the most frequent orthopaedic injury (13,2%) over an observation period of 17 years and in the National Football League (NFL) ankle sprains were documented to be the most diagnosis injury by far with an incidence of 29%. A study that followed an NFL-Team [33] showed a significantly higher amount of high ankle sprains in American Football than in other sport and, interestingly, the study revealed very low loss of participation days for injured players. The missed practice days for syndesmosis injuries was 15.4±11.1 days and for lateral ankle injuries, the loss from participation was just 6.5±6.5 days. These very fast recovery times combined with the relatively low recurrence rate are argued in the study with the presence of optimized neuromuscular pieces of training that lead professional football players to have improved dynamic stability that allows for a stable ankle platform. Another study [5] shows the impact of ankle injuries during the college career of American Football players. Before even entering the National Football League (NFL) and becoming professional football players, more than 50% of the athletes suffered ankle injuries during their High School and College careers. The injury rate in both college and professional football is extremely high, but it is also shown that specific and intense training can reduce the recovery times and therefore also the missed playing time. In respect to this claim, there is the need to add a few more personal considerations that also explain this low missed playing time. To become a professional or even just a college American football player, one needs to be really fit and ones' body really needs to be shaped and prepared for such a physical sport and this is achieved with an enormous amount of training time on and off the field. It can be said that from all the other mentioned sports, the American football player is probably the most physically trained and equipped athlete and can therefore handle musculoskeletal injuries better and with a faster recovery. But there is also another aspect that is involved with American football, and it is the fact that the pressure on the kids through high school, college and finally in the National Football League is higher than in other sports and in other circumstances. This is given because of all the money that is put in high school and college programs, the importance for prospects to show their talent on the field to achieve their dream to come in the NFL and finally because of the speed that a football career can be over if the players did not or are not able to produce their best performances. All these facts and assumptions can lead to a distorted view of the injuries and smaller injuries are just treated with painkillers and other non-curative drugs and consequentially to a faster recovery and lower absence times.

### 2.3.2 Risk of re-injuries and the problem with CAI

As seen, one problem is given by the high incidence of ankle sprains in sport, but a second problem, and probably even more important for the health aspect of the players, is given by a high reinjury rate by the involved players. The period for the definition of a re-injury varies across studies from within two months after return to full participation [2] to the end of the season [34]. Independent from the period, the injury must be of the same nature and location and must involve the same player. Within these studies, the reinjury rate spans from 9% to 11% resulting slightly higher than for all other observed injuries (7%). Even without a statistical significance, there are a few interesting considerations touched in the audit [34]. The first one is that the higher reinjury rate for ankle sprains combined with a slightly longer absence time (19 missed training days against 18 days) and one more missed match (4 missed matches against 3) show that the rehabilitation period after the first injury was too short and that the care and relevance given to the injury increased when it was too late and the reinjury already occurred. The extra missed game after a reinjury may not be statistically significant, but it shows that an extra step of precaution may be the better option. Another interesting consideration is given by the fact that more non-contact mechanisms were responsible for reinjuries than initial injuries (47% against 39%). This difference also highlights the fact, that the first injury wasn't treated enough and that the return to play came too soon. Nearby the reinjury rate, a systematic review [35] showed that a substantial proportion of all acute ankle sprains sustained during sports were recurrent. For example, 46% of acute ankle sprains that occurred in volleyball, 43% in American football, 28% in basketball, and 19% in soccer were recurrent injuries. Why the right treatment of, not only the first but of all ankle injuries is so important, is shown by the research of Ekstrand and Gillquist [36] describing that already in early days, many major ankle injuries were preceded by not well treated minor ankle injuries and by the fact that each and every ankle injury increases the risk of chronic ankle instability and increases the risk of reinjury [37].

Chronic ankle instability, short CAI, is a term used to describe certain insufficiencies of the ankle joint following acute or multiple acute ankle injuries [35]. It's important to note, that not always recurrent acute ankle sprains lead to chronic instability, but if not treated in the right way the probability of long-term damages and insufficiencies increases [38]. For the sake of the review, the state of presence for chronic ankle instability is defined as a condition that presents one or more of three individual contributors that persist following an acute ankle sprain. The three contributors are perceived ankle instability, mechanical ankle instability and recurrent ankle sprains. From the included studies in the review the highest contribution is given by reinjuries and with none ore less information about long-term perceived and mechanical instabilities. This is identified as a limitation in the long-term analysis of sport correlated ankle injuries. Authors of a second article [39] also recognize the overlap between reinjury rates and chronic ankle instability prevalence but focus their research on another long-term outcome of ankle sprains, the posttraumatic Osteoarthritis. Osteoarthritis occurs when the cartilage that cushions the ends of bones in the joints gradually deteriorates. Ankle sprains resulted to be responsible for 70 to 80% of all posttraumatic Osteoarthritis cases in the ankle joint [40]. Of these posttraumatic Osteoarthritis cases, half of them occurred already after a single acute ankle sprain, while the other half resulted from recurrent ankle sprains or chronic ankle instabilities. All the involved articles underline the necessity for more research in this field since the actual literature addresses mainly individual cases and are difficult to compare to each other. When the incidences and injury rates of ankle sprains in all kinds of sports are very well documented and investigated, the long-term effects of single and recurrent ankle sprains are still partially hidden and underestimated [40].

## 2.4 Rehabilitation after ankle sprains

The rehabilitation process after ankle injuries has a lot of variants that influence the type of exercises, the duration and the clinical interventions. First of all, there is to distinguish between injuries to athletes and injuries that happen in everyday life circumstances with the involved person not acting as a professional (or semi-professional) athlete. The differences in the rehabilitation process are given by the fact, that for non-athletes the pressure for a fast rehabilitation is not as high as for athletes, the time spent with physiotherapists for (professional) athletes is much higher than for non-athletes and that physiotherapy for non-athletes is not obligatory and, in most cases, also expensive. Another huge difference that influences, not the rehabilitation, but the full recovery is that, in a lot of cases, injuries that happen to non-athletes in everyday life circumstances didn't even receive medical attention because they are not perceived as serious enough and are thought to heal from its own. As it will be described in this section, this is clearly not the case and the importance of precise exercises and techniques are essential.

Another important aspect that has to be addressed, is the definition of the involved ligament or ligament group and the severity of the tear in those ligaments [15]. These aspects influence, not the type of exercises that are done during the rehabilitation, but the duration of the different phases and the duration until a full recovery. Obviously, a more severe tear in the ligament needs more time for the collagen fibres in the ligament bundles to restructure and completely heal. This implicates an elongated resting period, a longer period where exercises with no or minimal load on the injured foot are performed and a slower progression to balance and strength exercises.

Due to physiotherapists, the rehabilitation process after ankle injuries can mainly be divided into three phases: acute phase immediately after the injury, resting phase whit exercises with no or minimal load and finally the strength and balance phase where progressively more weight is put on the injured ankle that should lead to a full regain of pre-injury balance and stability. The lack of consensus [41] for the progression to the next phases of the rehabilitation process and on return to sport is a huge problem and will be assessed in this work. These conceptual differences lead also to different rehabilitation programs and different progressions. The following research on the rehabilitation process after ankle injuries will therefore contain different methods based on the medical literature and based on opinions and experiences of involved athletes and physiotherapists and will focus on acute ankle sprains.

### 2.4.1 Acute phase

The acute phase begins immediately after the injury and is characterized by symptoms like pain, swelling, tenderness, bruising and inflammation around the involved foot that can lead to difficulties in moving and bearing weight on this same foot. The inflammation subsequentially can cause swelling, oedema, hyperalgesia and erythema. Throughout the first 4-5 days a very popular approach to handle and reduce the symptoms are the so-called R.I.C.E and P.R.I.C.E methods [42]. The acronyms stand for Protection, Rest, Ice, Compression and Elevation and define the different components of these treatment paradigms. The Association of Chartered Physiotherapists in Sports and Exercise Medicine (ACPSM) created guidelines for the management of acute soft tissue injuries using the P.R.I.C.E. methodology [43]. Rest comes together with Protection and is required to reduce the metabolic demands of the injured tissue and thus to avoid increased blood flow. It is also needed to avoid stress on the injured tissues that might disrupt the fragile fibrin bond, which is the first element of the repair process. Here, different types of ankle supports and ankle orthosis come to play in order to stabilize the ankle joint. The application of Ice or any other method to reduce the skin and muscle temperature, reduces the blood flow and oxygen saturation and consequentially facilitates the capillary outflow in healthy tendons. Cooling the inflaming tendons also decreases the perceived pain. Compression is applied to limit the amount of oedema caused by the exudation of fluid from the damaged capillaries into the tissue and the goal is to stop haemorrhage and reduce the swelling. Controlling the amount of inflammatory exudate reduces the amount of fibrin and ultimately the production of scar tissue and helps to control the osmotic pressure of the tissue fluid in the injured area. Lastly, Elevation of the injured body site lowers the pressure in local blood vessels and therefore limits the bleeding. Elevation also facilitates the drainage of the inflammatory exudate through the lymph vessels. The duration of the acute phase and the consequential methodology to treat the patients can vary from just a few days up to several weeks. It highly depends on the severity of the tears in the tendons. Usually, the Resting phase is stopped when the inflammation and the swelling reduce and the patient is able to move the foot [44].

### 2.4.2 Optimal Loading

Throughout the years, the P.R.I.C.E. methodology was adjusted and updated. The major change in the dogma was the substitution of the Rest phase, with a phase of Optimal Loading. The new method, therefore, is called P.O.L.I.C.E. and includes early physiotherapeutic exercises under the so-called Optimal Loading [45]. Even though a short period of rest and unloading is required and is beneficial for the recovery, it should be of limited duration and restricted to immediately after the injury. A longer relaxation of the involved tissue is harmful and produces adverse changes to tissue biomechanics and morphology that consequentially can develop joint stiffness and muscle weakness [46]. Indeed, early activation of the cellular response to mechanical loading promotes structural changes in the tissue. In fact, this is called mechanotherapy and is the reason why doing exercises during physiotherapy helps to restructure the injured tissue, and the idea behind this type of method is to start with it as early as possible. A randomized control trial [47] tried to compare an accelerated intervention incorporating early therapeutic exercise after acute ankle sprains with a standard protection, rest, ice, compression, and elevation intervention. The trial analysed the outcome of 101 patients with a grade 1 or grade 2 ankle sprain. For the participants of the exercise group, exercises were prescribed for 20 minutes, three times a day, and focused on increasing ankle range of movement, activation and strengthening of ankle musculature, and restoring normal sensorimotor control. The results showed that an accelerated functional treatment, incorporating therapeutic exercises during the first week after an ankle sprain, produced significant improvements to short term ankle function compared with standard treatment. As seen, there are benefits from an early application of a functional treatment, the difficulty stays in the exploration and definition of the optimal loading that can be applied to the injured tissue, because if tissues are stressed too aggressively after an injury, the mechanical insult may cause re-bleeding or further damage, which could be worse than not doing anything [47].

Since there is no one-fits-all definition of how much a patient can and should do in terms of early physiotherapy, a balanced and incremental rehabilitation program needs to be created for every single case. Nevertheless, there are some guidelines and key concepts that can be applied for all types of exercises that try to optimize the loading on the injured tissue. A definition of optimal loading can be given as the load applied to structures that maximize physiological adaptation [48]. The applied loading is highly dependent on the tissue type, the pathological severity and presentation and the required tissue adaption for eventual activity. In this paper, the mentioned loading variables are the magnitude of the load, the direction, the intensity, the duration, the frequency and the nature of the mechanical load. Based on the conditions, the goal for the clinician is to combine and weight the loading variables in order to find the best possible outcome and to identify and progress the optimal level of difficulty of a movement or exercise that provides significant mechanical and neural stimulus while preventing poor quality, rigid movement or excessive overload of the injured tissue [48].

Early functional rehabilitation of the ankle should include range-of-motion exercises and isometric and isotonic strength-training exercises [49]. Typical range of motion exercises (see Figure 8a-d) in this phase are passive range of motion exercises where the clinician applies light pressure to facilitate the stretch, Achilles tendon stretches with the use of medical towels and the Alphabet exercise, where the patient performs movements of the ankle in multiple planes of motion by drawing the alphabet letters in the air. Strength Isometric and isotonic exercises such as Plantar flexion, Dorsiflexion, Inversion and Eversion, toe raises, heel walks and toe walks can be performed by using immovable objects as resistance or with the help of weights and the help of the clinician. These exercises did not necessarily need the assistance of a physiotherapist and are therefore also recommended for a home workout. The time per repetition goes from 15 to 30 seconds and the exercises should easily be performed 3 to 5 times a day. For all the exercises the use of a semirigid orthotic may provide somatosensory benefits and neutral alignment for proper muscle activation and reduce unnecessary strain on already stressed soft tissue [49].

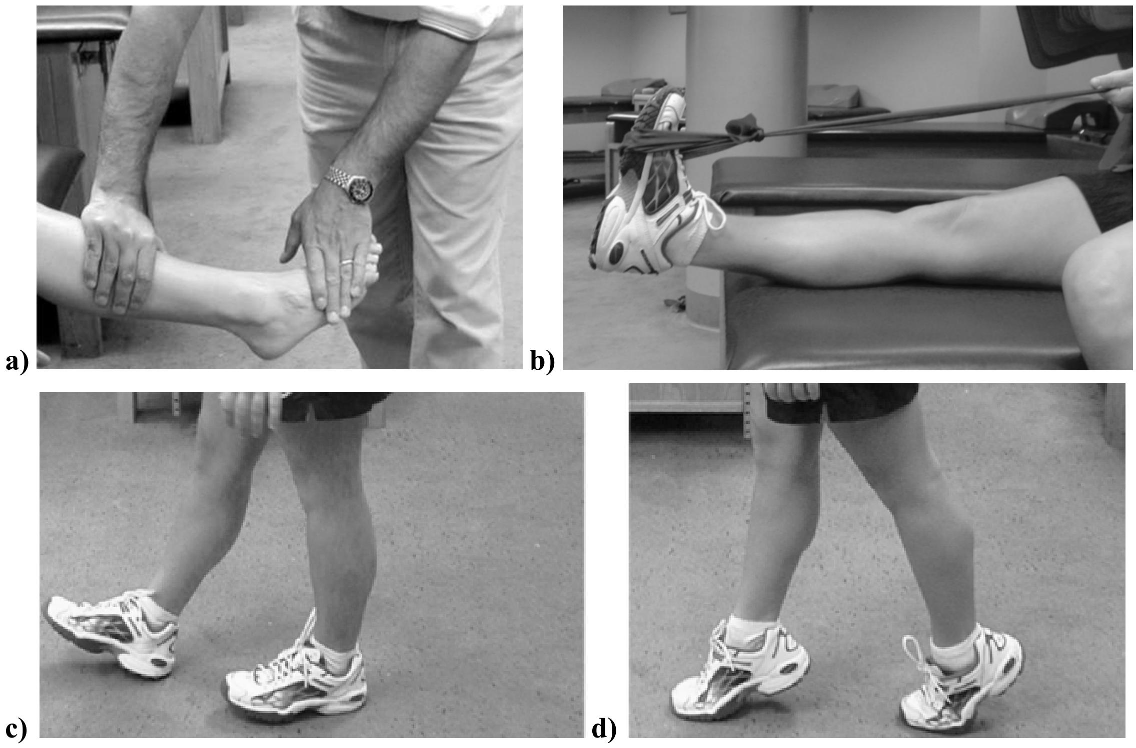



**Figure 8 Optimal loading exercises taken from [49]. a) Manually applied perturbation into inversion; b) Non-weight bearing Achilles stretching with an elastic band; c) and d) heel and toe walking**

### 2.4.3 Strength and balance exercises

With the introduction of the phase with optimal loading and functional treatment exercises, there is a smooth progress to the next phase of the rehabilitation phase. It can be seen as a progressive adaptation of the optimal load until pre-injury strength and balance is reached. In this phase, it is important to consistently increase the loading variables but keeping an eye on not overloading the tissue. The exercises in this phase consist of specific exercises to increase muscular strength in the injured tissue, but there should also be exercises aimed at the overall fitness of the patients. In this stage of rehabilitation, a progression of proprioception-training exercises should be incorporated. The progression criteria to these types of exercises is, in most cases, nothing more than the perceived pain of the patient. When the patient achieves full weight-bearing without pain, proprioceptive training for the recovery of balance and postural control is initiated. At the beginning of this phase, weight exercises can be performed in water in order to reduce compressive force and give extra support to the injured tissue. For the exercises outside the water, one of the most used devices is the wobble board (see Figure 9). It is used to destabilize the patient while standing on one or two feet. This activates all the muscles around the foot and in the leg to maintain balance. While standing on such wobble boards or other uneven surfaces, the patient is asked to perform different dynamic activities with other devices such as weights, medical balls and elastic bands. When the patient feels no pain while walking and the distance isn't limited anymore, slow jogging combined with cycling is initiated. Jogging then progresses to running, backwards running and direction changes. When arrived at this point, activity-specific exercises can begin in order to start the reinstation in the normal team or single training sessions. Therefore, the last steps should focus on sport-specific activities to prepare the athlete for return to competition [49].

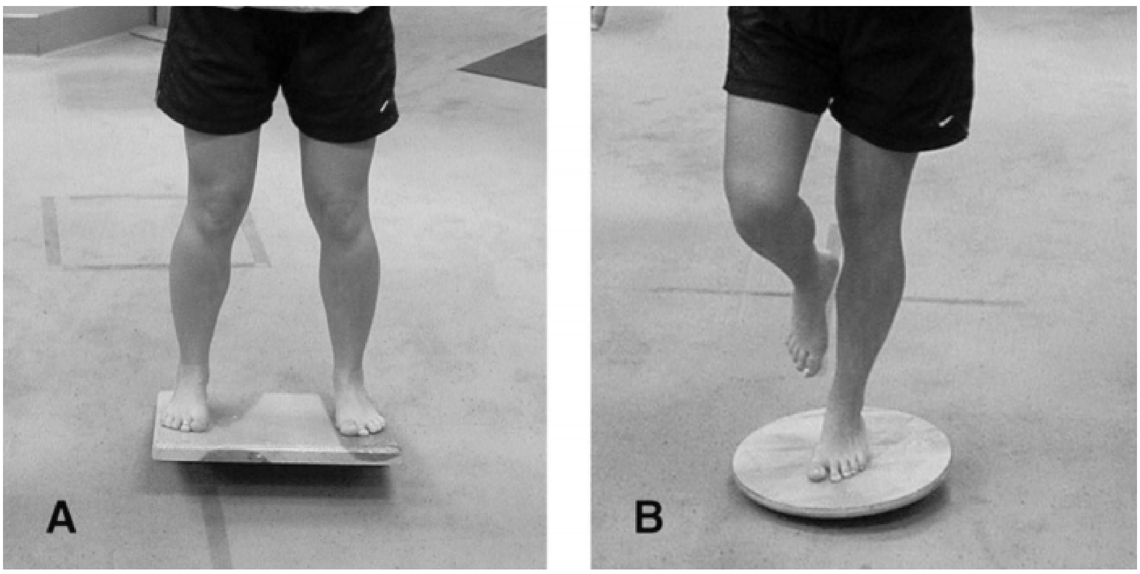



**Figure 9 Balance exercises with the use of two different balance boards [49]**

### 2.4.4 Return to sport decision

The decision to return to full practice and to be eligible to play in matches is probably the most delicate decision during the whole rehabilitation process. The decision is so difficult because all the involved parties have different ambitions, necessities and pressures. On one hand side, there is the willingness and also the pressure for the involved athletes to miss less possible playing time, and on the other hand, there is the health of the athlete, which should, but is not always the case, be the dominant aspect of this process. In the middle, there is the physiotherapist who should, in theory, give an objective view and who, in the end, is the one that has to give the green light for the player to go back to full practice. In theory, because he or she is exposed to the same pressures as the other involved parties. It is therefore necessary to find the balance to not rush the athletes back to normal activity but keeping in mind that the need of the organization and the ambition of the athletes is to come back from the injury as early as possible.

In order to clean the table and to standardize these procedures, a congress in Sports Therapy was held in Bern, Switzerland, in 2016 to define a consensus statement on return to sport [50]. The consensus statement is divided into four main sections and contains the definitions related to RTS and the sports participation context, models to help understand and guide the RTS process, evidence to inform RTS decision-making and priorities for future research.

To better define the steps and the actions during the return to sport phases, the continuum RTS-phase is divided into three elements: return to participation, return to sport and return to performance. With the last element to be the desired success of the complete rehabilitation phase.

The second phase describes three theoretical models that can help clinicians to make sense of the different factors that influence return to sport outcomes and aim to bring consistency and transparency in the return to sport decision making process.

The first model is The Strategic Assessment of Risk and Risk Tolerance (StARRT) framework [51] (see Figure 10). This three-step model should guide the RTS decision by estimating the risk of different short- and long-term outcomes associated with RTS and factors that may affect what should be considered an acceptable risk within a particular context. Athletes should be cleared to return to sport when the risk assessment, containing tissue health (step 1) and the expected cumulative load on the tissue (step 2), is below the acceptable risk tolerance threshold influenced by contextual factors (step 3).

The second model (see Figure 11) is the Biopsychosocial model and it aims to address the best interests of the athletes since it provides all involved stakeholders with a framework for considering biological, and psychological factors that influence the athlete during this process.

The third mentioned model aims to maintain the optimal loading during the rehabilitation phase. An example is made with the so-called Goldilocks approach [52]. The approach monitors the load of one training week against the average of the preceding four training weeks. This acute : chronic workload ratio should be progressed until a full load is reached.

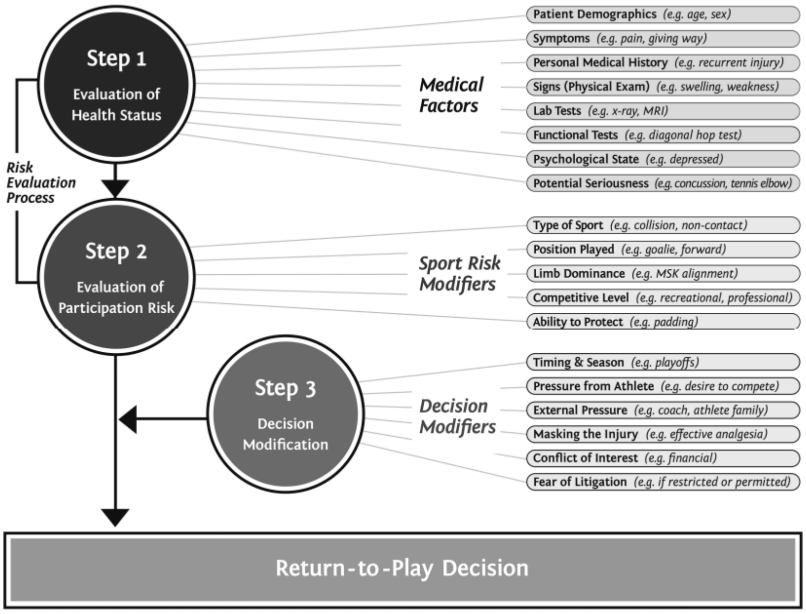



**Figure 10 Illustration of the three-step return-to-play (RTP) framework. This framework groups factors responsible for RTP according to the sociological source of the information (medical culture, sport culture, personal decision modifiers). [51]**

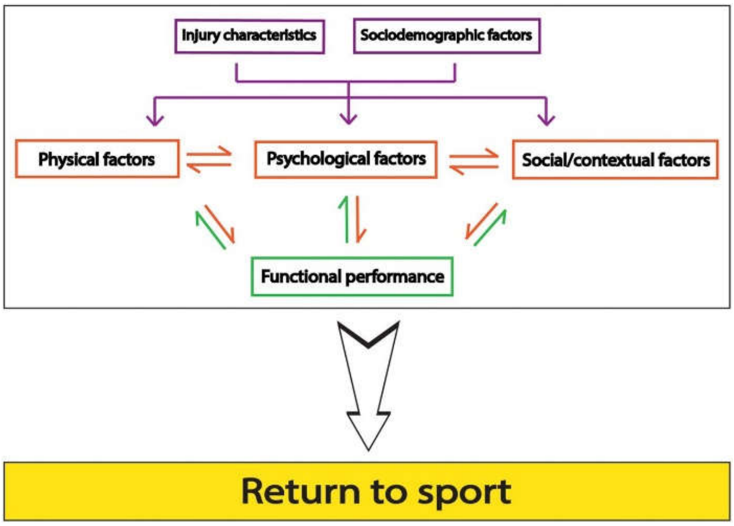



**Figure 11 Biopsychosocial model of RTS after injury.151 Examples of physical, psychological and social factors that may influence RTS are listed. [53]**

These three models should guide the involved athletes and physiotherapists during the RTS phases until the decision to complete the rehabilitation phase. Indeed, the third section of the consensus statement tries to identify the evidence to inform all parties about the RTS decision. In this section, the readiness to return to sport is analysed for commonly injured body parts, but unfortunately, ankle sprains are not mentioned. The criteria for return to play after ankle injuries are therefore analysed using a systematic review [41] published in 2020. The authors identified 8 different, and with different magnitudes of shared consensus across the included papers, domains that are analysed as criteria for return to sports activities. The domains are Pain and Swelling, Range of Motion, Strength, Static Balance, Dynamic Balance, Running, Sport Specific Movements and Patient-reported Outcomes. Inside these domains, the single included studies define criterion thresholds to assess the state of the athlete. While some thresholds are defined by subjective criteria, such as “Ability to balance without pain” [54], “Run at max speed without pain” [55], “Little to no pain while running” [56], “Ability to complete the test with little to no pain” [54] other thresholds are defined by exercise specific achieved results. Examples here are “10 successive heel rockers” [57], “Star excursion balance test result same as for uninjured leg” [57], “Consistent T-test time between 8.9 and 13.5s” [58] and the “Ability to take 3 steps and return and the to complete 6 hops” [59]. As seen, there are tables, programs, protocols and timelines that should be followed before returning to sport, but what is evidenced in this review, is the lack of consensus regarding the covered domains. In fact, a consensus was reached only regarding the need to assess sport-specific movement (90.9%). A partial agreement was reached regarding the use of a hop test (54.5%) and the need to assess static balance (63.6%), but for both, there is little consistency as to which test should be applied to assess the situation. A second problem is that, even though there is consensus about the application of some tests and exercises, no consistency was noted among the included papers regarding objective thresholds, leaving the return to sport decision open for subjectiveness, influences and pressures from other stakeholders. Even though in the consensus statement ankle sprains are not mentioned, the summary for other frequently injured body sites about the criteria for returning to play is the same as mentioned in the systematic review. In fact, further priorities and future directions are shared across the two papers. Both mention the importance of clear definitions, the identifications of prognostic factors for return to play outcomes and the identification and validation of tests to guide return to sport decision making.

To conclude, all the shared points and also controversies show the importance, but also the difficulty, to get this decision right. And the fact that there are so many different approaches, tests, evaluations and other subjective and objective inputs highlight this even more. By speaking and listening to different physiotherapists this whole debate is summarized as follows: you can have as many tests as you want, but in the end, the evaluation of the whole rehabilitation pathway (some physiotherapists called it rehabilitation experience) is the answer to the return to sport decision.

### 2.4.5 Psychological aspect and adherence to therapy

Nearby the identification of adequate and useful exercises, two other individual factors influence the outcome of a physiotherapeutic rehabilitation pathway: the motivation of the patient and the adherence to the therapy. As it will be described in this section, these two factors are highly correlated to each other, but both of them are necessary for positive physiotherapeutic results. Before starting to describe these factors, a short consideration needs to be done as in the case of the application of physiotherapy, because also in this case the difference between athletic- or sports-correlated physiotherapy and casual physiotherapy needs to be addressed. When an athlete gets hurt, he or she has to face completely different challenges and difficulties as a non-athlete. The differences start from the time-consuming factors, passing through emotional and personal factors and end with the desired and expected outcome. With the obvious regard to the severity and the type of the injury, these differences are clarified. An athlete, for example, has no other choice than to do physiotherapy after an injury, while a non-athlete needs to find the time for doing it. Then the emotions and personal aspects come into play, with clear differences. As already seen, athletes are under high pressure when it comes to injuries due to uncertainty for the future for more severe injuries, the rush to be back as soon as possible, eventual fallbacks, the personal sense of giving up or the sense of giving up on the team and the emotional aspect of not being able to do what one loves and what drove him or her to be where they are. For non-athletes, these aspects are quite different, because they need to handle the combination of work, personal life and physiotherapy, therefore fatigue, distractions, mental absence and lack of motivation are possible barriers to overcome. In the end, there is the expected outcome of the therapy. While for a non-athlete an acceptable state with no or even minimal pain could be enough for itself to define the physiotherapy as concluded, a professional athlete is required to continue until the perfect health state is reached and the performance is as good, if not higher than before the injury. There is the necessity to keep in mind these differences when general motivational aspects are analysed to increase the patient's adherence to the therapy.

The question about how to increase this adherence, come together with the question about how to increase the motivation of the patient to constantly perform rehabilitation exercises. Both questions share similar answers as they are influenced by emotional and psychological factors. Understanding these factors and their relationship is essential for the definition and integration of new physiotherapeutic models and methods.

Adherence can mainly be divided into two categories, clinic-based adherence and home-based adherence [60]. Clinic-based adherence consists of both, an indicator of clinic attendance at appointments and an evaluation of the behaviour during the treatment sessions. While the first is easy to measure, the second one is a subjective observation by the clinician. In order to standardize these observations, in 1995 the Sport Injury Rehabilitation Adherence Scale (SIRAS) was introduced [61]. The scale includes three observations that define the measure. The physiotherapist should evaluate the following three questions on a scale from 1 to 5: How was the intensity with which the patient completed the rehabilitation exercises during today's appointment (minimum to maximum effort)? During today's appointment, how frequently did the patient follow your instructions and advice (never to always)? How receptive was this patient to changes in the rehabilitation program during today's appointment (very unreceptive to very receptive)? The resulting score can be collected and the physiotherapist can track the patient's adherence over the whole rehabilitation period and intervene if necessary. This can be done for clinic- and appointment-based treatments, but, since the success of many physiotherapeutic programs is reliant on patients undertaking prescribed activities at home, it is also necessary to keep track of the patient's adherence to these types of exercises. Different to clinic-based adherence, in this case, the patient itself needs to judge and evaluate its own effort and dedication. Simple questionnaires or measurements scales may not be sufficient for good and reliant answers by the patients, therefore (digital) diaries were and are used for recording each time exercises or other treatment activities are performed. But, even more important than the care of the diary, personal and retrospective feedback talks between patient and physiotherapist are essential to measure home-based adherence. After seeing what adherence is and how it can be defined, barriers to treatment adherence and possible strategies to overcome these barriers were analysed with the help of a systematic review published in 2010 [6]. The review included twenty high-quality studies, each of them investigating barriers to treatment adherence in musculoskeletal injuries. The summarized results from these studies show that low levels of physical activity at baseline or in previous weeks, low in-treatment adherence with exercise, low self-efficacy, depression, anxiety, helplessness, poor social support or activity, greater perceived number of barriers to exercise and increased pain levels during exercise are barriers to treatment adherence. As for the authors of this review, each physiotherapist should be aware of these circumstances and react if they affect the patient's therapy. For example, physiotherapists need to better understand the felt pain by the patients and clear up and inform the patients believes that pain is not always harmful. Exercises should also start gently and then increase step-by-step to moderate and high intensity to counter the fears that a movement could cause damage or re-injuries [62]. Furthermore, patients with a low physical activity level need even more attention, dedication and presence than other patients. In this case, physiotherapists need to give even clearer explanations and instructions on how the exercise should be performed and even more (positive) feedback about how the exercise is going. Self-efficiency can be increased with strategies such as the definition and the agreement on realistic expectations and the setting of predefined treatment goals [63]. For patients that present anxiety, depression or have poor social support strategies to increase the treatment adherence could be the inclusion of group-based rehabilitation exercises, the addition of coping plans and the development of a good physiotherapist-patient relationship.

## 2.5 Digital rehabilitation

These mentioned strategies are some sort of classic physiotherapeutic solutions, but with the increasing technological evolution also the approach to physiotherapy underwent some modifications. This next section therefore will focus on how the physiotherapeutic approach changed, or is about to change, in the digital era, what are new used techniques and the possibilities that come with them.

The initiator of this revolution was the possibility to precisely measure the patient's movement and quality of movement with sensors, image acquisition and image processing. This precise information acquisition started to create an enormous amount of data that can be analysed by physiotherapists and supported by newly introduced figures, such as biomedical engineers, biomedical informaticians and big data analysts. The advent of these figures and the introduction of new objective measurements allowed the whole rehabilitation pathway to be characterized by interdisciplinarity, where physiotherapist, orthopaedists, doctors, trainers and specialized therapists can share their knowledge and speak on the same objective and evidence-based level of information in order to create a shared and patient-specific "experience". This whole process should, as said, be shared by all stakeholders but, most importantly, by the patient itself. The good thing with all these new possibilities and measurements is that the patient now can personally see its own process and progress and not be dependent on what physiotherapists or other clinicians say. The objective test and exercise results show the state of the pathway and patients can control and keep track of it, increasing consequentially the adherence to the therapy and the personal motivation.

In the following, two from the European Commission funded projects in the field of digital rehabilitation are presented as examples of the digitalization of healthcare. When with the first project a telerehabilitation method is presented, with the second project, in the next section, the application of serious games for rehabilitation purposes is introduced.

The first project is the Rehabilitation Hub: The World's first Digital Recovery Therapy [64]. The objective of the project was to implement a telerehabilitation solution that offers support for diagnosis and delivers effective, personalized therapy for chronic musculoskeletal disorders (MSD) patients. With wearable sensors and intelligent algorithms, physiotherapists can create a patient's specific rehabilitation program based on objective measurements of the patient's muscle strength and joint movements and observe, stay connected and eventually modify the program or exercise from remote. Two main obstacles were overcome during the testing phase of the project. First, the lack of objective and innovative measurement tools to monitor, control and clinically evaluate pathologies; and second the unfulfilled demand for a system that contemporarily involves patients, physicians and physical therapists during the rehabilitation process. In the end, two modules were developed. The Lynx ROM, for joint motion analysis, and the Lynx DYNAMO, for the analysis of applied force. The first module consists of two to four inertial sensors that can be placed on any joint on the body, measure the maximum and average range of motion and the movement speed and output the harmony of movement and position vs. speed graphs. The second module consists of one sensor that measures the applied (maximum and average) load and can be used to measure the time to reach the maximum load and the maintenance time on this load. All the data captured by the sensors is sent in real-time to a PC or Tablet, where a software automatically quantifies all the key parameters of the movement and outputs different types of visualizations and analysis of the current training session and exercise. With an automatically created final report, the patient and the physiotherapist can track the achieved progress over the different training sessions and interpret together the results. For home-based exercises, the data is directly sent to a ReHub cloud platform where an effective communication between physician, physiotherapist and patient can be established.

### 2.5.1 Serious Games

The second project introduces a fundamental aspect for this diploma thesis and for the digitalization of rehabilitation: the application of serious games in the medical sector. But before taking this second project as a best-practice example about how such projects needed to be structured, the newly introduced concept is better explained.

The term Serious Game as it is used nowadays was first mentioned by Ben Sawyer, CEO of American development company Digitalmill and co-director of the Serious Games Initiative, when he commented the great success of the video game America's Army by saying that "*Americas Army was the first well-produced serious game that found real success among the general publ*ic" [65]. It was possible to download the game for free and it offered simulations of military training exercises and combat missions. The serious concept behind this game was not the serious environment in which the game was played, but the fact that the best players were sent a letter with an invitation for an application to the real American army. The purpose of the video game, therefore, was to promote the image of the army and to serve as a recruiting tool. This game was seen as the origin of serious games, but it was shown that there were many other scenarios where games were used for more serious approaches than just for fun and entertainment, for example, there were early games used to illustrate a scientific research study, designed to train professionals or to broadcast a message [65]. After the success of America's Army the Serious Game Initiative, launched by Ben Sawyer, described the concept of serious games as follows [66]:

> *"The Serious Games Initiative is focused on uses for games in exploring management and leadership challenges facing the public sector. Part of its overall charter is to help forge productive links between the electronic game industry and*

*projects involving the use of games in education, training, health, and public policy."*

When this is a more general description of the concept behind serious games, a more technical description can be given by defining that the purpose of serious games is to get users to interact with an IT application that combines aspects of tutoring, teaching, training, communications and information, with a recreational element and/or technology derived from video games. This combination aims to make practical and useful content (serious) enjoyable (game). It is achieved by developing scenarios that are at once practical and enjoyable [67]. A visualization of the concept is shown in Figure 12, where serious games represent the intersection between educational contents, serious purposes, game techniques and a fun and storytelling aspect. Given these descriptions, in 2004, at the Serious Game Conference at the Game Developer Conference, the main market segments in which serious games could provide solutions to the clients were identified in the higher education, health care, corporate, military, non-government organizations and some other sectors such as journalism and politics [68]. When these are still the sectors in which serious games are mainly used, there is quite no limitation towards the application of serious games in other sectors.


**Figure 12 Context of application of Serious Games [69]**

But, in order to be successful, the balance between the fun and the serious aspect needs to be achieved. Without this balance, the game will not achieve the full effect of the serious purpose or will not be entertainable enough and the game will not be played or the playing did not distract the user enough from the underlying serious purpose [70]. Therefore, it is important to define a framework where serious games can be inserted and that contains all the important aspects that need to be considered when such a game is implemented. A proposed model [71] identified 7 characteristics that make up the conceptualization of a serious game used for learning approaches. These are the cognitive, psychomotor, and possibly effective skills which the user is to develop as a result of playing the game (Capability); the subject matter that is intended that the user should learn (Instructional content); the intended learning outcomes; the implemented game attributes and the game genre; learning activity designed to keep the user engaged during the game; the reflection of the learning activity by thinking about the purpose of the game; and finally the game mechanics and the game rules.

Since these characteristics are slightly different when a serious game is applied in the medical sector, the next two sections introduce this particular and, for the sake of this diploma thesis, very important field of interest.

### 2.5.2 Serious games for rehabilitation purposes

As seen, the term serious game is used to describe the usage of a (video) game with the purpose of it going further than just entertainment and fun. This more "serious" purpose, in this case, is of medical aspect. This new approach tries to take the joyful, entertaining, distracting and challenging part of a game and include it in an exercise in a physiotherapeutic context with the goal to increase the patient's motivation to perform the exercises and therefore the adherence to the prescribed therapy.

Before analysing the specific case of the application of serious games in ankle sprain rehabilitations, this next project is used to give an overview about what are the general goals and barriers that are faced when using this new approach during a rehabilitation pathway and what are the necessary steps for the conceptualization of such a project.

The REHAB@HOME project [72] is a game-based biomedical monitoring solution for upper body rehabilitation, especially the movement of the arms, the grip and the wrists for stroke patients. The main goal for this project was to enable elderly people to enjoy high-quality rehabilitation for a much longer period than the Health System can afford. Because of the elongated duration of the rehabilitation for over half of stroke survivors, only a small part can be done within acute-care hospitals and medical facilities. The rest is done in collaboration with a physiotherapist, but the invested time and the conditions are not comparable with those in equipped medical centres. Therefore, within the setting of this project, the adoption of suitable technical aids at home, together with a proper training program, can help reduce the patient's stay at the hospital as well as the need for moving him/her between home and a physiotherapy unit or a paramedical structure. This means, transforming the patient's home into a place where the physical and cognitive rehabilitation process can be performed in an intensive and controlled fashion. The basic project idea was inspired by existing commercial platforms, like Wii and Kinect, that allow the user to act within a virtual environment and interact with other users, thanks to special input devices and suitable technologies able to monitor the real environment and track the user's behaviour. The process for the creation of this specific serious game is exemplary for the implementation of game-based rehabilitation exercises and contains, and should contain, the following considerations:

1) In-depth knowledge of the rehabilitation operational context. This means, to study and observe the actual rehabilitation process, to identify the patient-specific diseases, disabilities and needs, the definition of a set of representative use and test scenarios and the adoption of a robust requirements engineering procedure

2) Definition of the rehabilitation platform with all the technical specifications and the design of the game-based solution, including the whole set of stand-alone devices components (sensors, actuators, textile items, communication modules, interaction, visualization and storage devices, etc.) that are needed for the setup of the serious-game

3) Assessment of the rehabilitation platform with testing and evaluation of each prototype with patients and professionals

4) Definition of an exploitation, development and commercialization plan by identifying the actual potentialities of the project outcomes in real life. This stage should also include the definition of a "service model", i.e., the most suitable way to integrate the new rehabilitation service within the portfolio of existing public healthcare services

5) Scientific validation of the patient's health improvements by comparing them to alternative rehabilitation concepts from existing therapy, physiotherapy, and neurophysiology methods

All these steps and definitions are needed to create a medical product with advantages compared to already existing approaches and methods. These are also the steps that were followed for the creation and conceptualization of this diploma thesis.
In this project, after the definition of the operational context and the definition of the objectives and the hardware devices, the implementation of a series of games was done. As already mentioned, the Microsoft Kinect technology was selected for the registration of the patient's movement registration and a total of six different games (see Figure 13) were developed.


**Figure 13 Different game scenarios used for rehabilitation purposes [72]**

Each of the games is accessed by patient hand movement to select, move, drag and drop objects inside the game. The games have been designed to be fun, motivating whilst stimulating both physical and cognitive development. They have been co-designed with both patients and medical professionals so that they can not only be played safely at home but also provide important data to the clinicians on the capabilities of the patient. Clinicians can thereby adjust the complexity or difficulty of the game to suit the patient development. The prototype of the serious game was iteratively evaluated, tested and modified during the first two years of the project with the setup of two pilot studies involving small groups of patients and their respective physiotherapists and a final trial was conducted in the third year at two rehabilitation clinics in Italy and Austria. 19 patients were involved in the final trial and performed 12 therapy sessions each. One session lasted 30-40 minutes and the participants played 5 days a week until 12 sessions had been played. With the hand of post-session questionnaires including user experience/satisfaction questions for the patients and system usability scale (SUS) questionnaires for physiotherapists, the acceptance and usability of the serious game were assessed. Overall, the owners of the project summarized the results by stating that "*the devices and games proposed to patients, caregivers and therapists were positively accepted. Several indications for improvements were also provided, mainly addressing the need for supporting calibration of the solutions to the range of motion and specific needs of patients, customization of the games, visual and audio elements of the games, motivational strategies to better engage patients and provide feedback on progress during therapy, support for collaborative forms of play. Further conceptual and usability advancement of the clinical interface for therapists were also uncovered during the prototype evaluation*". The motivational aspect together with the usability and user satisfaction stayed at a high level for two and a half weeks where the system was tested, indicating that the level of maturity of the integrated prototype released is quite good to support future deployments in real-life settings.

The positive feedback and obtained results led to the definition of an exit strategy and the try to enter the open market which is still ongoing [72].

# 3 State-of-the-Art-Research (STAR)

Now that the process of creating the concept and the serious game itself is clear, solutions for serious games used in the context of ankle sprain injuries are presented. This state-of-the-art research should elucidate the potential in this particular context and analyse what was already presented and published and how these solutions are used on the field. The state-of-the-art research includes three specifically developed applications for the sake of foot-injury rehabilitations and the use of conventional Xbox games in combination with the Xbox Kinect for the increase of balance and stability of the ankle joints.

The first one is The Mobile RehAppTM [73], an Augmented Reality (AR) based application for mobile devices. It offers different types of Range of Motion (ROM) exercises and allows the monitoring of the user's performance. The Mobile Augmented Reality (MAR) technology is used to track markers located on the feet of the user and translates their movement into interactive elements of a mobile game application without the need of using a game controller or additional sensors to operate. The application can be used to simulate two types of rehabilitative exercises, the so-called Alphabets and the Windshield Wiper (Inversion and Eversion Movement of the foot), two exercises where no additional furniture is needed. Both exercises aim to expand the ROM of the injured ankle. The game uses a marker, placed on the user's foot, to track the movement and to translate it in real-time in the application interface. The application consists of

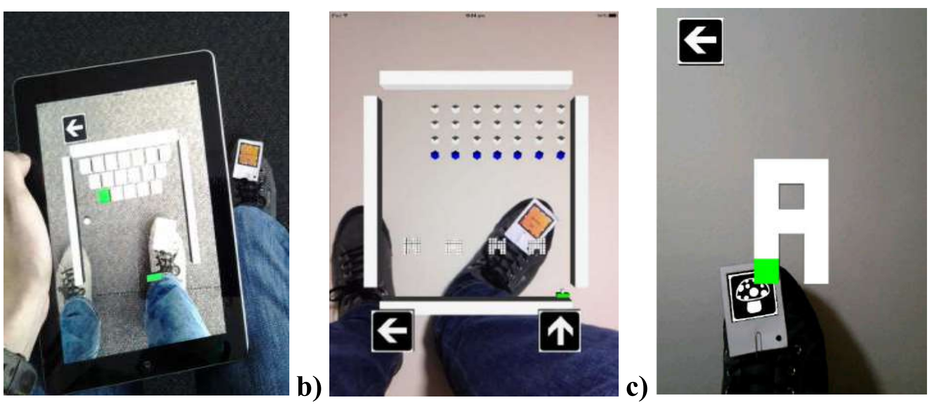

a) b) c)

**Figure 14 Augmented Reality game scenarios from the RehAppTM [73]. a) shows the implementation of the AR-kanoid game; b) shows MARS-Invader game implementation; c) the Alphabet exercise implementation**

three different games: The ABC, simulates the Alphabets exercise (see Figure 14c), The AR-kanoid, a recreation of the Atari's Arkanoid game with a padel that should prevent the ball from falling from the playing field (see Figure 14a) and the MARS Invaders, a recreation of the Atari's Space Invader game (see Figure 14b). The three exercises are played on an Android tablet or iPad while sitting on a chair.

The second application is based on a much more sophisticated and complex tracking method. The AnkleBot [74] by IMT is a frame that goes from the knee all the way down to the ankle with two linear actuators connected between the patient's leg and foot (see Figure 15a). The actuators can serve as both, as help and as resistance. This type of robot allows three types of tests: assisted play, with help of the actuators, resisted play, with the actuators acting a force against the player's foot movement and free play, with no forces of the actuators. The AnkleBot is used for the horizontal and vertical movement of pads in the DoublePong Game (see Figure 15b). The goal of the game is to maintain the ball in the game space by moving the pads and preventing a ball to fall down. This setup allows two degrees of freedom. To transform the elliptic movements of the foot into the quadrangular space of the game, an ellipse parametric equation was used for the calibration of the elliptical space.

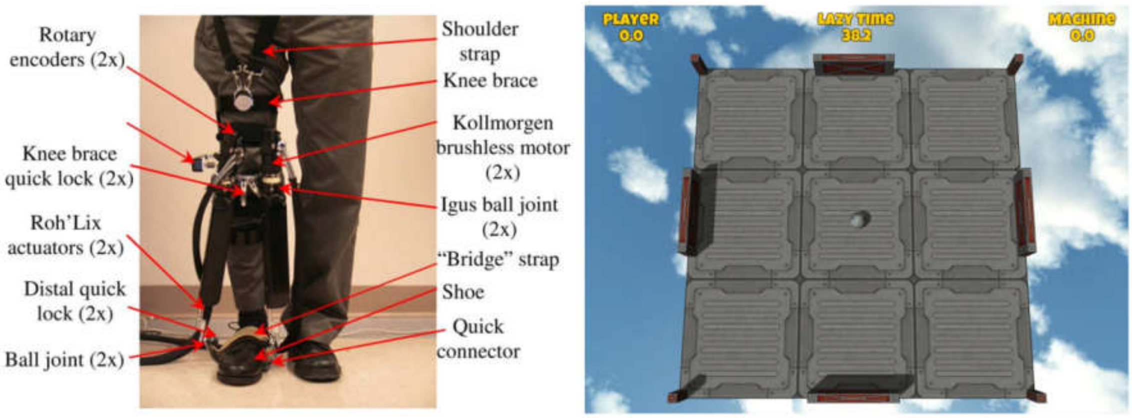



**Figure 15 a) Structure and description of the AnkleBot frame and b) the implementation of the DoublePong game scenario [74]**

A third application is the MoveYourFeet [75] exergame. The MoveYourFeet system is a mobile exergame for a combination of dorsi-extension and plantar-flexion exercises. For motion tracking, two wireless inertial movement units (IMUs) are used and it was developed as a 2D side-scroller game. Since the range of motion (ROM) may vary between users and times, a calibration is performed at the beginning of each session. The game is developed as a movement-based side-scroller game and will use both, the injured and the healthy foot to benefit from the positive effects of the contralateral therapy (see Figure 16). In the game, a ball has to be moved laterally by jumping from one trunk element to the next one. A jumping event is triggered when the user performed one complete repetition, which means a combination of plantar-flexion plus dorsi-extension. This paper includes also a user study where the game is applied to two age-related subject groups. 20 participants were included in the young adults group (18-29 years) and 21 participants in older adults (50-67 years). All participants were healthy and the goal of the study was the analysis of the usability of the MoveYourFeet application. The overall usability was rated excellent and completing the SUS questionnaire both age groups evaluated the MoveYourFeet system equally high. Although the older participants enjoyed the game significantly more, no effect was found for the variables number of repetitions, game duration, and repetitions per minute. While the usability was excellent, participants noted pain in the lower legs after intense sessions of the game. Since the game should be used for rehabilitation purposes, the pain is seen as an effect of the game and therefore with a positive effect.

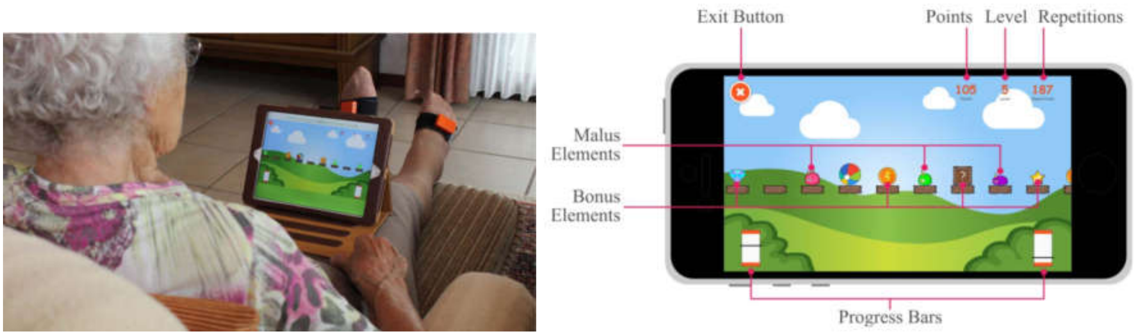



**Figure 16 Setup and interface of the MoveYourFeet serious game [75]**

The last presented article aims to explore the outcomes of Xbox Kinect intervention on balance ability, enjoyment and compliance for previously injured young competitive male athletes [76]. Sixty-three previously injured young competitive male athletes were divided into three groups: one group received Xbox Kinect (XbK) training, one group received Traditional physiotherapy (TP) training, and one group did not receive any balance training (Control). The measurements of the outcomes use the Biodex Stability System (BSS) and are based on the overall stability index (OSI) and the limits of stability (LOS). The games played on the Xbox Kinect are part of the Xbox adventure games and are Rally Ball [77], Reflex Ridge [78], River Rush [79] and 20.000 leaks [80] (see Figure 17a-d). Different games where high reflexes, balance and coordination are needed. The exercises used for the traditional physiotherapy were based on a mini-trampoline and inflatable discs. The analysis of the results, after ten weeks of training sessions for the experimental groups, show significant improvements of both the groups in comparison to the control group based on the balance and stability indexes. Between the two experimental groups, no significant differences were found in these outcomes. Another finding is that the Xbox Kinect intervention led to increased enjoyment and compliance and were perceived as less strenuous and more enjoyable than the traditional balance program. Reasons for positive effects of the games were identified in the sense of achievement by the athletes, the ability to become active participants in the training process and the specificity and frequency of the feedback provided to the participants by the system regarding the actual performance and the achieved results.

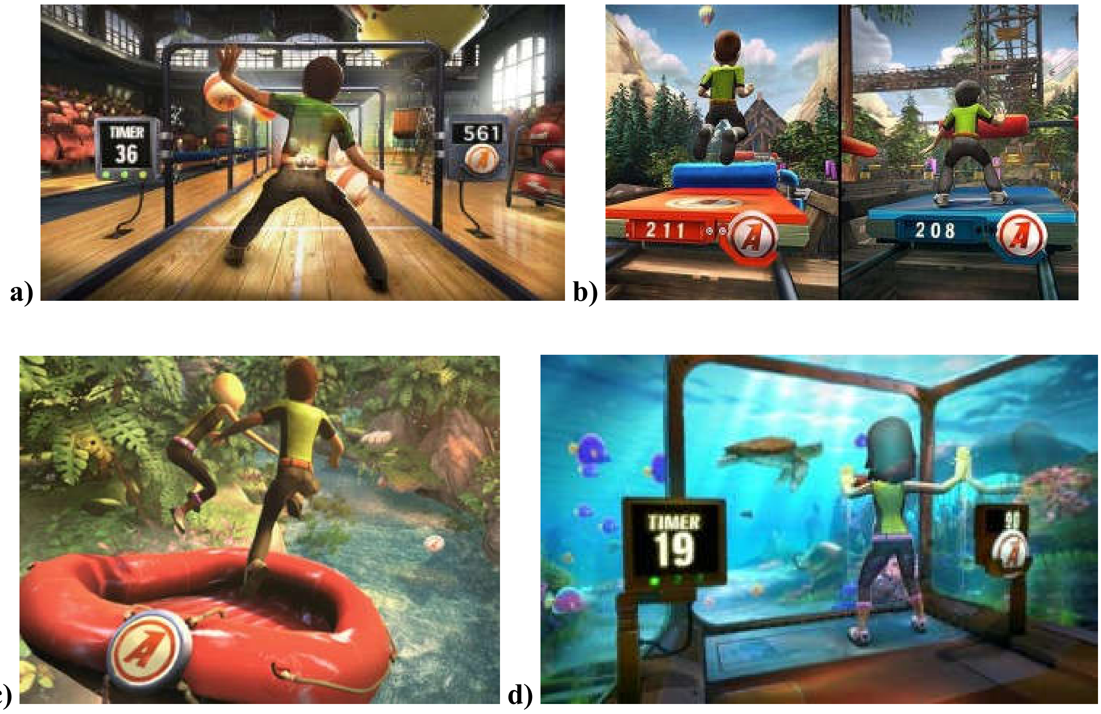



**Figure 17 Used games from the Xbox Adventure Game as part of rehabilitation programs: a) Rally Ball [77]; b) Reflex Ridge [78]; c) River Rush [79]; d) [80]**

As seen there can be different setups for the implementation and application of Serious Games for rehabilitations after ankle sprains, all of them with advantages, but also with limitations. The most positive aspects of the previously presented applications were the recreation of conventional exercises, the motivational aspect by including scores and levels, the allowance of more than two degrees of freedom, the tracking of the process during the rehabilitation and the flexible definition of the difficulty of the exercises related to the actual point in the rehabilitation pathway. But in general, these applications show, that there is still a lot of potentials that can be exploited with well-defined and easy to set up systems and that both the medical and motivational aspects are influenced positively with their application.

In order to judge the presented systems together with the system that will be presented in the next sections (the so-called "*Ankle Runner*"), Table 1 includes the characteristics and fundamental aspects of the five systems. These characteristics are the definition of the underlying technology, the number of degrees of freedom (DoF), the inclusion of a calibration procedure, the amount of different included exercises and game scenarios and their description, and finally a brief description of the main particularities that define the present system. Already with the summary contained in the table, it is possible to see first improvements that the system that is presented in this work brings with it.

**Table 1 Summary of the analyzed systems in the State-of-the-Art Research and comparison to the system that is presented in this diploma thesis ("*Ankle Runner*")**

| | Technology | DoF | Calibra-tion | N° Exer-cises | Description Exercises | N° Game Scenarios | Description of Game Scenario | Particularity |
|---|---|---|---|---|---|---|---|---|
| ***Mobile RehAppTM*** | Mobile Augmented Reality | 2 | No | 2 | Alphabets, Windshield Wiper | 3 | Alphabets, Arkanoid, Space Invaders | No need for other devices, only a smartphone or tablet is needed to play the games |
| ***AnkleBot*** | Robot with actuators | 2 | During runtime | 1 | Dorsi- Plantarflexion + Inversion Eversion | 1 | Double Pong game | Very precise registration of the movement and possibility to apply forces against the ankle movement |
| ***Move-Your-Feet*** | 2x IMU Sensors | 1 | Before Start | 1 | Dorsi- Plantarflexion | 1 | Side scroller jumping game | Training of both injured and healthy foot |
| ***Adventure Games*** | Xbox Kinect | 3 | No | - | No specific exercises, but different balance and stability movements | 4 | Rally Ball, Reflex Ridge, River Rush, 2000 Leaks | Utilization of conventional games used for rehabilitation purposes |
| ***Ankle Runner*** | 1x IMU Sensor | 2 | Before Start | 4 | Dorsi- Plantarflexion, Inversion Eversion, Heel Rises, Knee Squats | 3 | Follow path, Catch trophies, Avoid obstacles | Sport-related game scenarios, the inclusion of a multitude of exercises, possibility to include different rehabilitative tools, possibility to integrate new exercises |

# 4 Results and Methods

Now that the underlying theory is explained, all the mentioned aspects are investigated on the field to identify if the theory applies to reality. This was done with direct observations, personal experiences, talks with physiotherapists and involved athletes and with the creation of a survey aimed to analyse these aspects across multiple sports. Nearby the assessment of the application of the theory on the field, a second aim of the talks and survey is the definition and the identification of requirements to a serious game applied in the rehabilitation process after ankle injuries and the research of confirmation of the utility and usability of such a system. From the start of the work for this diploma thesis, there was the basic idea of the implementation of a simple runner game where the foot can be seen as the joystick of a controller and used for simple rehabilitation exercises. From the state-of-the-art research, it became clear that there already exist systems used in this context, but none of them implemented a game scenario where the movement of a body part translates into a running figure inside a video game. This section, with direct conversations and with the creation of the survey, therefore was used to determine the reproducibility of the idea and to identify further requirements that are necessary for the implementation of such a serious game,

After the transcription of the interview with a physiotherapist of a professional soccer club, the presentation of the results of the survey with 94 participants and the consequent identification of the requirements towards the serious game, this section presents in detail all the steps that led to the final prototype that was tested and evaluated together with physiotherapists and two injured young soccer players.

## 4.1 Theory assessment - Direct conversations with physiotherapists

The questionnaire, which will be described in detail in Section 4.2, was sent to friends that practice sport and also to physiotherapists of all kinds of sports with the gentle question to spread the questionnaire across the organization and the team to gather as many and as differentiated answers as possible. With some of the involved physiotherapists, two of them also of an organization that plays in the first Italian national soccer league, a short discussion came up where they were asked about their opinion and thoughts on the idea of this diploma thesis. All of them gave positive feedback especially underlying the motivational aspect that would benefit from the introduction of a serious game as a rehabilitation exercise. While these were just simple and short conversations, a much more intense and informative discussion was held with a physiotherapist of the F.C. Südtirol, a local football club that plays in the vertices of the third Italian national football league and that was contacted with the start of the diploma thesis. The physiotherapist in question was Gabriele Vanzetta, who works at the organization for 5 years and is responsible for both the youth sector and also the first team activity. The baseline of the discussion was represented by the questionnaire that was sent and that should be filled out by the players, but seen from another perspective, the one of a physiotherapist. The discussion contained general questions about the incidence and the therapy of ankle injuries, the importance of the motivational aspect during the rehabilitation process and the possibility to integrate a serious game application in the context of such injuries. The interview was recorded mid-season in February 2021, translated from Italian and summarized in this section.

"*Until this point of the season*", Gabriele Vanzetta said, "*we had two to three ankle sprains with a low to medium severity. Normally to the end of the season, if it is not an extraordinary year, we can expect to have between five to seven significant ankle injuries. This value, fortunately, is a little lower than the ones that are found in literature and can be traced back to the modern and recently renovated training centre with high-quality pitches and gyms. However, the amount of ankle injuries increases when also all the contusions, which occur at a higher rate than an ankle sprain, are counted. The three ankle injuries were caused by an inversion movement of the foot and two times the lateral and once the medial ligament was involved. These are also the most common injured ligaments and the most common injury mechanism when it comes to ankle sprains. With these types of injuries, the rehabilitation period takes at least two weeks but can range up to 45 days. If the injury happens to an athlete of the youth sector, the recovery time will be slightly higher since more caution is applied for them and also the pressures are lower. Recovery can also be achieved faster, but with significant short- and long-term consequences such as a higher load on the knees, persistent swelling and the possibility of chronic problems that could be of persistent pain and instability*."

"*If a player did not present any known problem or perceived pain*", he continued, "*no specific exercises are performed to strengthen specifically the ankle musculature. The problem here is that ankle injuries are often put in the background and the focus lies more on the knee and other lower limb regions such as the thigh, the groin and the calf. Nevertheless, with core-stability and balance exercises, the ligaments around the ankle are loaded and the musculature is activated. Though in the youth sector the time spent with these exercises is even lower and often if a player shows some problems or feels pain, exercises were prescribed. When an injury happens, the acute phase normally is characterized by the P.O.L.I.C.E methods, where the injured tissue is protected,* *compressed and elevated, ice is put on and initial optimal loading exercises are performed. The goal here is to load the surrounding musculature, peroneus and tibialis, of the articulation in a protected range to keep them activated in order to prevent relaxation. With relaxation, the brain recognizes the weak region and some sort of deactivates the muscles and this is what is tried to avoid with optimal loading exercises in a protected range. Range of motion and isometric and isotonic contractions are performed for around one week. After this week, the ranges and the loads are increased until the athlete feels no pain, the ankle swelling passed away and normal walking is possible. After that, normally for another week, balance and strength exercises are performed with the use of balance boards, elastic bands, weights and by blinding the athletes in order to promote sensitivity in the ankle musculature. We as physiotherapists see the progression of the whole situation across the rehabilitation phase and, together with the feedback of the involved players, when we feel that the ankle is clinically healed, the player can return back to the pick and begin to run, make direction changes and begin to training with specific exercises involving also the ball. When he regains a good physical condition and no pain is felt while running and while training a progressive reintroduction in the team activity is initiated. During the rehabilitation period, players are supervised and followed the whole day, in the morning and in the afternoon and for the home only rest and ice is prescribed. As already mentioned, ankle injuries are the injuries with the highest re-injury rate and are often underestimated and thought that they heal from alone. Obviously, this is not the case and therefore our job is to be as clear as possible with the players and elucidate the severity of the injury and the importance of a well-defined rehabilitation. Exercises of the first phase of the rehabilitation are often annoying, boring and frustrating and it is visible that the players' motivation is not that high and often they are distracted or with the thoughts somewhere else. We all are fully convinced that a higher concentration and awareness towards the exercises while performing it would increase its effect and we already try to force the players to be mentally focused and concentrated during the exercises. For example, lasers are put on the player's foot and he needs to follow lines that are put on the wall with the light of the laser by moving the foot. This is just an example, but the utilization of a videogame where the athlete can perform exercises and be fully concentrated on the exercises would clearly be a benefit. It would also be possible to control the players if the exercises are performed, even when they are at home. Another interesting aspect could be the fact that with a videogame the agonistic soul and each players' ambition could increase the motivation to perform the exercises, maybe also as a competition between other players or with us physiotherapists. Important features that should be implemented in a serious game are the possibility to adapt the range of motion in order to have some progression steps, the possibility to use different medical items such as balance boards and elastic bands, the possibility to put the sensor on different parts in order to register multiple movements and to perform multiple exercises and finally the already mentioned possibility to perform multiplayer type exercises to increase the teams' motivation and competitiveness*."

Gabriele Vanzetta terminates by giving his final considerations and advice by saying that physiotherapists should be better in educating, especially young athletes and to increase their sensibility towards, not only rehabilitation exercises when an injury happened but also towards prevention exercises. He concluded by saying that a videogame definitely could increase the compliance and the motivation of the involved athletes towards physiotherapy and exercise and that it definitely could be a good instrument for both rehabilitation and prevention exercises, especially in the youth sectors.

## 4.2 Theory assessment – Survey

As elucidated in the description of the theory and from the discussion with physiotherapists, the whole process of an ankle injury and the consequent rehabilitation is characterized by a rational and an irrational part. The rational part is given by the injury itself and the, by the medical state of the ankle ligaments and bones dependent definition of the rehabilitation process. The irrational part is the combination of all the feelings, emotions, pressures and other mental aspects that arise during this whole process. To assess both the rational and irrational components of involved athletes a survey was created and dispatched across professional, semi- and non-professional athletes of different sports. After personal information about the athlete (gender, age, sport, team, division/category, position and years as a (professional) athlete, the survey collects responses divided into three sets of questions:

1) The first set contains questions regarding the personal history of the athletes regarding ankle injuries. They should give an overview of the impact of these injuries on the players' careers and how much is done in training to prevent such injuries. Specific questions in this set are, how dangerous the sport, and the played position, are for suffering ankle injuries, the amount, mechanism and severity of suffered ankle injuries and an ordering of body parts based on the risk of an injury

2) The second set of questions is about the rehabilitation process after ankle injuries, which exercises were performed, the time spent on these exercises, how the re-integration in the training happened and the mental aspect during the rehabilitation process. Specifically, these questions should analyse if the rehabilitation process follows the guidelines elucidated in the theoretical part, how the return to sport decision is done across different sports and situations and if there were re-injuries or other complications after this decision was made

3) The last questions consider the utilization of a serious game for rehabilitation purposes and aim to understand the possible athlete's acceptance, usability and thoughts of this new rehabilitation solution. Specific questions consider the feasibility of such exercises inside a video game, the motivational aspect and if it would increase with a video-game-like solution and the importance that different features should be implemented inside the game. In the end, further considerations, indications and personal experiences were collected

The survey was created with the online survey tool SurveyHero (www.surveyhero.com) and was shared on different platforms to gather responses from multiple sports. In total, 94 responses were collected with a completion rate of 72% (68 participants) and an average completion time of around 15 minutes. All the collected answers were downloaded, analysed in python with the pandas and NumPy modules and finally visualized with the Altair module. The involved sports and the involved participants per sport are shown in Table 2. The main included sports, and also the ones touched in the epidemiology analysis, were soccer, basket, volleyball, American football and rugby. The demographic analysis of the participants shows an overrepresentation of males in all sport except volleyball. Volleyball is also the sport with the lowest mean age and the fewest practised years. Participants of all other sports show a lot of experience in their sport with around ten years of practising the sport. The participants level of agony goes from non-professional up to second and third national leagues and one participant even from the first national league. This vast diversity will bring a lot of different insights and differences in treatment and recovery pathways will be analysed.

**Table 2 Overview of the participants of the survey**

| Sport | Participants | Gender | Age (Mean) | Practised years (Mean) |
|---|---|---|---|---|
| **Soccer** | 18 | 18 M | 28.3 | 13.2 |
| **Basket** | 8 | 7 M, 1 F | 27.5 | 10.0 |
| **Volley** | 6 | 1 M, 5 F | 23.1 | 7.1 |
| **American Football** | 2 | 2 M | 27.0 | 11.0 |
| **Rugby** | 45 | 45 M | 27.7 | 11.8 |
| **CrossFit** | 5 | 3 M, 2 F | 28.6 | 4.7 |
| **Horseback riding** | 1 | 1 F | 24.0 | 8.0 |
| **Judo** | 1 | 1 M | 18.0 | 10.0 |
| **Mountain bike** | 1 | 1 M | 37.0 | - |
| **Nordic Ski** | 1 | 1 F | 26.0 | 10.0 |
| **Swimming** | 1 | 1 M | 30.0 | - |

### 4.2.1 Ankle injuries in general

Before diving into personal experiences and rehabilitations, sport-specific results are shown. The first plot shows the sport-specific ankle injury risk (see Figure 18). The question was: How dangerous is your sport for suffering ankle injuries? Value the risk between 1 (No risk) to 7 (High risk). Contact sports such as rugby, American football and soccer together with sports where jumping and landing, such as volley- and basketball, or eventually just landing, as it is the case for horseback riding when someone falls or steps down from the horse, were the sports with the highest risk for ankle injuries. Nearby the overall risk of ankle injuries, the participants were asked to rank the following body parts based on the risk of an injury on that body parts. The body parts were:

- Ankle or Foot
- Arm, shoulder or hand
- Head
- Hip, groin or thigh
- Knee
- Other body parts

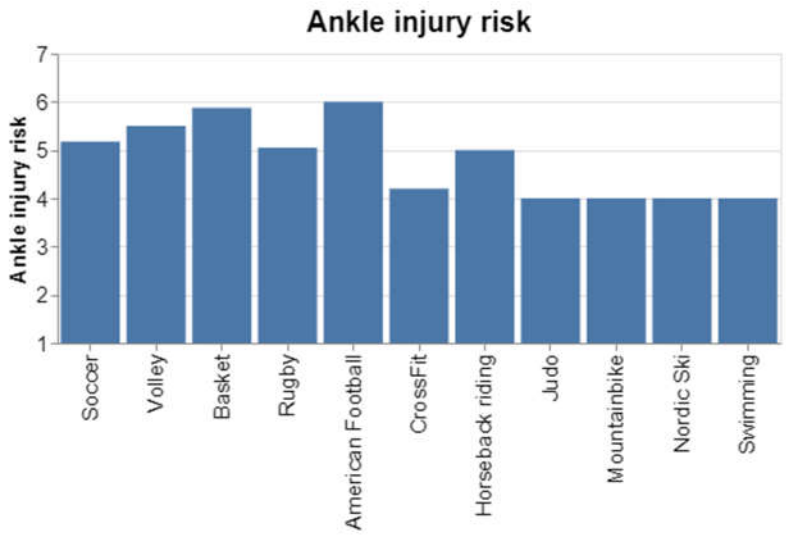



**Figure 18 Ankle injury risk for the different sports. Scale from 1, No risk, to 7, High risk).**

To the body part with the highest risk, rank 1 was assigned, and for the body part with the lowest risk, rank 6 was assigned. The results for all the involved sports (see Figure 19) show, that the ankle is the most injured body part in volleyball and basketball and the second most injured body part in soccer after hip, groin or thigh injuries. These results are comparable, with some minor differences, to the results of the systematic review on ankle injuries and ankle sprains in sports [1] where for all the involved sports the most injured body sites were listed.

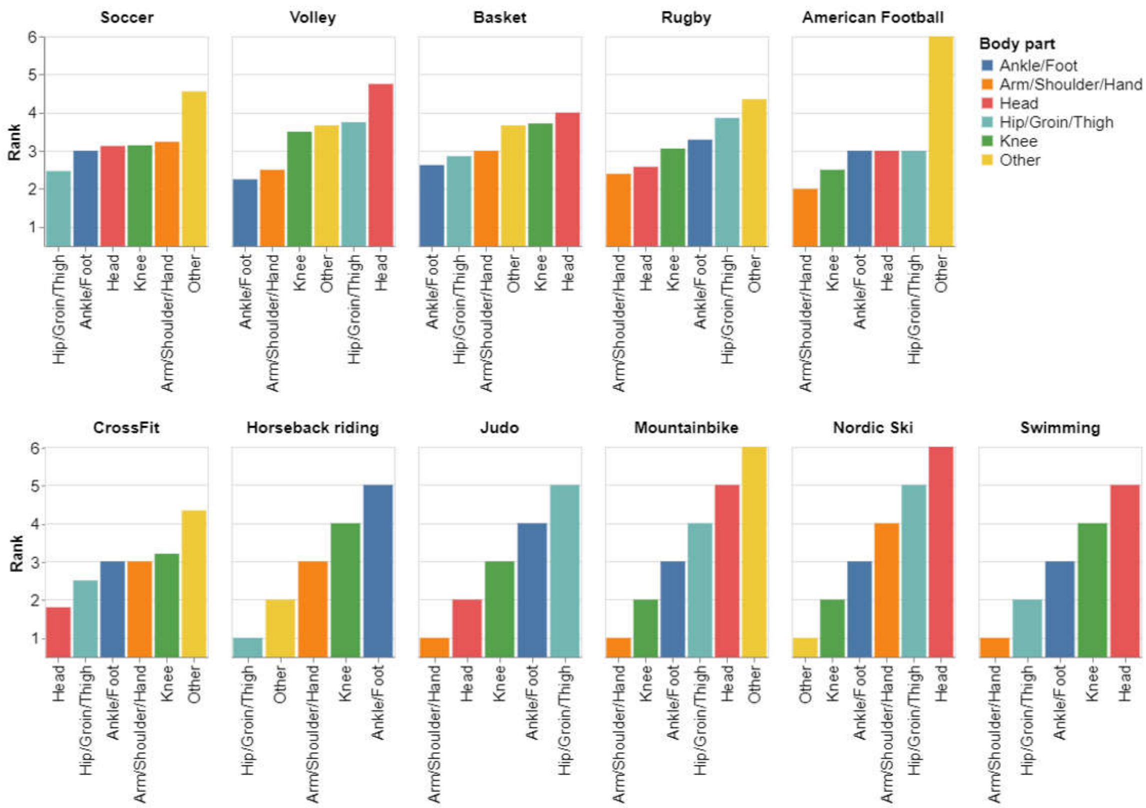



**Figure 19 Order of body parts based on the risk of injury for each analyzed sport**

The next visualization (Figure 20) shows the number of ankle injuries each participant had suffered during his or her career. As expected, the incidence of ankle sprains is relatively high, in fact, only 10 participants out of 94 declared to not having suffered an ankle injury. Taking into account that 3 of these 10 participants are part of the sport, volleyball, with the lowest average age and with the actual shortest career, the incidence can be considered to be even higher. For all others, at least one ankle injury happened during the career with the highest incidence being found in basket. Over all participants, a mean of around 3,3 ankle injuries per participant was calculated. The impact of ankle injuries on their agonistic career was judged similarly across the sports except for volleyball with a lower impact and personal experiences for participants who practised CrossFit and Mountain bike that led to a higher impact (see Figure 21). For the other participants the distribution is around the middle of a scale from 1 (No impact) to 7 (High impact), what can be interpreted, combined with the outcome of the incidence analysis, is that ankle injuries happened regularly but the missed playing time was not enough to define ankle injuries as highly impactful on the participants' career.

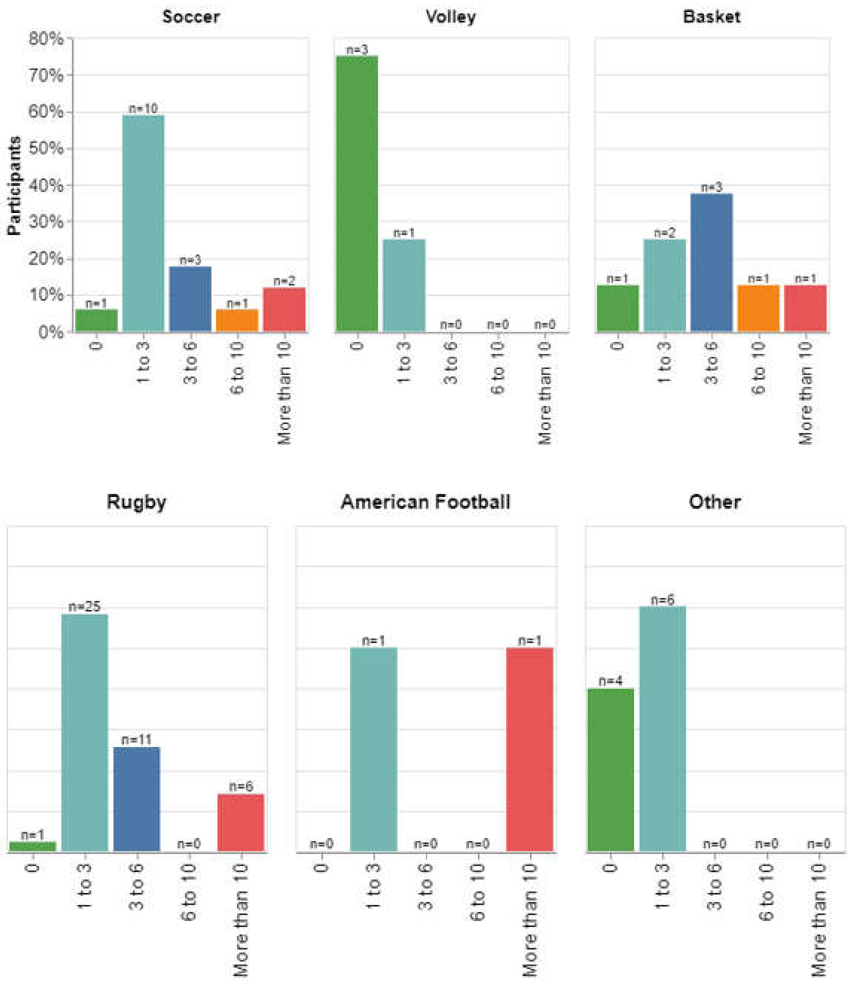



**Figure 20 Distribution of amount of ankle injuries suffered by participants of the different sports**

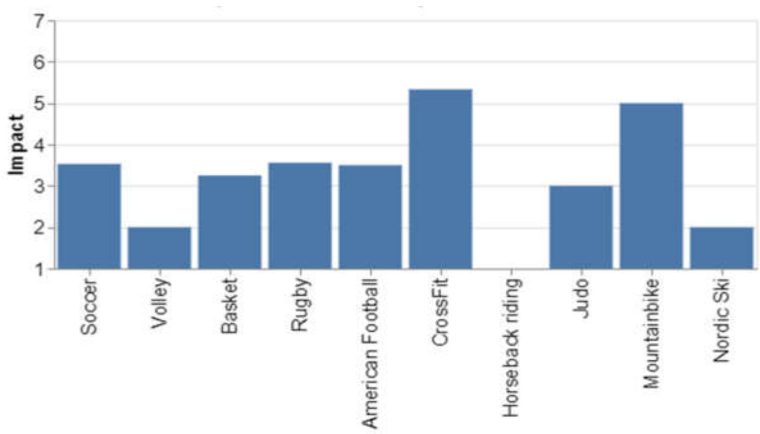



**Figure 21 Impact of ankle injuries on the participants' career**

The last two visualizations before describing the personal experiences of the participants show the mechanism (see Figure 22a) and the involvement of other players (see Figure 22b) when the injury happened. The results show, tendencies towards injuries that happened due to contact with other players and the expected high tendency towards an inversion movement of the foot that caused the injury. Nevertheless, a heavy contact sport such as rugby, present also a significant portion of, normally more severe, eversion ankle injuries.

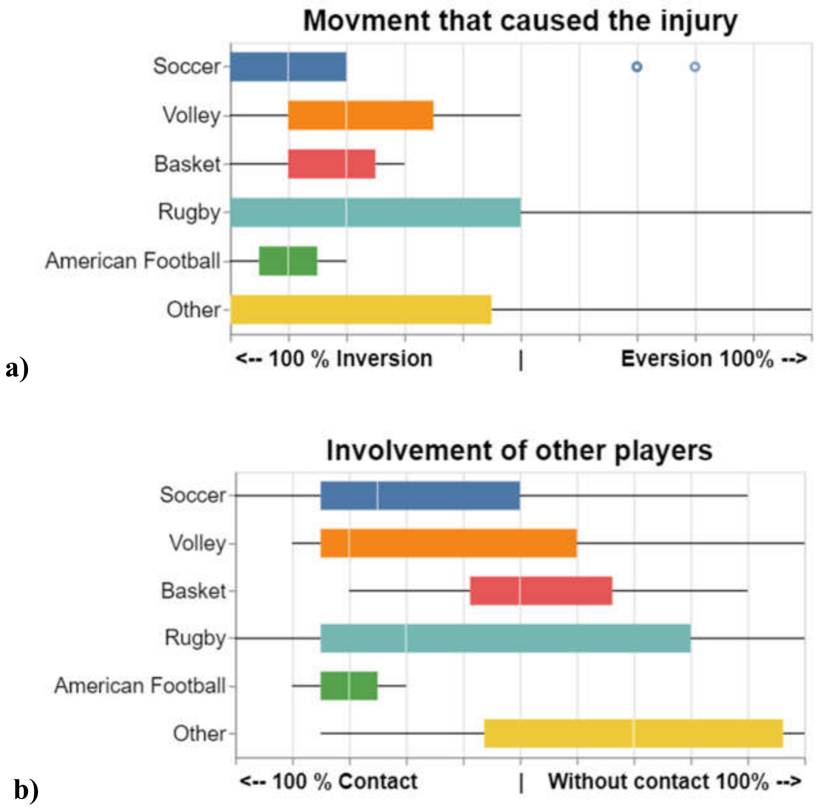



**Figure 22 Distribution of the scenarios that led to the injuries for the different sports. a) showed the distribution between inversion and eversion movements that caused the injury; b) shows the distribution of the involvement of other players when the injury happened**

Now that the overall impact of ankle injuries on the participants' careers was elucidated, the focus falls on single injuries and the consequent missed playing time. In the answers, the whole palette of possible ankle injuries is present. From simple to more severe contusions, passing through ankle ligament tears, involving both later ankle ligaments and syndesmosis and finally arriving to ankle dislocations and bone fractures. This is reflected also by the estimated missed training days for each participant's most severe injury (Blue box in Figure 23). Taken into account that the question regarded only the most severe ankle injury, the median of the missed training days after that injury resulted to be of slightly over one month (40 days), but there were also many more severe cases where the missed training days accumulated from a half up to more than a year including 7 participants that needed surgery after the injury. This is also reflected by the high mean absence time of around two months (68 days). The total missed playing time (Orange box in Figure 23) can give a better indication of how the moderate impact of ankle injuries on the participants' careers can be interpreted. Indeed, the median of 90 and the mean of 133 missed training days can be translated to the miss of half a season throughout the career due to ankle injuries.

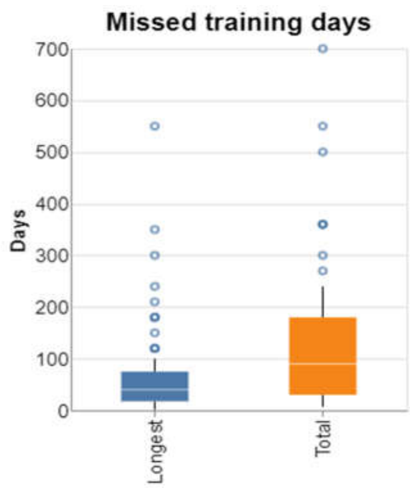



**Figure 23 Missed training days for the longest rehabilitation after an ankle injury (Blue) and the total missed training days due to ankle injuries (Orange)**

Nearby questions about personal injuries, this set of questions aimed also to understand how much time is spent during training to prevent these injuries. As expected, minimal to no time is spent during training specifically for exercises to prevent ankle injuries (see Figure 24a). It needs to be said, that balance, stability and lower limb strength exercises are exercises that are regularly performed by the athletes and they also try to activate the musculature around the ankle, but several other exercises specifically focus on this part of the foot and these are the exercises that, as for the participants of the survey, miss during the training routine. The next two questions result in a bit of controversy but bring the problem of ankle injuries good to a point. The first question is about how much time is spent, besides training, on these types of exercises that are missing in the training itself. The answers (see Figure 24b) show that quite no time is spent with a physiotherapist or alone for these exercises and this is a controversy to the answers to the next question. The participants were asked if they think, that increasing the exercises and the time spent aimed to prevent ankle injuries would decrease the risk of injury and finally the number of injuries. With a vast majority (see Figure 24c) they answered that they think that the injuries would decrease with more specific and intense training sessions and exercises. This controversy is typical for the cases where a problem is known and visible and nothing or not enough is done to prevent or to contrast this same problem. And this is exactly what happens for ankle injuries. The impact on the players' career is shown by the number of injuries and by the missed playing time, but as it seems to be the case, not enough is done in training to prevent these injuries.

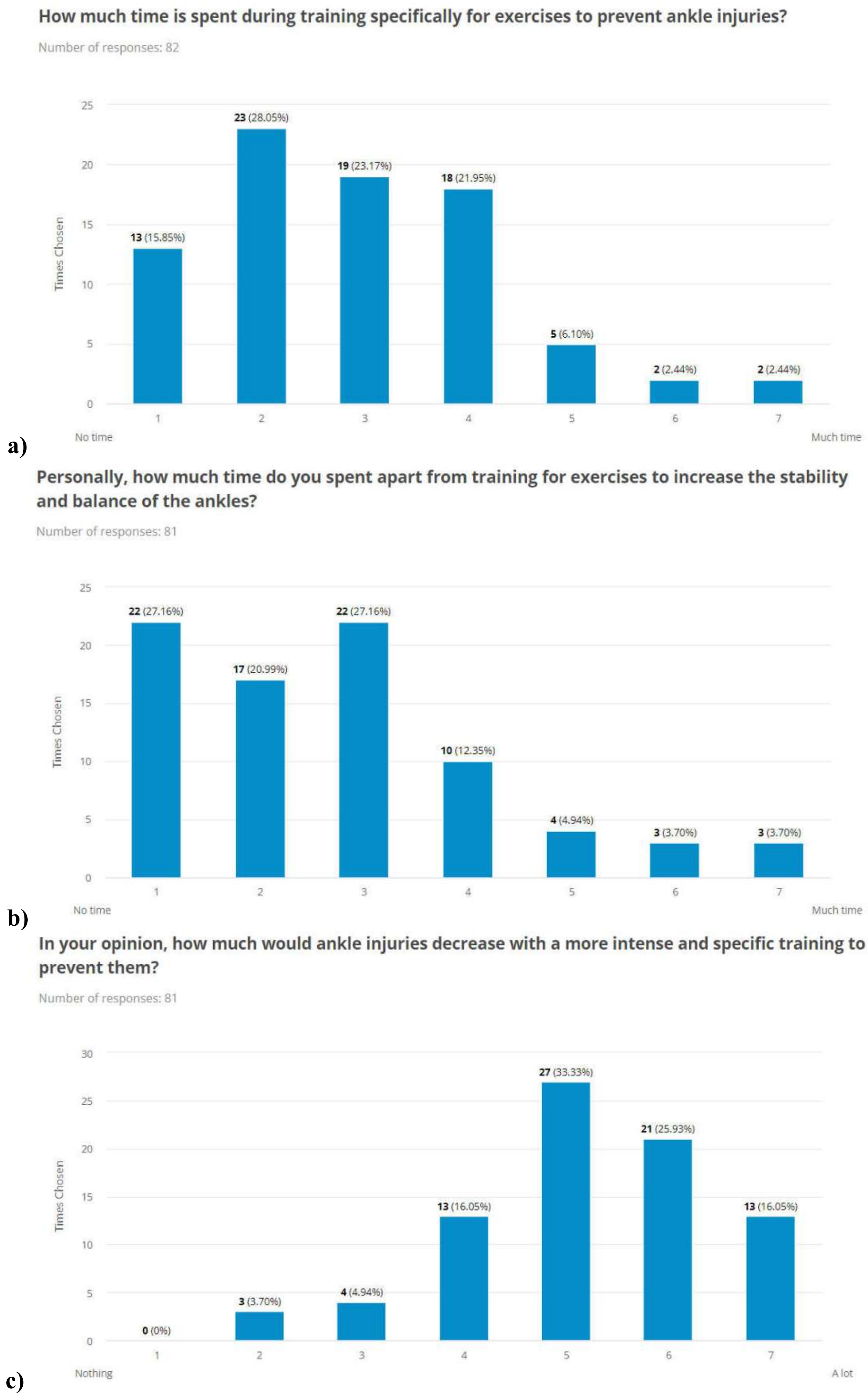



**Figure 24 Results of three questions regarding the time spent with ankle specific exercises during training (a), at home (b) and if ankle injuries would decrease if more time would be spent with these exercises (c)**

In fact, these thoughts are shared by the participants, because when asked if the time spent during training with such specific exercises should be increased, 85% (57 participants) answered with yes (see Figure 25.1). The percentage went up to 97% (65 participants) (see Figure 25.2) when asked if these exercises should be increased and potentiated already in the youth sector. This last statement highlights the problematic situation even more because a more specific training and explanation would bring a solid base of education and sensibilization to the problem when the involved kids or athletes are about to start their shorter or longer careers. And, as it seems and as personally witnessed, this sensibilization is missing, not only in the youth sectors but also in general.

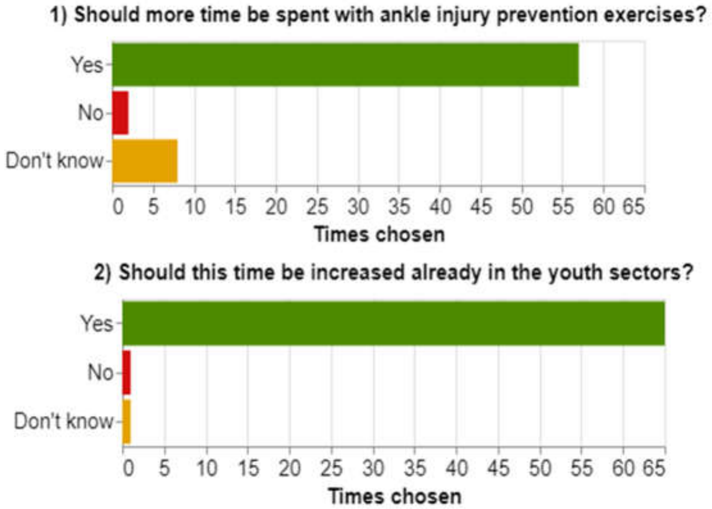



**Figure 25 Answers the questions if more time should be spent for ankle specific exercises in training (1) and in the training of the youth sectors (2)**

### 4.2.2 Rehabilitation and personal experiences

After these deeper insights on the impact of ankle injuries on athletes of different sports, their rehabilitation process was the focus of the second set of questions. More precisely the first phase of the rehabilitation and the decision to return to sport. For the first phase, the participants were asked to describe how long they had their foot immobilized and for how long they had to perform range of motion and other exercises with no or minimal load on the injured foot. The distributions are shown in Figure 26 and describe both immobilization and light rehabilitation exercises from one to three weeks. The interesting part of these values, is the fact, that the two periods are similarly long and are therefore overlapping. This gives an indication, that already in the first phase of rehabilitation exercises were performed and evidence, therefore, the case for the practice of optimal loading exercises on the field. The most used items for these exercises were resistance and elastic bands, ankle weights and Bosu and Medusa balance boards. Some examples of performed exercises were (taken directly from the answers):

- Simply moving the fingers of the foot
- Stability on Bosu
- Stability, coordination and foot movement
- Stretching and free body balance
- Proprioceptive exercises and activation of the muscles around the injured tissue
- Squat and other types of bodyweight associated exercises
- Balance works with balance boards and eccentric movements with elastic bands

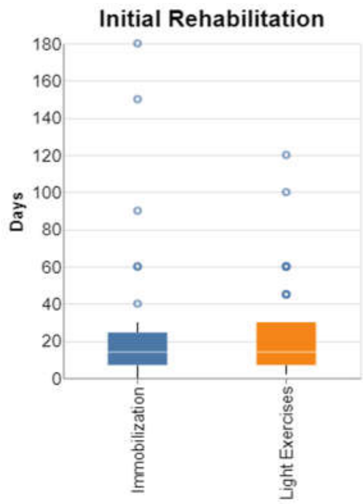



**Figure 26 Duration in days of immobilization (Blue) and light exercises (orange) during the initial phase of the rehabilitation**

As seen in the description of the rehabilitation process in Section 2.4, the performed exercises are all exercises that try to find the optimal loading of the injured tissue to keep the muscles activated and to start as early as possible with rehabilitation exercises. Together with these early rehabilitation exercises also exercises to do at home were prescribed to some participants, 29 in total. From the answers to the question for how long, how often and which exercises were performed, the difference between full-time athletes and part-time athletes became clear. If the first ones declared that only exercises on the training canter were performed, the other ones needed to perform these exercises regularly at home for the duration of the rehabilitation process and even further. Participants here said that they had to perform exercises for around 10 to 15 minutes for at least two to three months, another one said that he had to perform exercises for the whole duration of the recovery process of four months, then one participant declared that he had to perform exercises three times a day for three months and another one even declared that he needs to perform stretching and balance exercises for years after the intervention. Even though for other participants the time spent at home for these exercises was lower; one to two times a day for two weeks or once for half an hour for two weeks for another one; they still are involved in a significant portion of rehabilitation processes. One participant said that he did not had to perform exercises at home, but maybe it would have been better if he did. This also shows the importance of these exercises and that they take, and need to take, a lot of time. The next few questions regard the motivational and psychical aspects while performing rehabilitation exercises for both at home alone and with a physiotherapist. The participants were asked to self-judge their commitment and motivation ranging from 1 (low) to 7 (high). The answers are shown in Figure 27 and except for some outliers, all participants see the importance of the psychologic aspect during the rehabilitation pathway and the vast majority of the participants seems to have handled it very well during personal experiences. In fact, both their own motivation and concentration were judged between 5 and 7, which are significantly high scores. One score point lower the dedication for home exercises is judged. With a score of between 4 and 6, this aspect still achieved a positive result, but it is clear that the motivation and concentration decrease when the exercises are performed away from a training or medical centre. Even though this result could be expected, it still needs to be addressed and solutions need to be found in order to keep the dedication towards the exercises at least as high as when done together with a physiotherapist or in an environment different from that at home.

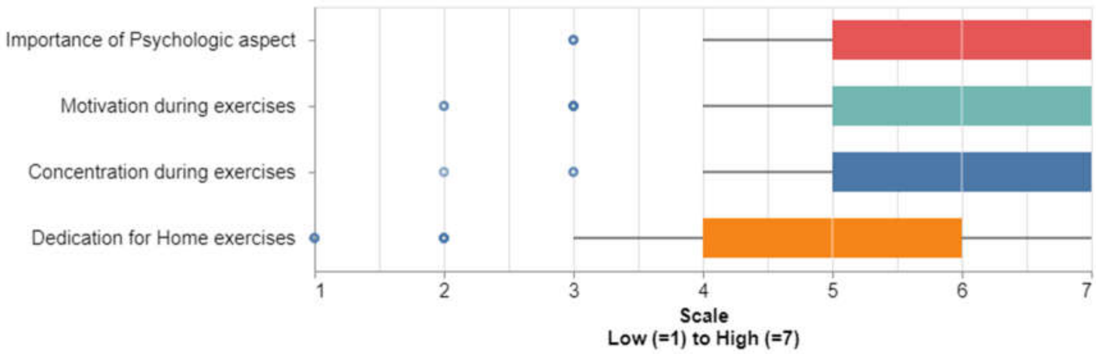



**Figure 27 Self-assessment of psychological and motivational aspects during physiotherapeutic exercises and concentration towards these exercises**

When asked what and how much is done by one personally and by the medical staff or physiotherapists in order to keep the motivation and concentration as high as possible during the single exercises and during the whole rehabilitation process, the answer, in the majority of the cases, felt back to what is done by one personally. In fact, most participants responded that it was their own willingness to come back from the injury that was the leading factor for their own motivation. Some tell about seeing other teammates practising being the greatest motivation and others saying that simply wanting to get back on the field drove them to give the maximum during the rehabilitation sessions. Major props that were attributed to physiotherapists and other collaborators were to be always there when they were needed to explain exercises and the actual state of the therapy, to show interest towards the progression and the medical state of the injured tissue, availability for regular controls and to be some sort of positive distraction to keep the moral up between the exercises. Unfortunately, the fact that many participants mentioned that nothing was done by physiotherapists to extra motivate them, evidences an important aspect that needs more attention.

Another unfortunate finding of this survey regards the decisions of progression to the next phases of the rehabilitation process and finally the return to sport decision. Unfortunate because around 60% (39 participants) of the participants declared that due to personal pressures or pressures by the organization steps of the rehabilitation process were skipped to achieve a faster return to play. This is a worrying aspect and is highlighted even more by the next question asked to the participants. They were asked if this forcing led to new injuries and fallbacks and for almost 40% (25 participants) of the participants this happened, resulting in an additional, and possibly evitable, re-injury rate of around 7%. The distribution of the responsibility (see Figure 28) slightly tends towards more personal pressures that led to an anticipated return to play. This not clearly defined responsibility opens the discussion that even if the organization is not seen as completely guilty for a forced comeback, implicit pressures from the organization may played a significant role and consequentially increased personal reasons and pressures that at the end led to the forced comeback.

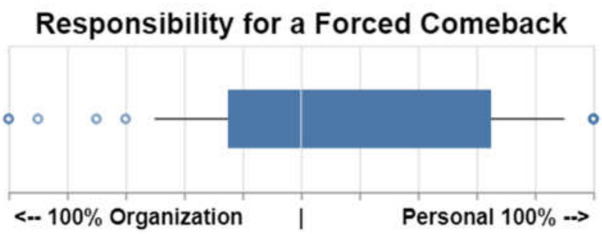



**Figure 28 Responsibility distribution for a forced and accelerated Return to Sport**

That the participants blame themselves for the too fast comeback is visible also in the answers to what were indications and evaluations that led to the progression to rehabilitation phases with full weights and finally to the return to practice and the return to sport phases. Only three participants mentioned that specific tests were done to assess the mobility and the stability of the ankle before the progression to these next phases. Eleven more participants declared that it was the physiotherapist that gave the indication to progress and in 26 cases it was the own feeling and level of pain that defined the progression to the next phase. Significant answers that define the situation and describe the participants evaluations were:

- When my ankle was strong enough
- When I regained enough stability and strength
- I didn't make any evaluation with nobody, simply when I felt that I could load my ankle

- After the diminution of the pain
- Limit of pain in order to jog
- Gut feelings
- Evaluation of pain and stability
- Personal evaluation
- When the swelling and pain decreased
- When I was able to jog well
- I had to play

### 4.2.3 Serious Game for rehabilitation purposes

The last set of questions aimed to understand the participants' thoughts on the utilization of a serious game for rehabilitation exercises. First of all, they were asked if they think that classic rehabilitation exercises could be recreated inside a videogame and little more than 50% (35 participants) sees this possibility. The majority of the other portion (30 participants) is not sure if it is possible and only two participants did not think that it is possible. When asked which exercises they could see inside a videogame most participants answered with balance, stability and mobility exercises with the utilization of different balance boards and elastic bands.
After that, a series of questions regarding the motivational aspect was asked. They were asked if they think that the utilization of a serious game would increase their motivation and dedication to perform rehabilitation exercises both at home alone (Figure 29.5) and in general (Figure 29.1). Then if they think that, if the exercises are recreated within a videogame, this would increase the concentration towards the exercise while performing them (Figure 29.2) and if this consequentially would increase the physiological effect of the exercise (Figure 29.3). Furthermore, they were asked if the utilization of a videogame would increment the time spent with rehabilitation exercises (Figure 29.4) and if the fact that they and the physiotherapists immediately can see the achieved result of the exercises by a score implemented in the game would bring mental benefits by triggering the own ambition (Figure 29.6). For all these six questions more than half of the participants, with a mean of almost 65% (44 participants), were in favour of the question, underlying the positive influence that the application of a serious game would have on both the mental and also on the psychical and medical aspect. What stands out from the answers, is that almost 94% (63 participants) think that an increased concentration towards the exercises while performing it would lead to a better effect of the exercise itself. Two more specific questions were asked to judge the importance of the possibility to self-assess how the exercises are going and the progression of the rehabilitation process by seeing personal scores and parameters of the game and how the impact of the serious game would be on the state of

mind. 71% (48 participants) and 66% (45 participants), respectively, judged the possibility of control as important and the impact on the state of mind as positive.

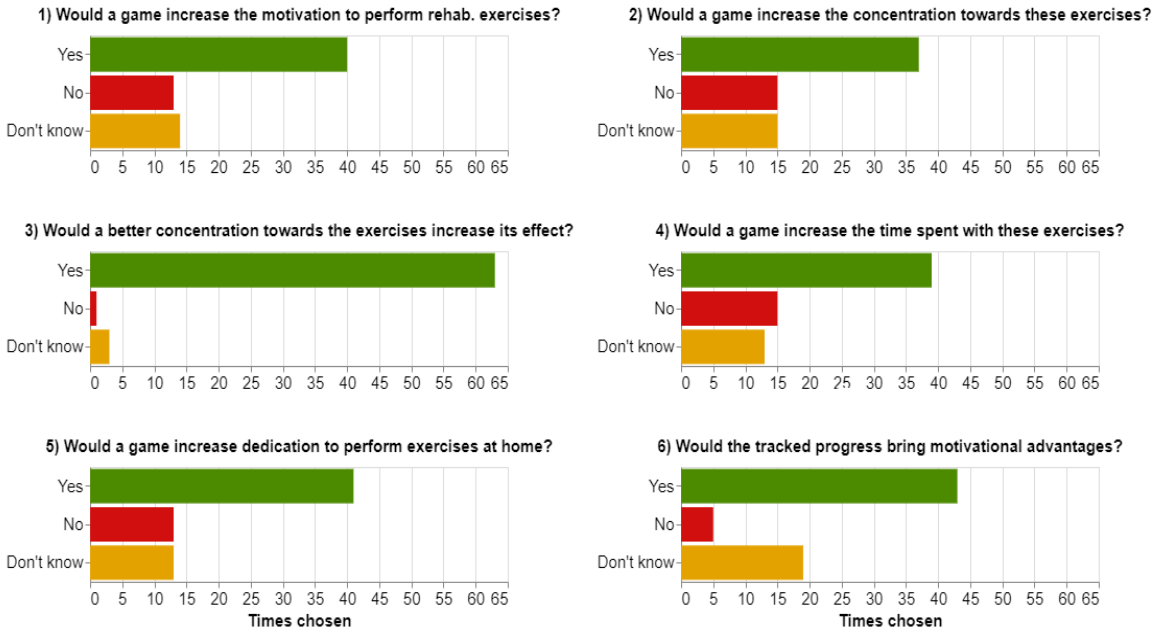



**Figure 29 Results of different answers regarding the utilization of a serious game during the rehabilitation process and impact on the psychological and motivational aspect**

After the psychical aspect, the participants were asked to judge the importance that the serious game includes a series of other characteristics for a better acceptance. They needed to assign a value (None, Low, Medium, High or Very High) defining the importance for each of the following characteristics:

- Visualization of points and scores
- Tracking of the achieved results
- Recreation of more exercises
- Adjustable difficulties
- Different game situations and levels
- Game situation adherent to your sport
- Possibility of Multiplayer
- Customization of player figure

The results (see Figure 30) show a relatively high importance for all the characteristics except the implementation of a multiplayer setup and the possibility of the customization of the player figure. The highest scored features were the recreation of a game situation adherent to the own sport, the implementation of different game situations and different exercises and the possibility to keep track of the own results and the progression. Furthermore, a field was inserted where the participants could define other features and indications they wanted to be implemented. Interesting inputs were:

- Possibility to play the game alone, without the help of physiotherapists
- Light vibrations when the exercise is not performed correctly
- Showing the days to return to play
- Comparison with other players and with the not injured articulation
- Leader boards
- Injury and body-part specific programs
- Portability on a mobile phone or tablet

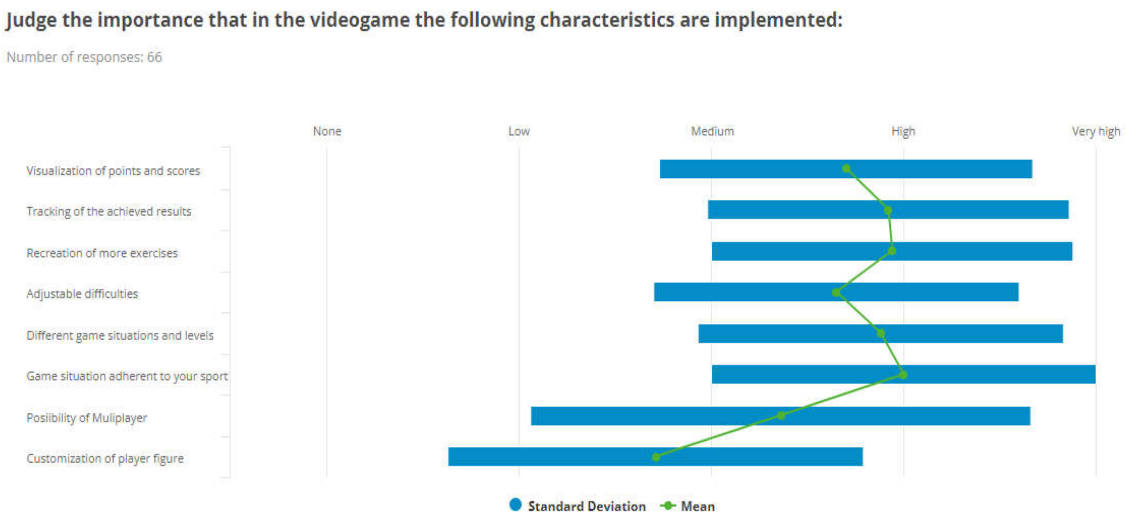



**Figure 30 Judgment of the importance that the videogame implements different features**

With the last question, the participants were asked if they would consider using this application for their own rehabilitation process and almost 82% (55 participants) answered with yes. Then they could give some final considerations or advice. One told that he suffered multiple ankle injuries during his career and the ones he recovered best, were the ones where he had the possibility to be immediately followed by a physiotherapist. Another one finds it a very nice and innovative idea to heal and to prevent ankle injuries, but if it works it should be expanded for other injuries. Two last participants remarked the importance of prevention exercises and the importance of exercises at home and mentioned the fact that a solution involving a videogame could increase the time spent with these exercises.

Last but not least, they were asked to rate the whole idea and the overall rating resulted to be 4.3 out of 5 stars.

### 4.2.4 Summary and takes of the survey

The high number of participants (94 in total), the provenience of different sports and from different categories and the shared high number of practising years led the survey to be a good indicator of the impact of ankle injuries and their rehabilitation pathway. As seen, ankle injuries are quite frequent injuries and can cause longer absence periods with greater severity. In contrast, the problem with ankle injuries is that in a lot of cases the importance of the injury is underestimated and the players' rehabilitation is not taken as seriously as it should be. Further negative aspects are the problems with re-injuries and chronic ankle instabilities, which seem to be even higher in lower leagues and the world of semi-professionalism. Furthermore, from the survey it results that prevention exercises should find more space during training, starting from the youth sector in order to increase the sensibilization towards long-time consequences and the importance of an adequate rehabilitation. The decision for the return to sport should also be addressed whit the start of the rehabilitation and clear indications should be found in order to not put all the pressure on the players and let them decide to return to sport simply when they feel no pain. Indications, for example, could be given by the achieved results with a serious game. In fact, the survey showed a high acceptance of the idea to use a videogame for rehabilitation purposes where both players and physiotherapists can track and interpret the progression with the utilization of the achieved scores and results. Nearby the visualization of the results, with the serious game different game situations adherent to the own sport should be recreated and with the possibility to perform different types of exercises for a maximal acceptance. The overall score and the good participation in the questionnaire showed the importance of this whole situation around ankle injuries and that new approaches can be a solution to a series of minor problems that need to be addressed in order to ensure a better and safer rehabilitation pathway for the involved athletes.

## 4.3 Definition of the requirements to the serious game

In Section 2.5.2. the roadmap for the conceptualization and implementation of serious games in the medical sector was presented. The first step contained an in-depth knowledge of the rehabilitation operational context and the adoption of a robust requirements engineering procedure. This was achieved with the intense analysis of the theoretical background, the identification of potential improvements of already published solutions, methods and products and the assessment of the on-field situation with the creation of the survey and the interviews with a physiotherapist. With these steps, the rehabilitations operational context was clarified and from all the different steps various inputs for the requirement engineering were collected. Major conclusions and consequent requirements towards the implementation of the serious game are:

1) Ankle injuries are often underestimated and less to no time is spent on specific prevention exercises. When an injury occurs, early rehabilitation exercises in a protected range should be performed for a better and faster recovery. The major challenge for these exercises is the identification and the progressive adaptation of the optimal loading. A serious game used in this context therefore should include the possibility to individually adjust the range of motion and the difficulties of the exercises and it should also allow monitoring of the achieved results and the used parameters to keep track of the progression.

2) Rehabilitation exercises in the first phase, where the range of motion is limited, the ankle is still sore and the movement of the foot may cause pain to the involved patients, are often frustrating and monotone, but essential for the rest of the rehabilitation process. A serious game should bring diversity and new motivation in this phase and therefore it is important that, with the serious game, different exercises and different game scenarios can be tried. The implementation should foresee the registration of different movements and the integration in different game scenarios and levels to keep the patient's motivation and concentration as high as possible.

3) Not always the whole rehabilitation process can be performed at a training or medical centre, if this is not the case, home exercises are often prescribed. The motivation to perform these exercises is lower than when they are performed together with a professional and it is not possible to control if the exercises were done or not. The serious game could be a solution for this problem because the motivation could be higher if the exercise is incorporated in a videogame and it would allow the supervision of the exercises and the achieved results. The prerequisite for this achievement lies in the ease of setup and the portability of necessary hardware and medical devices and items. Only with a quick and easy setup, the acceptance of patients and physiotherapists will be reached, otherwise, the system will not penetrate into daily routines.

4) The analysis of published serious game-based solutions already showed possible application scenarios and their medical and psychical advantages. What really stands out, is that the patients, if the game has a good implementation, did not feel that they are doing rehabilitation exercises, but they see it as a play-like moment where joy and competitiveness are the major perceived sensations and emotions. This increases the acceptance and the motivation to perform the exercises even more. Therefore, a further requirement towards the implementation of the serious game, evinced also by the answers to the ques-

tionnaire, is the recreation of sport-adherent game situations within a familiar environment. This will detach, especially young patients even more from seeing this moment as a moment of rehabilitation and trigger their gaming and competitive instincts.

The following table summarizes the identified results, categorizes them and describes briefly how they are implemented or integrated into the final game. With the identification and presentation of the requirements, the first phase of the diploma thesis was concluded and the implementation phase was initiated.

**Table 3 Summary of the Requirements towards the serious game**

| Requirement Description | Type | Implementation / Integration |
|---|---|---|
| Recreation of (multiple) conventional rehabilitation exercises | Functional Requirement | Conventional exercises are identified and the integration into the serious game is tested and evaluated together with physiotherapists. The registration of all different movements and exercises is done with the same IMU sensor and there is the possibility to integrate one or two degrees of freedom |
| Individual adjustment of difficulty and Range of Motion | Functional Requirement | Before the start of every level, the user needs to define his/her maximal range of motion that is then translated into the maximal position inside the game |
| Visualization of scores and tracking of progress | Functional Requirement | The score is calculated from the number of caught trophies or by the correctly passed cones and visualized together with the range of motion at the end of every level |
| Maximization of user acceptance | Non-Functional Requirement | The game scenarios recreate situations that are familiar to the target group of the system by including a well-designed avatar and animation and by inserting them into a familiar playing environment |
| Portability and quick setup | Non-Functional Requirement | At the start of the game, the sensor should automatically connect to the playing device to allow the user to play the game without the help of a physiotherapist/expert |

## 4.4 Implementation

As already mentioned, with the definition of the requirements towards the system, the second phase of the diploma thesis started. From the schematic visualization of the work of the diploma thesis (Figure 1 in Section 1.4), the part regarding the second phase is extracted and visualized in Figure 31 to give an overview of the structure of these next sections. These contain a detailed description of all the steps of the implementation phase containing conceptual indications and followed technical guidelines. The first steps of the implementation phase are the hard- and software selection, the creation of the playing ground, the registration of the movement of the foot with different approaches and methods, the modelling of the avatar to increase the enjoyability of the game and the integration of first movements and exercises into simplistic game scenarios. From these first steps, a first prototype that simply includes the conceptualization of different game scenarios is created and presented to a physiotherapist of a professional football club to gather first impressions and feedback. Together with this physiotherapist the best exercises, movements and game scenarios are identified and consequentially integrated into the final prototype. After different game engineering steps, where the prototype is transformed into a finite and playable game, the training program and the testing scenarios are planned and defined.

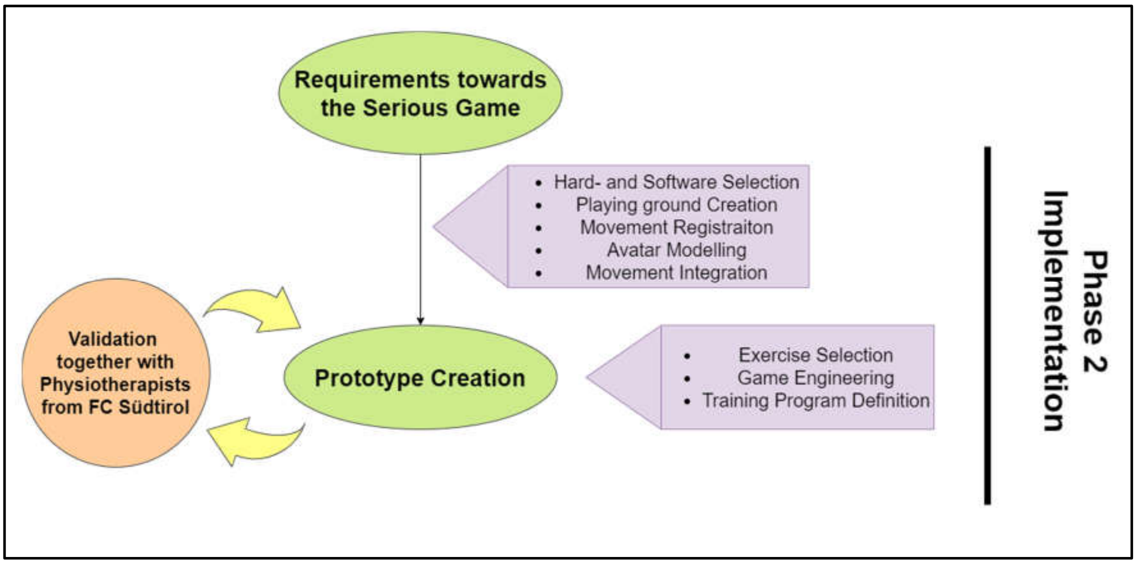



**Figure 31 Visualization of the second phase of the diploma thesis**

From the direct conversations and the answers of the questionnaire, it became clear, that the idea of the runner-game scenario would work in the context of ankle injury rehabilitations, therefore, the basic idea of the conceptualization of the game situations was to recreate classic rehabilitation exercises inside a videogame starting from simple range of motion and contraction exercises. From the observation and the definition of these exercises it was noted, that there were exercises that were performed on one axis (= with one degree of freedom) and exercises that were performed on two axes (=two degrees of freedom). In exercises such as isotonic contractions with an elastic band, the movement of the foot goes just on the directions of one axis, e.g., left to right while for exercises such as the Alphabets exercise, where the patients need to draw the letters of the alphabet in the air with the movement of the foot, the movement can be registered along two axes, up and down and left and right. This is a significant difference when it comes to implementing the movements inside a videogame based on these foot movements and is addressed further in this section. For the moment, the conceptualization contained the intention to implement both these exercises inside the game. Since from the beginning there was the intention to evaluate the serious game together with athletes of a soccer club, soccer was chosen as sport to which the game should be adherent. As playing ground therefore a pitch with grass should be taken and the game situation should be familiar to the player.

With these basic conceptual ideas in mind, the different steps that lead to the creation of the final prototype are described in detail in the next sections, starting with the description of the process of the selection of hard- and software components for the construction of the game and the registration of the players' movements.

### 4.4.1 Hard- and Software selection

The selection of the software for the implementation felt on Unity together with the programming language C#. Unity offers an intuitive interaction between different components inside the game and offers the possibility to import and integrate predefined assets into the scene and let the player interact with them. Unity was used in a previous project with its 2D interface, but for this project Unity 3D was chosen. This allows more freedom in the implementation of the game scenarios and will result in a better and more enjoyable game. Unity is installed on a notebook running Windows 10 with an Intel Core i7-8750H CPU @ 2.20GHz, 6 Kernels, 8 GB RAM and an NVIDIA GEFORCE GTX GPU.

For the selection of the hardware to register the movement of the foot a few considerations were done. The device should be portable, relatively cheap, provide precise and real-time measurements, allow the user to move in the space and it should allow a quick and easy setup. The major decision was between a direct or an indirect registration of the movement. A direct registration would use a sensor that is put on a moving object or body part and by moving it, it directly sends the registered measures to a processor unit. In contrast, an indirect registration would use devices that are placed in a fixed position and register the movement of the involved object or body part with cameras or other sensory units. Examples of these last methods are the Xbox Kinect and the Leap Motion. Even though both work best in other circumstances; the Xbox Kinect is used to register the movement of the whole body and the Leap Motion works best for the registration of the movements of the hands; they could have been adapted and used for this project. After an accurate analysis of the pros and the cons of these technologies, the decision felt on a direct registration of the movement with an inertial measurement unit (IMU) sensor. The main reasons were given by the theoretically easy setup, the price, the portability, the possibility to put it on different body parts and recreate multiple exercises and the high sensitivity regarding the measurements. With the selection of the type of the device, the choice of the hardware felt on the METAMOTIONRL [81] from Mbientlab (see Figure 32). It is a wearable device that offers real-time and continuous monitoring of motion and environmental sensor data and it was already used for other projects in the institute. The sensor is a 9-Axis IMU and Environment Monitoring Sensor and it contains a Gyroscope, Accelerometer and Magnetometer and resulted in a Sensor Fusion output with a sample rate of 100Hz. Sensor fusion combines data from different sensors to compute something that cannot be calculated from one sensor alone. There are 4 operation modes that use different combinations of the included sensor:

- NDoF: Calculates absolute orientation from accelerometer, gyro, and magnetometer
- IMUPlus: Calculates relative orientation in space from accelerometer and gyro data
- Compass: Determines geographic direction from the Earth's magnetic field
- M4G: Similar to IMUPlus except rotation is detected with the magnetometer

The output, depending on the mode, is one of acceleration in g-units, angular velocity in degrees per second, magnetic field in Tesla, orientation in Quaternions and Euler Angles and linear Acceleration and gravity in g-units. The real-time data transfer is achieved via a Bluetooth Low Energy 4.0 module and the sensors contain Swift, C++, Java, JavaScript and Python APIs to communicate with the device.

The sensor was ordered by the research group for Industrial Software (INSO), the institute at the Technical University of Vienna where the diploma thesis was written, and made available for the time of the diploma thesis.

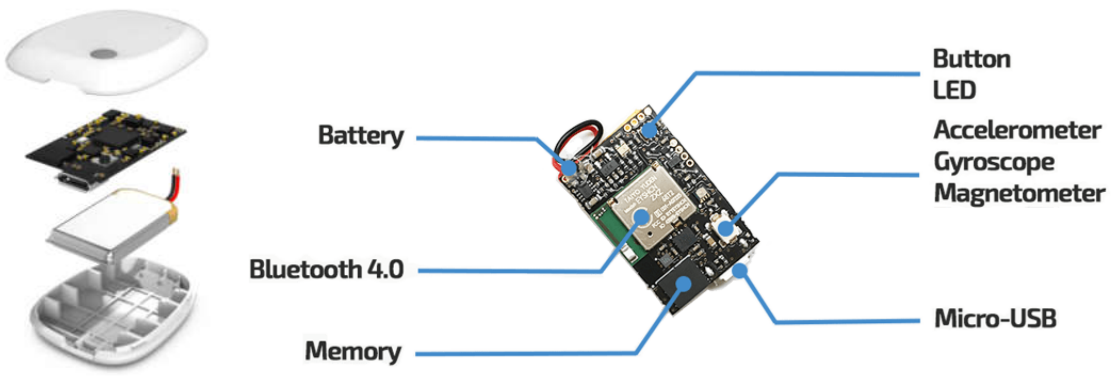



**Figure 32 Structure and composition of the Metamotion Sensor by Mbientlab [81]**

### 4.4.2 Playing ground creation

After the selection of the hardware, the programming part could have started with the first step: the creation of the playing ground. As already mentioned, there is the necessity to create two different game scenarios because of the differences in the involved degrees of freedom for the various exercises. For exercises with two degrees of freedom, the idea was to recreate the Alphabets exercise and to let the patient follow the lines that form the letters by moving a game object over them. For this, a plane was recreated with a grass type surface, walls were added to create some sort of arena, and the shades of the letter “A” surrounded by some cones (see Figure 33). The material components of the wall and the grass were taken out of the Terrain Textures Pack [82] from the Unity Asset Store and the 3D cone object was downloaded [83].

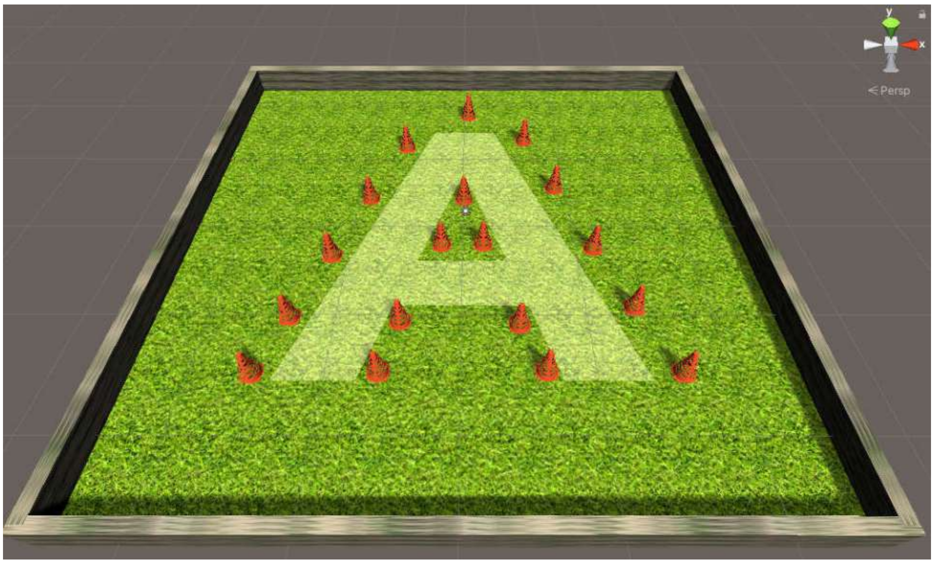



**Figure 33 Playing ground for first game scenario on a plane**

For exercises with just one degree of freedom, there were different possibilities to handle the only present degree of freedom. The movements of the patient that are transformed in movements inside the game are simple isotonic contractions, which means that the movements are on one plane for example from left to right. This can be implemented in a static game scenario such as pong games or space invaders where the player can move an object in one direction, but it can also be implemented in a more dynamic runner-like game scenario where a player is constantly moving forward and the positioning on one axis can be modified by the users/patients input. Since the target sport is soccer, this more dynamic approach was selected for an initial implementation. The main challenge with runner games is the creation of the environment. Because of a constant forward movement, it constantly needs to be updated and adjusted to the actual position of the player.

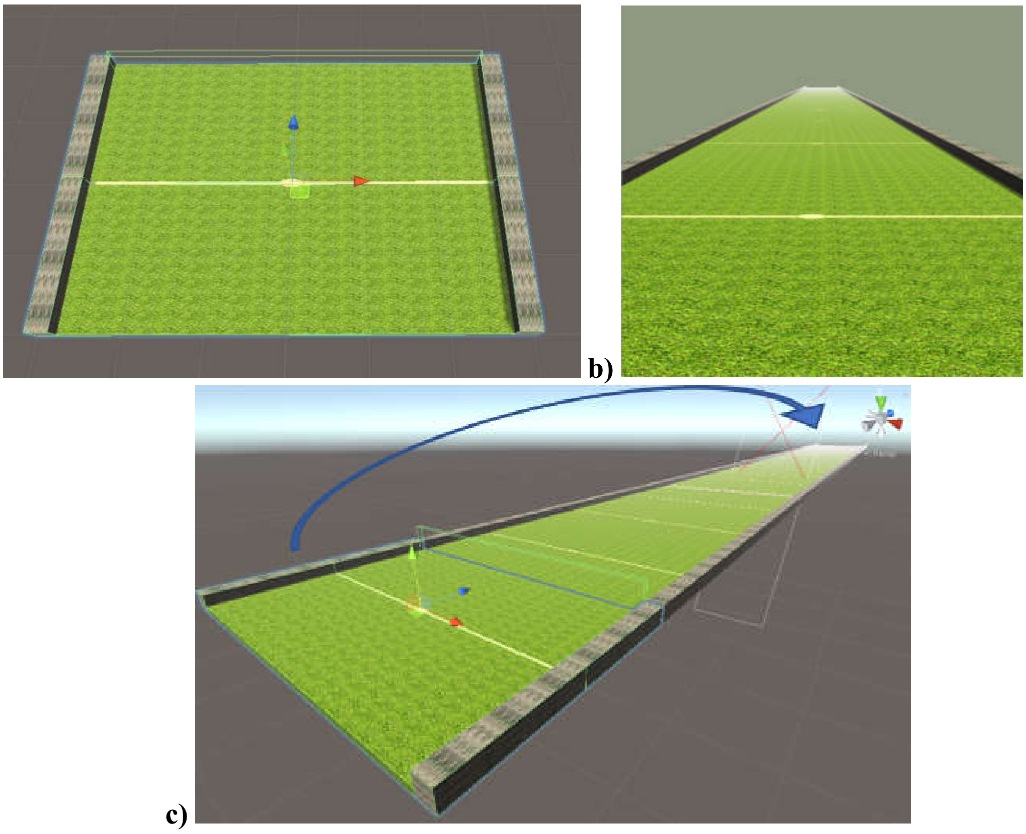
a) b) c)


**Figure 34 Images from the playing ground creation. a) One component of the ground; b) from the users perspective it should look like an endless field; c) mechanism to create the endless field**

Normally there are two possibilities to do this, either the environment is fully encoded and fully rendered at the start of the game, or it is constantly recalculated and newly rendered. The first option allows inserting more details in the environment but limits the size of the map due to memory consumption and could generally load the computing power and result in a less fluid game. With the second possibility, pure endless runner applications can be created, because the map expands dynamically and the memory is not overloaded. A drawback here is that this extension needs to be programmed and it is, therefore, more difficult to insert details and other more complex variables. Here, the endless runner is implemented as follows: The structure is the same as for the first game scenario and is composed of a plane with a grass-type surface and two walls on the sides to define the playing field (Figure 34a). To create, from the players perspective an endless-looking field (Figure 34b), the plane is expanded with a transparent cube that ranges from one side to the other and is placed on the extremity of the plane. This cube is used just as a trigger to signalize that the player passed the extremity. This plane then is duplicated 18 times and placed in series (see Figure 34c). By moving forward, the player releases the trigger each time the transparent cube is passed and a script is called. The script takes the list of all the plane objects, orders it by the Z-coordinates and moves the plane with the smallest coordinate in front of the plane with the highest coordinate. This continuous movement will result in a dynamically updating endless runner environment and by defining the position of the camera based on the position of the player, this endless field is animated.

### 4.4.3 Movement Registration

After the creation of the game environments, the next step, and probably the central aspect of the game, is introduced. It is the implementation of the movement registration. What is meant, is the process from the data transfer from the sensor to the PC and the consequent transformation of the sensor's data information to the movement of the player in the game. These two parts can be detached from each other by defining the contact point between them as the output of the sensor with its orientation given in Quaternions or Euler Angles. Normally, this process should be handled in this sequence, but due to a shipping time of around three weeks, the sequence was reversed and different methods to transform coordinates and orientation matrices to the movement of the player in the game were tested in order to be prepared when the sensor output would be evaluated.

The movement methods were tested for both scenarios the endless runner with a constant forward movement and the movement in all directions on the plane. In Unity, there are several possibilities to move an object from one position to another and based on the circumstances they work better or couldn't even be used. For example, one possibility is to add a constant force to the object and moving it in the direction it is facing. The force can be updated each frame or there can be a formula that defines the applied force. Another possibility is to use a predefined component that can be assigned to the object, the Character Controller, and implement the movement in a script that takes methods from this component in order to move the object. The Character Controller has an integrated method *Move* that takes a vector with three values that represent the motion by combining the direction with the speed and moving the object towards this new position. Since the Character Controller also contains a method *JumpSpeed*, that allows the user to define a jump when a certain key is pressed, this solution is often used to create simple jump and run games. Two last solutions use the *MoveTowards* method and the direct access on the transform component of each object. The transform component of an object defines its position, scale and orientation each by a vector with three components for the three axes. The *MoveTowards* method takes as arguments the current position of the object, the target position and the speed with which the object should move and calculates, for every frame, the position on the line between the actual and the target position and places the object in that position. Also the last method directly applies to the transform component of an object, but instead of calculating the position based on a target position, it calculates the position based on a movement vector. The selection of the right method, obviously, depends on the input method and therefore they were all tried out based on the tested input. During the testing phase, a simple 3D cube was taken as an object to move that should represent the player. The first two input methods, the keyboard and the mouse were tested. For these two methods, the Character Controller and the *MoveTowards* methods were used. When the keyboard input worked very well on the plane where the directional buttons define the directions the player should move on the plane, the mouse input was used to test the endless runner scenario. In this case, it worked very well because the *MoveTowards* method was used and by placing the mouse on the upper side of the screen and transforming the screen coordinates into game coordinates the player constantly moved forward. Even though these methods worked very well, it immediately became clear that these methods would not work with the output of the sensor.

In order to make a step towards the processing of the output of the sensor, the joystick of a PlayStation 4 controller was taken as an input method. The controller is connected via Bluetooth to the laptop using the platform Steam [84] and the magnitudes on the vertical and horizontal axes are taken for the left joystick. These magnitudes are values that range from -1 to 1 depending on the position and the consequent inclination of the joystick (see Figure 35a). Using a transformer value, the magnitudes on the x- and z-axis are transformed into coordinates on the game plane and using the *MoveTowrds* method the player moves towards this input defined target position. The basic assumption is that the range of motion of the joystick is mapped onto all coordinates of the plane, this means, that a neutral position of the joystick corresponds to the central position on the plane and, for example, the position of the joystick as in Figure 35b, corresponds to the position on the left border in the middle of the plane. By doing this, all the positions on the plane correspond to a combination of magnitudes of the joystick.

a)  b) 

**Figure 35 Registered movement from a ps4 controller from a) to b)**

This concept is very important and it will also be applied with the sensor in a second moment. Indeed, the resulting magnitude is nothing more than a trigonometric value defined by the inclination of the joystick and the length of the joystick itself and, as it will further be explained, the movement of the foot, for some types of exercises, can be seen as the movement of the joystick. For now, the utilization of the ps4 controller showed that this concept would work in combination with the *MoveTowards* method.

In order to close the gap even more towards the output of the sensor that still had to arrive, the data of other IMU sensors were tried to extract. The sensors in question are the IMU sensors integrated into smartphones. Each smartphone contains those kinds of sensors in order to rotate the image on the screen when the phone is rotated and to detect the movement, for example, during a game. The only problem is that the data of these sensors is not accessible easily. Different tries were performed to access the data through the android root and other methods to directly access the phone running information. Since all tries failed, an application-based solution was searched. Several apps show the data of all kinds of sensors, but only one app was found that logs and sends data in real-time: the Sensorstream IMU+GPS [85] (see Figure 36a, b). This Android App deals with Hard- and Software sensors that are integrated into smartphones and allow the user to select and observe the current values of all IMU sensors and in addition also the GPS position. From the selected values a stream is composed in CSV-Format that is sent by WLAN to a client or is saved on the SD-Card. The stream via WLAN uses the User Datagram Protocol (UDP) and the IP Address and the Target Port can be inserted before the stream is started.

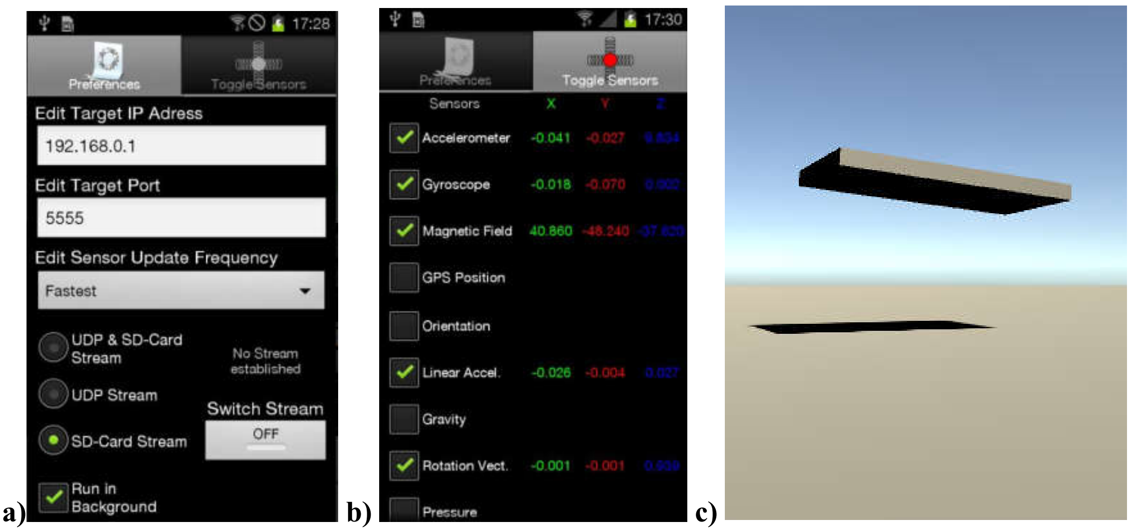



**Figure 36 a), b) Screenshots of the Sensorstream IMU+GPS [85] and c) Object that emulates the movements of the smartphone**

The description in the Google Play Store furthermore contained a code description to receive the data on the client. The python code creates a socket from the host IP Address and the Port and retrieves the information through this socket. This python code was used to transfer the data from the sensor to the laptop. The next step was to forward the data from the python environment to the C# environment that programs and controls the game in Unity. This task was achieved using a method published on GitHub by Youssef Elashry [86]. Also in this case a python socket is created on the Localhost to send and receive data from C# to python and vice-versa. In this particular case, data is sent from python to C#. To send the sensor data from the mobile phone to

C#, these two methods were integrated into each other so that the output of the first method is the input for the second method that sends the data to Unity. For the first time now sensor data could have been used to control objects in Unity with some good results, with the only problem being that the smartphone could not be placed on the foot due to the size and the fact that it slipped and shifted when the foot was moving. Anyways, with a simple rectangular object (see Figure 36c), the registered movements of the mobile phone were transformed in the orientation of the object.
This was done to identify possible limitations of this transformation. Two major limitations were found. The first one is the fact, that the mobile phones orientation data had ranges from 0 to 360 degrees on the x-axis and ranges from -180 to +180, while in Unity there are no ranges, the orientation values simply go from -inf to +inf. This resulted in the problem, that even though the orientation is detected correctly, by moving the device over the range values, the orientation is swapped and resulted in a wrong visualization. The second limitation is the well-known gimbal lock phenomenon. The gimbal lock happens when Euler angles are used to describe the rotation of an object and two of three angles cause the rotation around the same axis, losing in fact one degree of freedom [87]. This particular scenario happens when two axes collapse into one transformation and are the result of a sequence of rotation on the different axes. For this application, the gimbal lock will not represent a problem, but it was noted during this testing and therefore mentioned.
After some testing with the sensors of the smartphone, the ordered sensor arrived and the achieved knowledge could be used and applied for the registration of the movement with the IMU sensor. But before even starting with the registration, the challenge was to transfer the data from the sensor to the laptop. When the sensor was ordered, one of the reasons was the apparently working API with C# and Windows. But when the setup of the sensor was first tested, this combination seemed not to work, in fact, on the [88] mbientlab Community Forum, the developers of the firmware on the sensor announced that the support for Windows and C# is going to be stopped due to reliability issues and the lack of Windows/C# engineers on their team. This inconvenience led to a series of tries to get the transfer of the data to work. With the first tries, it was tested if there is still a way to get it done with the same notebook where the game was started to be programmed. The integrated Linux commands and the initialization of a Linux Virtual Machine were tried, but both possible solutions had problems with the Bluetooth modules that the sensor needs to create the connection. After this, it became clear that a second notebook is the only viable solution. An older laptop was taken where Linux was already installed to try if it would work. After the update to a newer version of Ubuntu, the dependencies were installed on Python and the connection between sensor and laptop seemed to work. Since the used notebook was relatively old, heavy and bulky a newer and handier notebook was taken and used for the data transfer. On this machine, Ubuntu was installed and the same dependencies were downloaded and installed on Python. After the updates and installation, the connection to the sensor was achieved also on this second notebook and the different modalities, outputs and functionalities of the sensor were

tested. With a Python script, the sensor could be programmed to blink the LED and to send different sensor fusion outputs or to access directly one of the sensors. During this testing phase, two major issues were identified. First, the installed firmware on the sensor resulted to be very unstable, causing different types of errors and second, the range of the connectivity resulted to be limited. First errors occurred already when the connection between the Python API and the sensor is initiated. When this works errorless the first time, each next connection resulted in a “buffer overflow” error and the script collapses. In most cases, after a second try, the connection was reassumed, but in other cases, multiple re-connections were necessary to reinstate a connection. When this was a manageable issue, the problems that came with the second issue were much more important. While testing and playing around with the sensor, it was noted that the Bluetooth connection between the sensor and the notebook was quite sensible and the range was restricted (interestingly this was dependent on the site to which the Ethernet cable was connected to the notebook). But the even bigger problem was, that each time the connection between the notebook and the sensor was lost, the firmware resulted to be in a completely buggy state from which it just randomly came out. When the connection was lost, obviously, no data was sent to the notebook and it could be noted. Since the connection, once lost, did not reinstate by itself, the script needed to be stopped and re-run. This already caused the first error message and different tries were needed to even re-get the connection. Then, the problem was that that the sensor resulted to be in a state, where its own modules were not found or detected and the sensor was not scriptable. In some cases, this again caused the abruption of the script and the consequent problems of the re-connection. It was noted that there was no indication about when the sensor would come out of this state and randomly, after some tries, the sensor found its own modules and the transfer of the data could be re-assumed. In the community forum, no workarounds or solutions were found what led to the conclusion that the only reasonable cause for this issue is given by the installed Bluetooth dongle in the notebook and the compatibility with the sensors Bluetooth port. Anyways, with a stable connection, the data transfer worked very well and the restricted connectivity range could be handled with a higher vicinity between the notebook and the sensor. This, together with the fact that when an error occurred the Python script needed to be stopped and re-run several times, were the reasons to maintain this two-notebook setup, where one notebook is used for the data transfer and the second notebook is used for the implementation and finally the visualization of the game.

At this point, one last major challenge of this part of the project was to send the data from one notebook’s Python script to the second notebook’s Unity environment. The challenge was to create a network in which the data transfer could be achieved as it was the case when the smartphone sensor data was sent from python to Unity. In that case, the Localhost was used to send and receive data. In this case, the utilization of the Localhost was not possible, because two notebooks were involved. Passing through a Wi-Fi network was not an option, to not be dependent on firewalls and other security aimed protections, therefore, a cable connection between the two notebooks was instantiated. By setting up an Ethernet connection and using the IPv4 settings as shown in Figure 37 for the Windows and Ubuntu network protocols a stable connection could be achieved. At this point, by using this same IP-Address the data could be transferred from the sensor to Python on one notebook, and from python to Unity on the second notebook and objects in Unity could be moved with the data from the sensor.

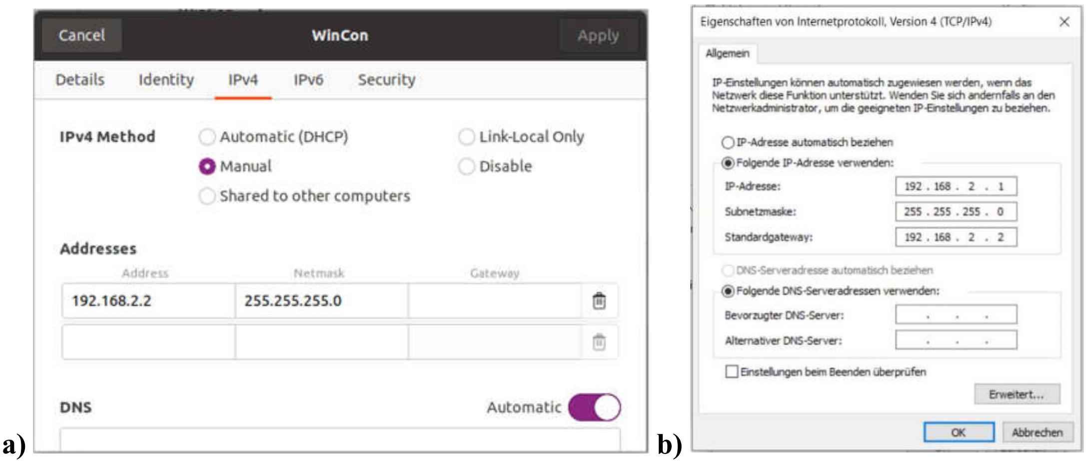



**Figure 37 a) Unity and b) Windows network connection settings for the data transfer**

### 4.4.4 Avatar modelling

After the creation of the connection and the consequent possibility to move an object with the data from the sensor, the moved object needed to be transformed into a more soccer adherent game object. Since the idea was to create a runner game, where the patient by moving its foot, or another body part, can define the direction of a running figure, the next step was to create the avatar for this figure. The patient should enjoy playing the game and should feel the adherence and the vicinity to his or her sport, represented by soccer in this particular case. To increase this emotional aspect, the avatar must come with a good and detailed rendering and realistic animations. The three individuated requirements towards the avatar, therefore, were a human-like appearance, a human-like running animation and the recreation of a soccer-like figure by wearing soccer clothes and soccer shoes. Since no pre-existing model was found, the avatar was self-made with the Blender tool [89]. Blender is a free and open-source 3D computer graphics software tool set that can be used for rendering, modelling sculpting, rigging and a series of other functionalities such as the creation of simulations and video editing. For this project, the modelling and animation parts were used for the creation of the avatar. Since there was no prior knowledge of Blender, before the modelling could start, introduction and basic command tutorial exercises were done. During this introduction, a very good tutorial was found on YouTube from the author Jelle Vermandere [90] where the process of making a 3D Character for a game in Unity is explained from the very beginning until the integration of the character into a Unity scene. Indeed, the process elucidated in the tutorial was followed and it worked flawlessly. The next part describes in detail the milestones and the different steps included in the tutorial and the way they were implemented in this project in order to create the avatar of a running soccer player. The process mainly can be divided into four parts:

1) **Sketching and modelling**: the very first step is the creation of a sketch of how the character should look like. Even though the GitHub page of the tutorial [91] contained the 3D model of the character in question (Figure 38a), the sketch and the form of the character needed some modifications. Therefore, a sketch of the desired form of the character was searched and downloaded [92]. The new sketch (Figure 38b, c) had shorter extremities and a bigger head and fits better the game concept because it will result in a smoother running animation. Both the original 3D model and the new sketches were imported in Blender and by modifying edges, surfaces and borders the model was tweaked until the shape fits the sketch (Figure 38d). While doing this two other particular details were modified, the pants were transformed into short pants and the shoes were trasnformed into soccer boots by adding cleates on the sole (Figure 38e).

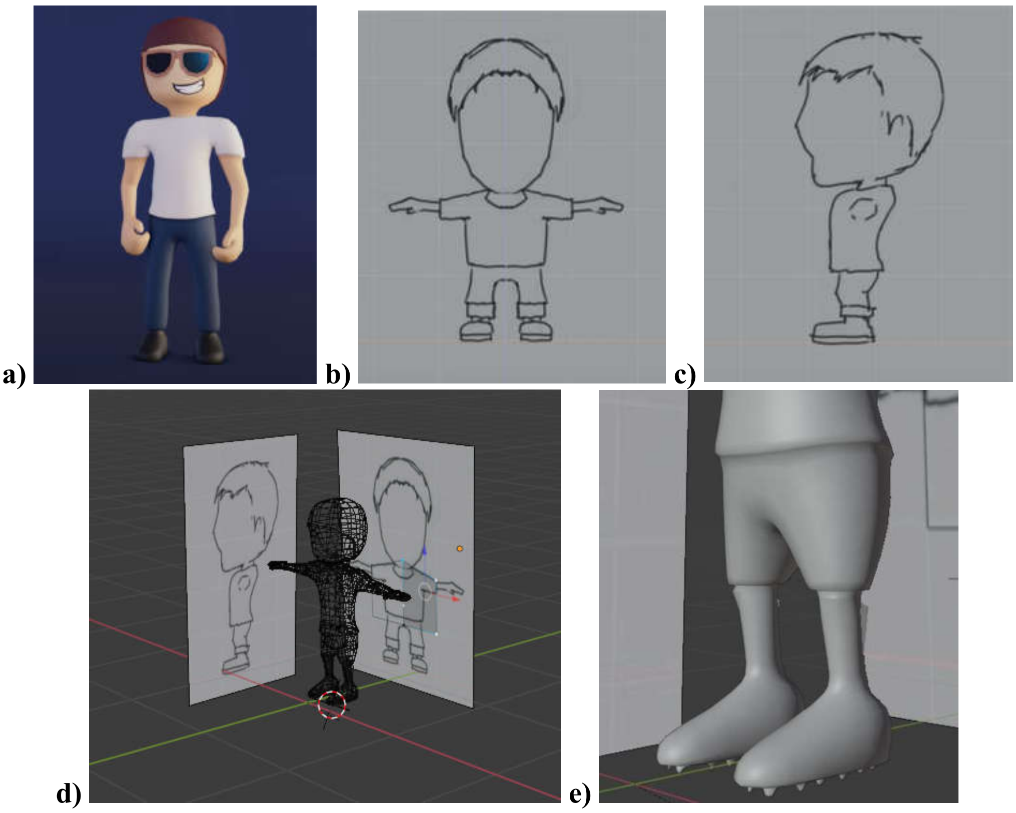
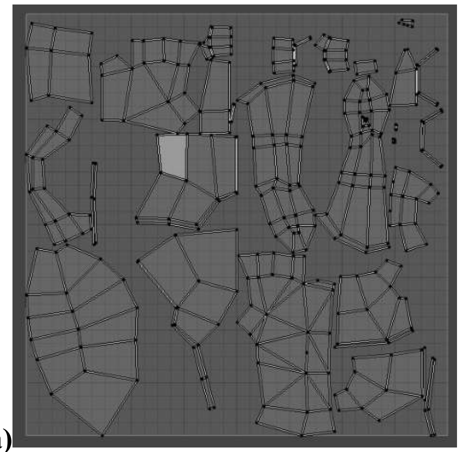
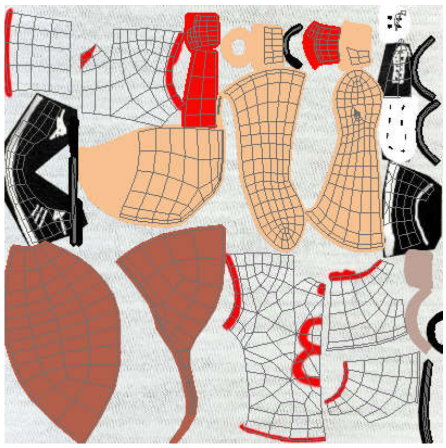



**Figure 38 Phase of the Modelling part. a) Original 3d character of the tutorial [90]; b) and c) New imported sketch [92]; d) Imported 3d model of the avatar and modelling with the images of the new sketch; d) addition of the cleats on the sole**

2) **UV-Unwrapping and Texturing**: before being able to apply a texture to the model, the surfaces need to be unwrapped. UV-unwrapping is a method to lay out all polygons that form the surfaces of the model on a flat plane. Since it is not possible to lay out the whole surface as one, the surfaces need to be virtually cut in order to flatten out these surfaces. These cuts should follow the seams on the clothes and on other edges where the flattening makes sense. By unwrapping all the virtually cut parts, it is possible to flatten out all the surfaces (see Figure 39a). Each flat part now can be assigned to a material with different textures (colour, shading, roughness, specular, etc.). Since there was the intention to test the application of the serious game together with some athletes of the F.C. Südtirol, their kits [93] were taken as templates for the texturing of the outfit (see Figure 39c). With a function called "Texture Baking", the created textures of each material can be "baked" or printed onto the previously created image with the different surfaces (see Figure 39b). This procedure allows creating just one material that applies to the whole surface. It is now possible to draw directly on the baked texture image or also on the model itself in order to add the final details to the textures, such as the details of the cleats and the details and the number on the shirt. The final model, together with the copied shirts, are shown in Figure 39d.

a)

b)


c)

d)


**Figure 39 Steps of the UV-Unwrapping and Texturing. a) Unwrapped surfaces; b) Colored surfaces; c) Shirt of the F.C. Südtirol [93]; d) Final 3d model of the avatar**

3) **Rigging and Animating**: the last two steps in Blender were needed to move the model and to create the running animation. Before creating the animation, the model needed a skeleton to move the different parts of the body. Blender already has an integrated human rig that can be used, therefore there was just the necessity to move, shrink and rotate the bones so that they fit the correct body parts of the model (see Figure 40a) and that the movements of the extremities look realistic. If this was not the case, there is the possibility to adjust the value of the influence a bone has on a certain polygon. When the movements were smooth enough, the rig and the model can be parented and the animations could be created. For the moment just two animations were created, an idle and a running animation. The idle animation should just be a simple movement of the body that will be used while the calibration of the sensor positioning before the game starts. In order to create an animation in Blender, a timeframe needs to be set, the initial and the final pose should be the same, and in the middle, the positioning of the bones can be adjusted for every frame. The second animation was the running animation. A series of images (see Figure 40b) show four different frames of the animation, where the legs and the arms were placed in the positions as they were running. From the initial and end and all the in-between positionings of the bones and extremities, Blender creates a smooth and well-defined animation.

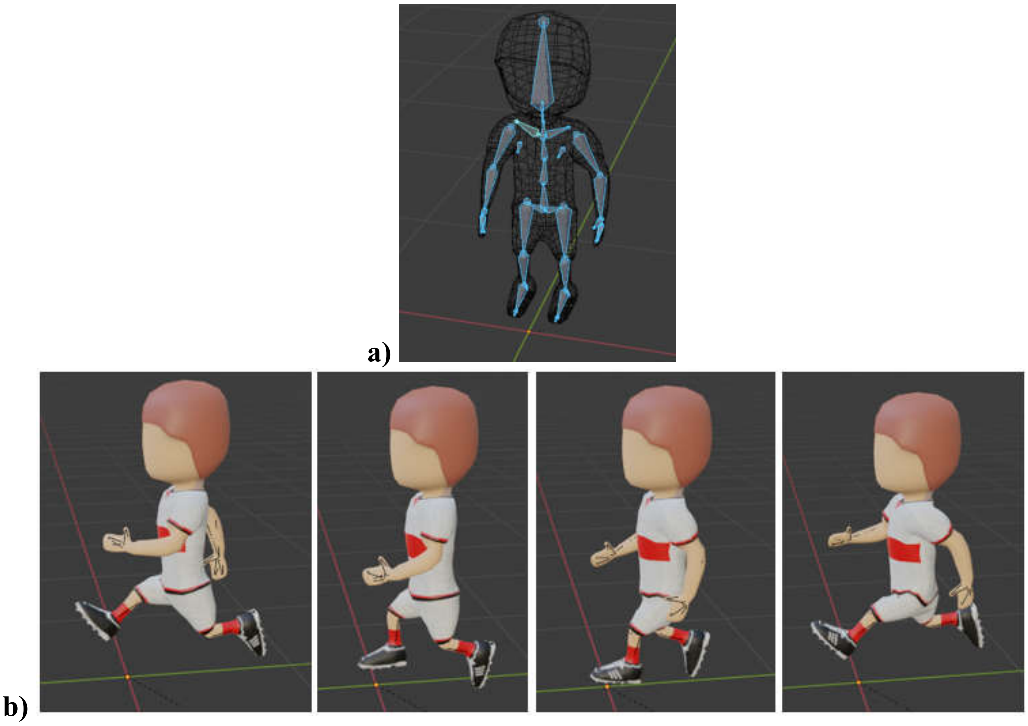


**Figure 40 a) Rigged model and b) Moments of the running animation**

4) **Export**: The last step was simply the export to facilitate the import in Unity. For this, the model is exported without the texture as a 3D object. This object can be placed into a Unity scene and by creating a new material with the mask of the previously created image of the textures this can be placed on the object. The animations are imported automatically, but there is the necessity to split them and to add them to the AnimatorController of the object. In the AnimatorController there is the possibility to define the transitions between the two clips and to define the transition times. With this set, the creation of the avatar was concluded and it could be progressed to the implementation of first game scenarios.

### 4.4.5 Movement Integration

When the interview with the physiotherapist Gabriele Vanzetta was done about his own experiences with ankle injuries and how they are treated, he gave his availability to evaluate further implementations and first prototypes in order to give some indications about what are circumstances in which the serious game would make sense and which are the exercises that should be integrated into the game. To do so, he needed to see the structure of the game and how the setup would be. Therefore, the next phase of programming should create these first gaming scenarios and identify what are movements that can be registered by the sensor and how they can be implemented in the game. From the initial test runs with sensor data and the achieved knowledge from the testing with the PlayStation 4 controller, it became clear that angles and trigonometry should be the keys to success. The possibility to detect a movement and the consequent definition of the new position only using the Accelerometer or the Magnetic field were tried initially, but the solution was discarded immediately due to the too high drifts and imperfections in the data measures. But, by using the sensor fusion algorithm and the resulting output, the orientation of the sensor could be used with highly accurate results. When on one side the position could be measured with very high accuracy, it also puts a limitation. The limitation is that only those exercises could be recreated where well-defined angles could be measured and only the differences of the span of these angles could be registered and transformed into movements of objects inside the game. Therefore, exercises or movements were searched and tried where the ankle ligaments and the surrounding musculature are activated and loaded and where the movement is characterized by well-defined angles.

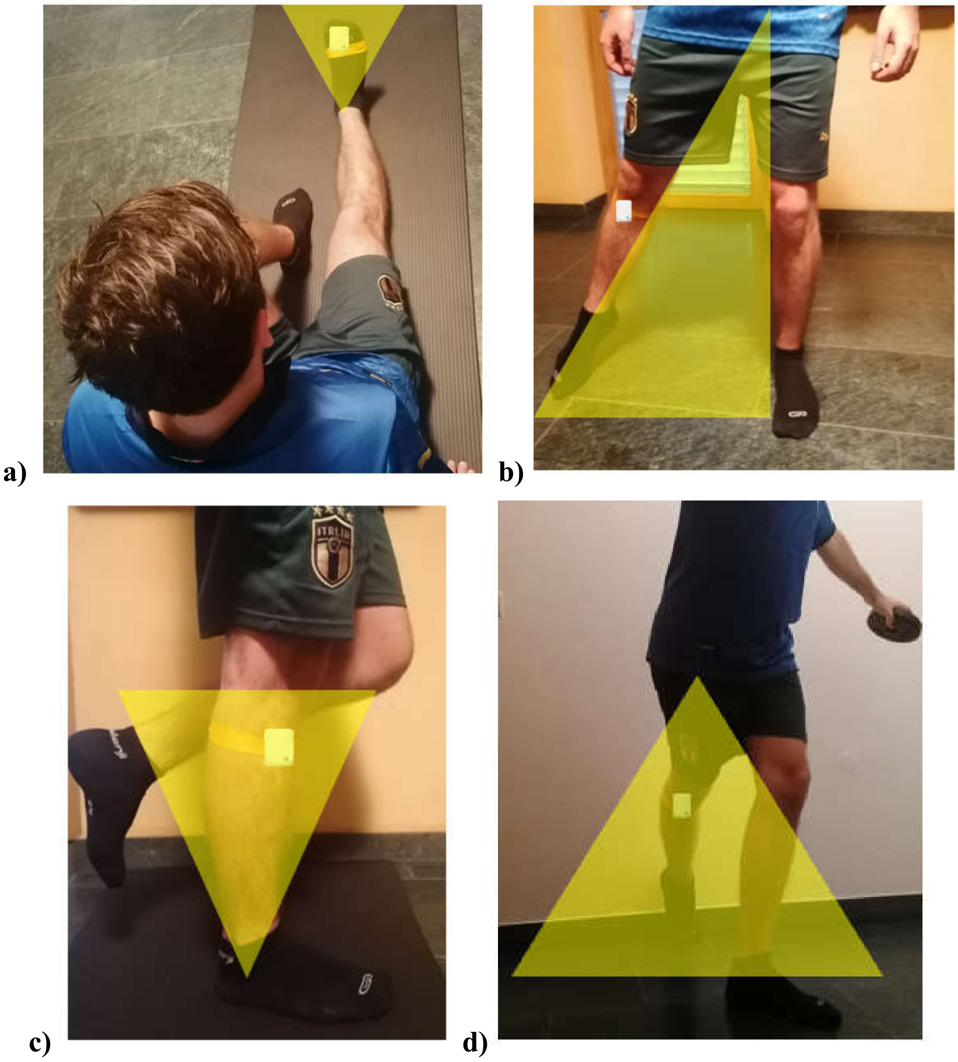



**Figure 41 Example of exercises that are included for the registration of the movement**

Figure 41a-d show some of the tested poses and exercises. For all of them, an angle is defined that can be registered by tracking the orientation of the sensor. For the first two poses, the orientation of the sensor can be registered on two axes and resulting in an implementation where two degrees of freedom could be used. Starting from these exercises, the movements that were made during the exercises were tried to be implemented one by one into the game scenarios. These were the steps that were followed for each of the exercises:

1) Getting the right angles. By observing the received data from the sensor while doing the exercises, the involved angles, that characterize the movement during the exercise, were identified, parsed and selected to be forwarded from one notebook to the other one

2) Implementation of the player's movement. The registered angle values are received in the Unity script for each frame. Now, this angle needed to be transformed into the position of the player inside the game. As already mentioned, there were circumstances where one angle is used and circumstances where two angles were used. Even though they rely on the same concepts, the implementation was slightly different:

   2.1) One degree of freedom:
   When one angle is used to define the position of the player, different strategies were tried to achieve the best performance. Starting with the assumption that the player should constantly be running forward it was challenging to transform the resulting angle values into the correct position inside the game. Since the orientation changes did not behave like buttons (on or off) a movement based on the CharacterController was excluded. Neither a movement based on the *MoveTowards* method was feasible because it resulted to be not responsive enough. Therefore, a less complex and artistic but notwithstanding efficient method was used. With the player constantly running forward (z-axis in Unity) by applying a constant velocity vector pointed forward, the position on the horizontal axis (x-axis in Unity) is directly modified based on the angle of the sensor. This direct positioning means, that the coordinates on the x-axis are modified after the application of the movement vector. This results in a very responsive and fast left and right movement combined with a constant forward movement of the player. Since from the start on the player is running, the running animation is always turned on.

   2.2) Two degrees of freedom:
   In contrast to the first game scenario, in this scenario, the player is not running constantly forward but the movement is completely defined by the values of the two involved angles.

Since the playing field is composed of a quadratic plane, every position needs to be reachable by the maximal ranges the patient can afford with the exercise. The playing field can be seen as a coordinate system and each point needs to be mapped to the combination of two angles, resulting in the coordinate of the player on the playing field. When for the first scenario the *MoveTowards* method did not work well, here it resulted to be the best method. With the mapping of each point on the playing field to each angle combination, for each frame, the position could be calculated and the player moved towards that position at a certain speed. When the player arrived at that position, and the angles did not changed in the meantime, the player stops running and stays in that position. When the distance to the next target point resulted to be greater than a predefined cut-off the player re-starts the running animation and moves toward the target point. Also in this case, the movement resulted to be smooth and responsive

Now that the implementation of how the player movement is working for the two game scenarios is defined, the central and essential concept of how the distances of the movements on the axes are calculated is explained. The goal here is to define where the player should be placed on the x-axis for the first scenario and which are the target points towards the player should move for the second scenario.

The positioning is retrieved directly from the sensor data as follows: before the start of the game, the user has to calibrate the positioning of the sensor by defining its range of motion and consequentially the maximum ranges of the involved angles. This means, that he/she needs to pose for a short period of time (5 seconds) in each position where the maximal and/or minimal angles of the exercise are defined (P2 and P3 in Figure 42). These angles correspond to the extreme positions of the playing field inside the game (E1 and E2 in Figure 42) on the horizontal and eventually on the vertical axis. Now that the maximal angles and the predefined coordinates of these extreme positions in the game are known, trigonometry comes to play. The range of motion is given by the range of the angle that is formed by connecting these extreme points with the anchor point (P1 in Figure 42) and by identifying the central position (P4 in Figure 42) on the virtual arc that connects the extreme points, two equal right triangles can be created.

Each of the two triangles spans half of the range of motion and reflects the positions on one side of the axis in the game. The values of the maximal angles resulting from the calibration are then used to calculate the length of the edge spanning between the anchor point, P1, and the point at the maximal range, P3. This edge of fixed length can be seen as the length of the leg (or the foot, based on the exercise that is performed) and it will not change during the game, therefore it can be used for the calculation of the constantly changing position of the vertex P3 during the game.

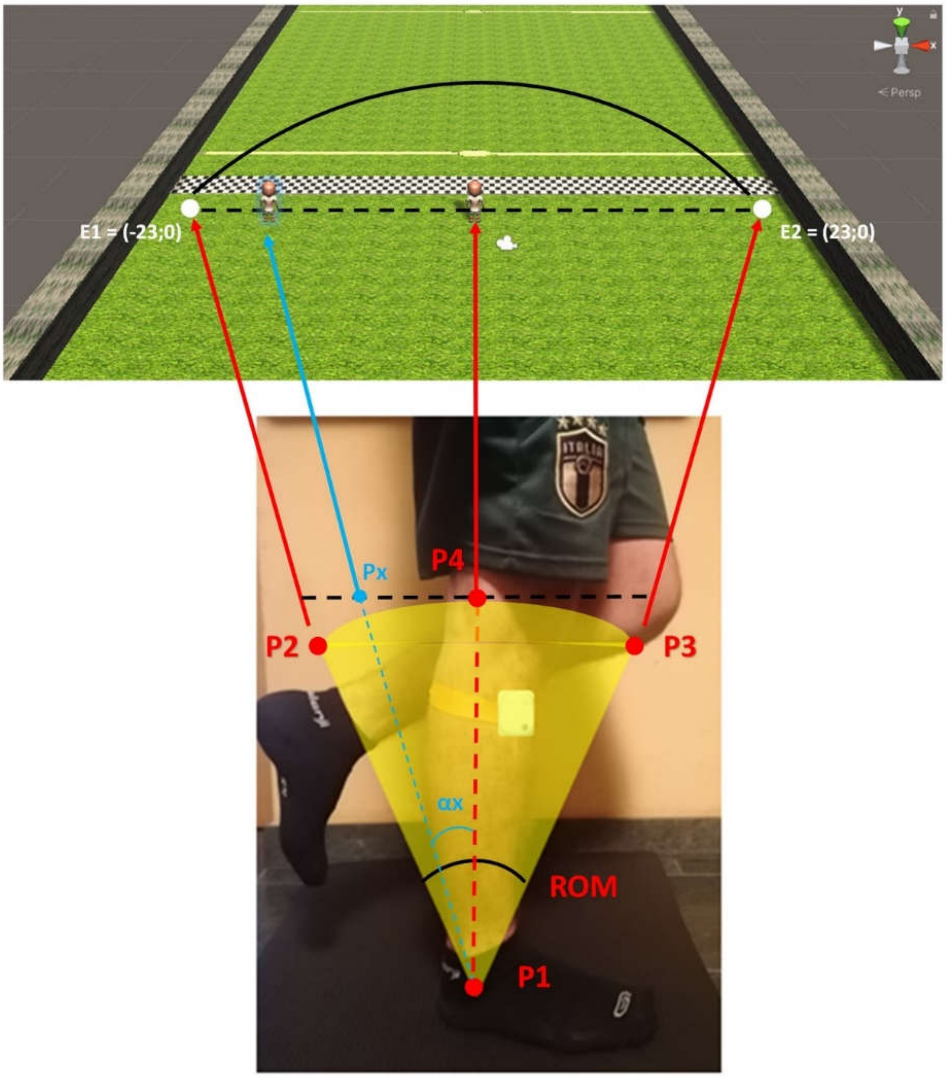



**Figure 42 Representation of the concept of the mapping from the users' movement into the movement of the player inside the game. The exercise is composed of squat movement of the right leg.**

With the use of trigonometry two angles and one edge is enough to determine all the other missing values. In this case, the two angles are given by the rectangular angle and the angle that resulted from the calibration; and the length of the known edge is given by predefining the coordinates of the extreme points, E1 and E2, in the game and by setting the middle of the playing field as the origin of the coordinate system. For the example visualized in Figure 42, by using the formula

5) $$\sin(Max\ range) = \frac{E1.x\ (=23)}{h}$$

the length of fixed edge *h*, between the anchor point and P3 can be calculated. If there is only one degree of freedom, the calibration is done only on one axis, while for two degrees of freedom the calibration needs to be done on both the axis to identify the length of the fixed vertex and the position of the central point. After the conclusion of the calibration, the game starts and at each frame, the sensor sends new angular data and the position of the players needs to be updated. When during the calibration step the coordinates of P2 and P3 were known, now, for each frame, the coordinates of the new position, *Px*, are calculated knowing the length of *h* and the angle *αx*. For each new data that is sent from the sensor, the first thing that is done is to check if the angle is greater or smaller than the angle that characterizes the central point (=half of the range of motion). This is needed in order to determine the sign (+ or -) that is placed in front of the distance from the origin and *Px*. Then, using the formula

6) $$Px.x = \frac{\sin(\alpha x)}{h}$$

the coordinates, in the case of the example Figure 42 only the x coordinate, since the z is updated automatically while the player is constantly running forward, is calculated. With the calculation of the new coordinate, the player will be placed at these coordinates and rendered at that position

in the next frame (blue concept in Figure 42). In the scenario with two degrees of freedom both the x- and the z-coordinate is calculated in this way and from them the resulting target position is put together, towards which the player then moves.
Since the characteristic angles change is depending on the exercise, the implementation of the player movement resulted to be slightly different for every exercise. But, this also means, that new exercises that follow this same principle with characteristic angles could easily be integrated into the game.

### 4.4.6 Creation of First Prototype

Now that the movement of several exercises is translated into the movement of the player inside the game, game-engineering interventions were performed in order to bring to life the different game scenarios. During the creation of these game scenarios, the focus was to identify and show the possibilities towards different scenarios that then, in a second moment, would be implemented into completely working and playable games. A total of six scenarios were created at this point, three of them were based on one- and the other three were based on two degrees of freedom. The background ideas and the implemented characteristics are described in the following:

1) Alphabets
   For this exercise, a letter, or any other shape, is highlighted on the surface and the user should cover the whole highlighted surface by running over it and by staying inside its limitations. Here, cones were added around the shape and a ball was placed in front of

the player that should be dribbled along the path in order to create a more soccer-related scenario. The steering of the movement was performed with the movement of the foot in all four directions as in Figure 41a.

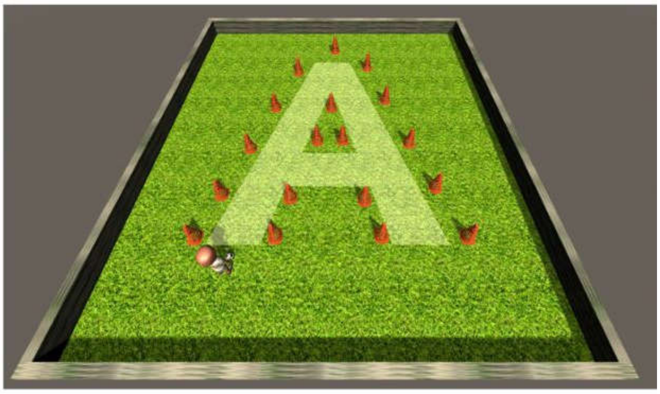



**Figure 43 Alphabets exercise game interface**

2) Star excursion balance test

The Star excursion balance test is a common exercise that is used to assess the mobility and the balance of the ankles. By planting one foot, usually the injured one or the one that should be assessed, the user is asked to slide with the other foot as much forward as he/she can along lines that are attached on the floor in a star-like shape without losing the balance. By measuring the most distant touched point on each line, the overall balance of the ankle can be assessed. Here, in this scenario, a model of a Champions League trophy [94] is placed along one of eight axes starting from the central point. By emulating the same movement as for the real star excursion balance test, the user can move the player towards the trophy and collect it. When the player returned back to the central base, a new trophy was spawned along another line. For this exercise, the movements shown in Figure 41b were used. When this movement worked very good on one side, as soon as the legs crossed each other the characterized angles were not that clear anymore, resulting in inaccurate mappings of the positions.

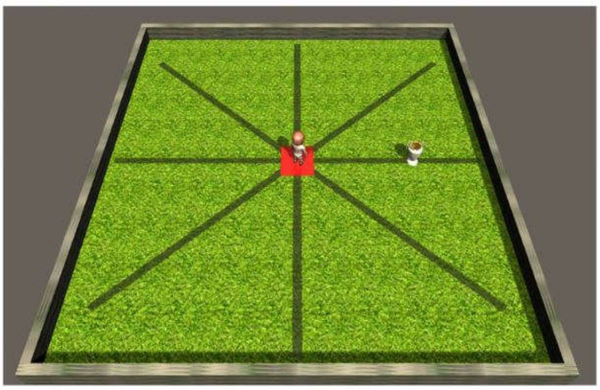


**Figure 44 STAR Excursion balance test game interface**

3) Balancing plane

With the balancing plane, a different game scenario was tested. In this game scenario, there is no running player, but the whole plane is moving. The idea of the game is to have a ball on the plane that should be rolled towards the trophies by avoiding the holes. The ball follows the physical rules and is moved by rotating the plane that directly mirrors the orientation of the sensor. The exercise scenario would put the sensor on a balance board, or on a weight that the user is holding, and while standing on the board, or while balancing on one foot and holding the weight with stretched arms in front, the user modifies the orientation of the plane by moving and rotating the sensor.

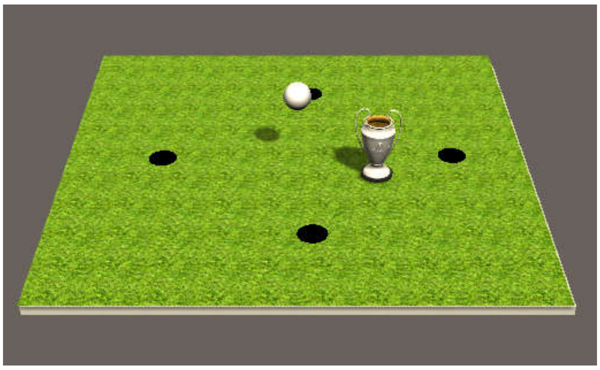


**Figure 45 Balancing plane game interface**

4) Running – path

The next three exercises are all three based on the player always moving forward and with the orientation of the sensor defining the horizontal position of the player. The exercises for the movement of the player can be of every type, the only important thing is to have one characteristic angle that can be measured and that allows the movement of the player. In fact, of the previously presented exercises and movements (Figure 41a-d), all can be used for these exercises. In this particular game scenario, the player needs to stay inside a path made of small soccer cones while running forward. The cones were created in Blender and different colours were added in Unity. For all these running scenarios a soccer ball is placed in front of the player to simulate the dribbling that is done in normal practices.

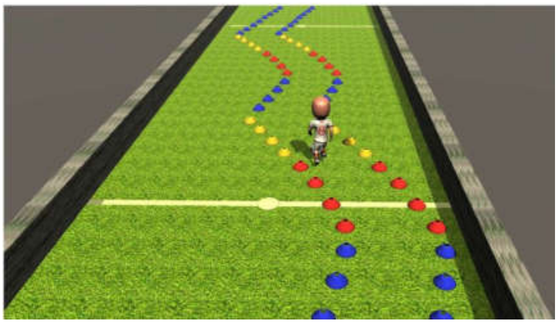


**Figure 46 Running path game interface**

5) Running – obstacles
For the second game scenario, different objects and items are placed on sparse on the playing field that a soccer player normally finds on the pitch, such as different types of cones, nets and freekick walls, to form an obstacle-run where the player should run through. Except for the soccer net [95], all obstacles were self-created in Blender.

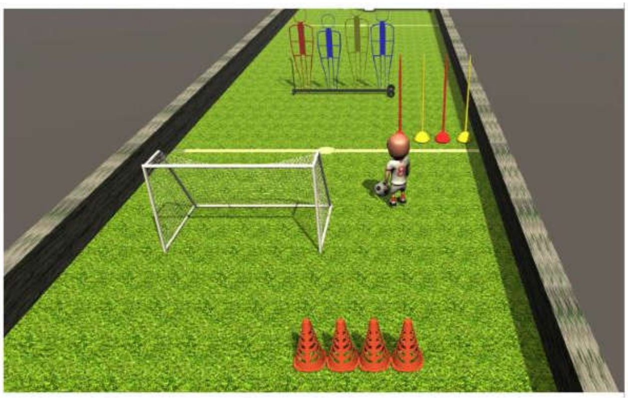


**Figure 47 Running obstacles game interface**

6) Running – opponents
For the last game scenario, the player should dribble past opponents that are running towards the player. The opponents were made from the same 3D object as the player and a script tells them to constantly run forward.

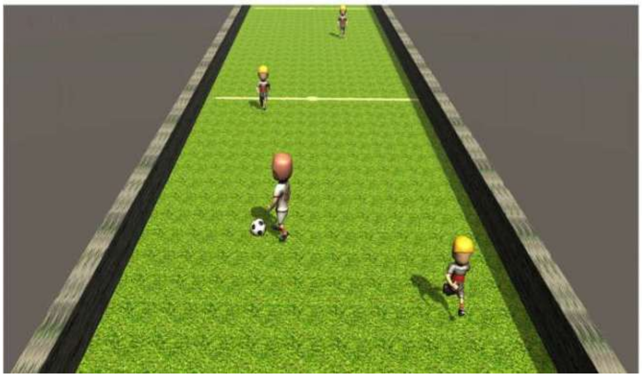


**Figure 48 Running opponents game interface**

The game-engineering steps for the creation of this first prototype were kept at a minimum, this means that no collision between game objects was registered, the placed obstacles were hard-coded in their respective positions and there was no re-spawning of the obstacles and of the path. The main focus was simply on the representation of different possibilities and game scenarios that are then analysed together with a physiotherapist.

### 4.4.7 Testing and Evaluation of First Prototype

With the integration of the sensor movement, the definition of four exercises and the simplistic implementation of these six game scenarios the very first prototype was evaluated together with the physiotherapist Gabriele Vanzetta. At the training centre of F.C. Südtirol, these different exercises and games were tested and evaluated and different conclusions were drawn. The main focus of the evaluation of the prototype was first, to check if the setup and the application of the serious game would work, and then to identify those exercises and game scenarios that make the most sense and that should further be implemented.

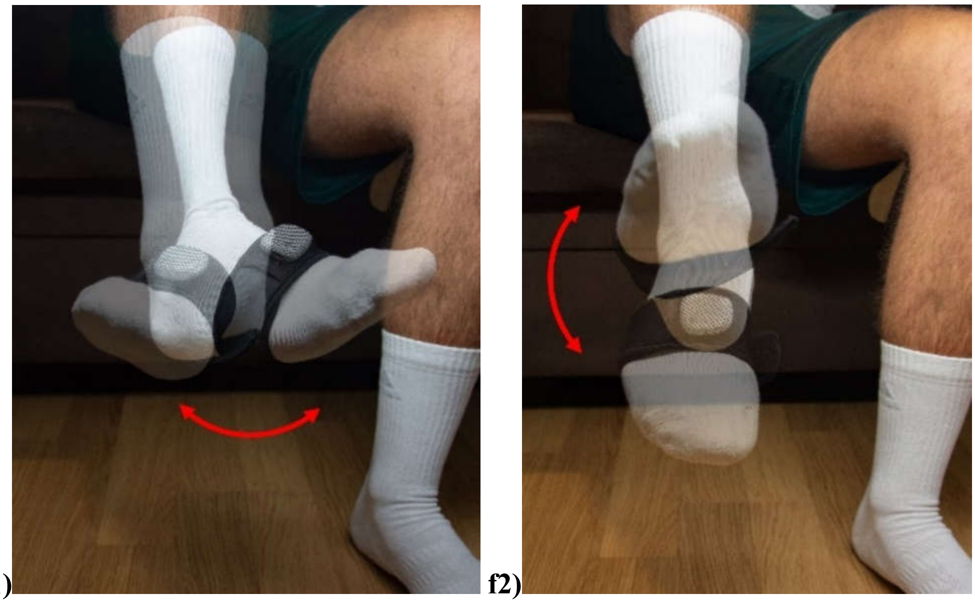
During these early phases of testing and with the implemented setting, it became clear that the movement of the player inside the game resulted to be much smoother when the range of motion was relatively small. For example, the exercises where the sensor was put directly on the foot worked much better than the exercises where the sensor was placed along the leg and the movement of the whole leg was taken as the movement to translate into the players' movement. There was also the indication, that with more complex exercises the concentration towards the exercise is higher than it would be with an exercise where just the foot needs to be rotated. An example. The exercise where the star excursion balance test was recreated, even though the exercise makes sense and is effective, it is already a complex exercise and to reach the maximum point on the line is already an incentive to be concentrated and motivated during the exercise. In contrast, simple contractions, range of motion exercises, foot and toe flexions and curls are much more frustrating for the involved patients. Nearby these considerations, Gabriele Vanzetta was impressed by the enjoyable aspect and the playability of the game scenarios and by the easiness of setting up the range of motion during the calibration phase. This last aspect resulted to be essential because it allows utilizing the game in the acute phase by setting up a protected range, but also in later exercises by using elastic bands in order to strengthen the ankles' surrounding musculature. The overall good impressions led to the conclusion that the application of the serious game would definitely have a positive impact on the rehabilitation process of ankle injuries and that the focus should be on simplistic exercises. These exercises are not only very efficient in an early rehabilitation phase under optimal loading but could also be progressed to later rehabilitation phases and used also as prevention exercises.

At the end of the evaluation, the next steps were planned. After the implementation of the selected exercises, a second round of evaluations was programmed together with other exponents of the soccer organization F.C. Südtirol. This second evaluation phase should also include athletes that are in the process of rehabilitation after ankle injuries in order to assess their acceptance of this new method and how a rehabilitation session would be approached with the utilization of a serious game in it.

### 4.4.8 Integration of identified exercises into Final Prototype

With the positive feedback from the first application of the serious game together with a physiotherapist and with the identification of several new and already present movements and exercises, the goal now was and to implement a working game engine around the identified exercises and to filter out those exercises that were too complex or not efficient enough.
The selected exercises were the following:

1) Horizontal (Figure 49a) and vertical (Figure 49b) inversion and eversion movement of the foot
2) Dorsi- and plantarflexion of the foot (Figure 49d)
3) Toe and heel raise (Figure 49e)
4) Knee bend and squat (Figure 49c)
5) Combination of in- and eversion and dorsi-and plantarflexion of the foot (Figure 49 f1-f2)



f1) f2)

**Figure 49 Implemented exercises and movements**

Except for the last one, they are all exercises based on one degree of freedom, meaning that they will be played with a constant forward movement of the player in the game and they combine both exercises where no weight is put on the ankle and exercises where the patient uses the own body weight to load the ankle. The last exercise is a combination of the first two exercises and allows two degrees of freedom and will have a separate game scenario. For the newly included exercises, the part of the setup was done as described in the section before in order to register the movement along with the characteristic angles and to let the player move in the right way.

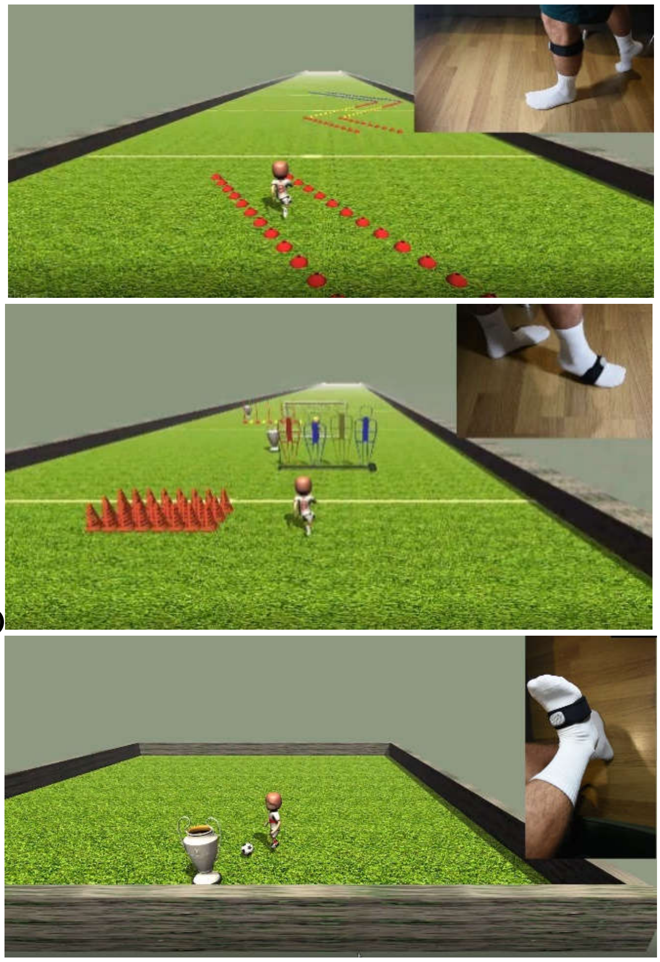
### 4.4.9 Scene-Management of Final Prototype

With the registration of the exercises and movements done, the game engineering was re-assumed. It was chosen to keep only two game scenarios for the endless-running games and one scenario for the game played on the plane and allowing two degrees of freedom. Since the user should be able to choose the movement to perform and the game scenario before starting the game, an interaction menu was created to achieve this task (see Figure 50), for the visualization of the menu. The Menu should also give the possibility to define the duration of the game and eventually select the difficulty for each level. By clicking on the Play button, the game is started with the selected options. Before defining how the three levels were implemented, the background script and the scripts for the different movements are explained. When hitting the play button, the selected options are saved to the storage as '*PlayerPrefs*' objects, this is a way in Unity to pass variables across different scenes, and since the menu interface was created as a separate scene, this needed to be done.


**Figure 50 Menu interface where the game scenario itself, the level, the exercise and the playing time can be selected**

After the menu scene, the game scene is loaded. Since there is only one game scene a background script, scriptmanager, was created to set up this scene according to the selected options. When the running games, called *Ankle Runner,* are loaded, the endless road is activated and the plane is deactivated and vice-versa if the other game, called *Trophy Hunter,* is loaded. After the setup of the playing field, the calibration process is started. Here, depending on the selected exercise, all the involved maximal ranges are detected. A short text advises the user of the position in which he/she should stay for 5 seconds to determine the maximal ranges. In the background, during these five seconds where the user should stand still, the mean of all incoming values for the analysed angle is calculated. After the five seconds, the next mean for the next maximal range is calculated and so on, until the user placed the sensor in all involved maximal ranges. After the calculation of the central points and the length of the missing edge, as described in the previous section, the game itself starts. Depending on the selected game and level, the scriptmanager loads a separate spawn-manager script for each of the three game scenarios. When for the second game, the Trophy Hunter, the spawnmanager has the only task to spawn a trophy somewhere on the plane after the player catches the only one present on the screen (see Figure 51c), the spawnmanager scripts for the two scenarios of the first game are slightly more complex. For the running game with obstacles and trophies (see Figure 51b) the spawnmanager script keeps track of all already spawned obstacles on the playing field and spawns new obstacles along the field when the player arrives at a certain distance from the most distant obstacle. This ensures that new obstacles are always spawned at the same distance between each other and that the user did not see too far from where the player stands. In between every second obstacle, a trophy is spawned and in order to increase the difficulty to pass through the obstacles, the trophies are always spawned at the opposite half of the playing field as the one before. When the soccer ball, placed always in front of the player, makes contact with the trophy, the trophy counts as caught and a sound signal is emitted. Otherwise, when the soccer ball makes contact with one of the obstacles, the forward running is blocked and the player can only run sideways to pass by the obstacles.

For the second running game (see Figure 51a), the player should follow a path made of small soccer cones. The paths are spawned one after another and are composed randomly following a set of rules. Each time the player is approaching the end of the current path, a new path is spawned. The components that form the path are pairs of two cones with the same colour placed horizontally to each other always at the same distance. The spawnmanager script creates segments of such pairs by shifting them vertically and horizontally to form a diagonal set of pairs pointing towards the opposite direction as of the previous segment and by taking a different colour as the previous one. The length of such a segment range randomly from 5 to 20 cone pairs, but is stopped when the pairs come too close to the borders of the playing field. Finally, from two to five segments are concatenated to form a path. Between each pair of cones, a transparent cube is placed as a trigger to detect if the player correctly passes in-between the cones. Also in this case it is the soccer ball that activates the trigger and an acoustic signal is emitted to signalize the success.



a) b) c)

**Figure 51 Implemented game levels with the movement of the sensor that steers the player inside the game. a) Ankle Runner -Path; b) Ankle Runner – Obstacles; c) Trophy Hunter**

Independently from the game mode, objects, paths and trophies are spawned until the time set at the start of the game is reached. While the second game changes immediately the scene when the time is reached, for the first game mode a finish line is spawned instead of new obstacles and cones and the new scene is loaded when the player crosses this finish line. The final scene shows the achieved score, resulting in the percentage of coughed trophies or the percentage of correctly passed cone pairs (see Figure 52a) for the first game mode and the amount of in total caught trophies for the second mode(see Figure 52b); and the range on the characteristic angle of the selected exercise. For the second game mode, where two angles and therefore two ranges are present, the mean of the two ranges is shown.

a) 

b) 


**Figure 52 Final scene interface. a) Ankle Runner scenario with the percentage of caught trophies or correctly passed cone pairs; b) Trophy Hunter scenario with the amount of caught trophies**

With the final score and with the indication of the range of motion, the performance can be judged and the progress can be tracked. The user now can choose between restarting the game with the same selections, returning back to the menu and modifying the game scenario, the exercise or the duration of the game or quitting the game and closing the application. After all these conceptualization and implementation steps the application was ready to be used. Before stepping over to the final testing phases a presentation video was created by recording the screen with the actual game and by putting the registration video of the foot movement as Picture-in-Picture in the video. The created videos are present in the additional materials.

## 4.5 Testing scenarios

From the creation of the final prototype, the third and last phase of the diploma thesis was initiated. As for the second phase, Figure 53 gives a schematic visualization of the testing and evaluation phase. Here, two testing scenarios were planned in order to assess the acceptance by involved patients and also to check the usability and portability of the system. The first testing scenario was seen as some sort of dress rehearsal for the second scenario and should give indications about how the procedure could work, how long the exercises should be, how the connectivity with the sensor works and how the sequence of the exercises should be created. Nevertheless, also the users' progress, feelings and emotions are observed and evaluated.

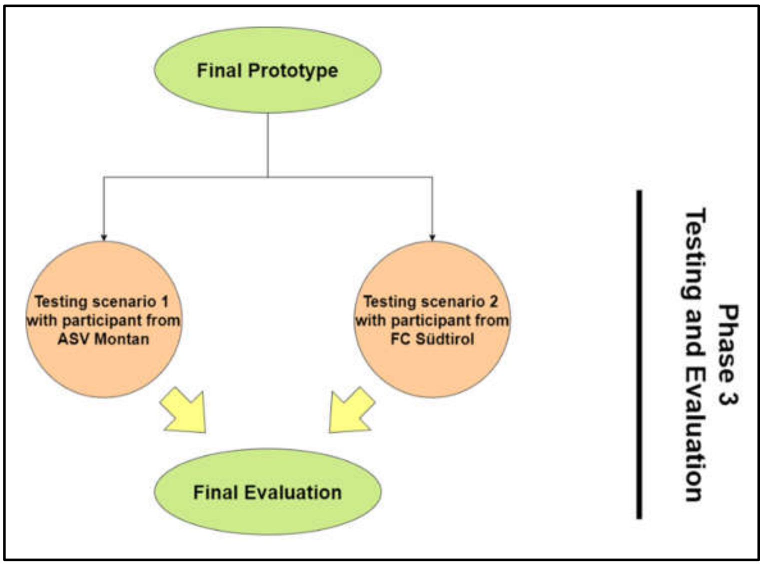



**Figure 53 Schematic visualization of the testing and evaluation phase**

### 4.5.1 Testing scenario 1 with a participant from ASV Montan

This first testing phase was planned together with a young local soccer player that plays in the local soccer selection. D.P. is twenty-three years old and suffered over one month before the start of the testing an ankle injury, not by playing soccer, but in other circumstances. He did not have to take surgery, but X-ray images showed the involvement of lateral ankle ligaments and also the pinching of a nerve. He, therefore, had regular physiotherapeutic sessions and had to stay absent for a longer period of time from the pitch. Even though the physiotherapist recommended a longer resting time, after around three weeks, he restarted to train with the team but continued to stay out for the games. Since there is no professional medical staff at the local soccer team, it was his decisions and his feelings that led to the return to sport and since the ankle ligaments weren't healed completely, the ankle swelled up after the training session and some movements still caused pain. This was the state when the testing of the serious game started. It was a state where the rehabilitation process was still ongoing and where a phase of exercises aimed to strengthen the surrounding musculature should be performed. It is important to mention that the three planned sessions were performed in parallel to his normal training sessions, where he would have performed some warm-up exercises and then he would have trained normally with his teammates. As already mentioned, three sessions were performed in one week (Monday, Wednesday and

Friday) in parallel to his normal soccer training sessions. For each of the training sessions, an exercise plan was created. The training plan foresaw three repetitions for every exercise-game combination with an increasing playing time, 30, 45 and 60 seconds for each repetition. The first two repetitions should allow the user to get confident with the exercise and with the game and for the last repetition, the achieved score and the range were annotated in order to track the progress over the training sessions. For the exercises with one degree of freedom both running game scenarios were performed. The training plan and the achieved results for each training session are shown in Table 4. The comparison between the first and the third session shows an increase in the overall range of 3.5° and an overall increase of 8% for the scores (see also Figure 54 and Figure 55). These results show both an increase in the confidence in the ankle and an increase in the ability to steer the player. But what really stands out was the reached playing time and consequentially time spent with rehabilitation exercises. When during a normal training session, the only time spent with specific exercises that load the ankle ligaments was during the warm-up exercises, now, more than 20 minutes per session were spent with highly specific exercises. In total, over 1 hour was spent with these exercises during the whole week. From D.P.'s feedback, it became clear that this approach really helped him to spend more time with these exercises and that it triggered his inner motivation and ambition to become better and to see the progress in front of his eyes and not only across what the physiotherapist said during the sessions.

**Table 4 Results of the three training sessions with D.P. from ASV Montan**

| Exercise | Level | Repetition | Duration | Session 1 | | Session 2 | | Session 3 | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Range | Score | Range | Score | Range | Score |
| Game 1 Mode 2 | Level 1 (Obstacles) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 50° | 45% | 45° | 78% | 62° | 85% |
| | Level 2 (Path) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 68° | 69% | 50° | 75% | 60° | 84% |
| Game 1 Mode 3 | Level 1 (Obstacles) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 36° | 80% | 38° | 82% | 38° | 83% |
| | Level 2 (Path) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 24% | 88% | 32° | 85% | 29° | 73% |
| Game 2 | Trophies | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 46° | 20T | 48° | 23T | 49° | 21T |
| Game 1 | Level 1 (Obstacles) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 15° | 80% | 20° | 91% | 20° | 90% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Mode 4 | Level 2 (Path) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 18° | 75% | 21° | 81% | 20° | 89% |
| Game 1 Mode 5 | Level 1 (Obsta-cles) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 39° | 80% | 49° | 84% | 51° | 81% |
| | Level 2 (Path) | Rep 1 | 30s | / | / | / | / | / | / |
| | | Rep2 | 45s | / | / | / | / | / | / |
| | | Rep 3 | 60s | 48° | 85% | 43° | 89% | 47° | 79% |

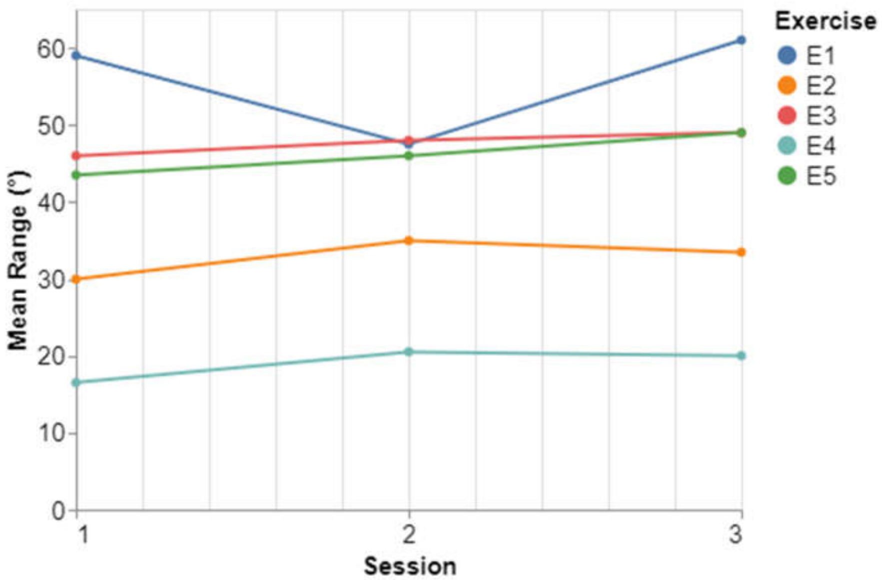



**Figure 54 Progression of the mean range from the two noted repetition per exercise and training session of D.P. from ASV Montan**

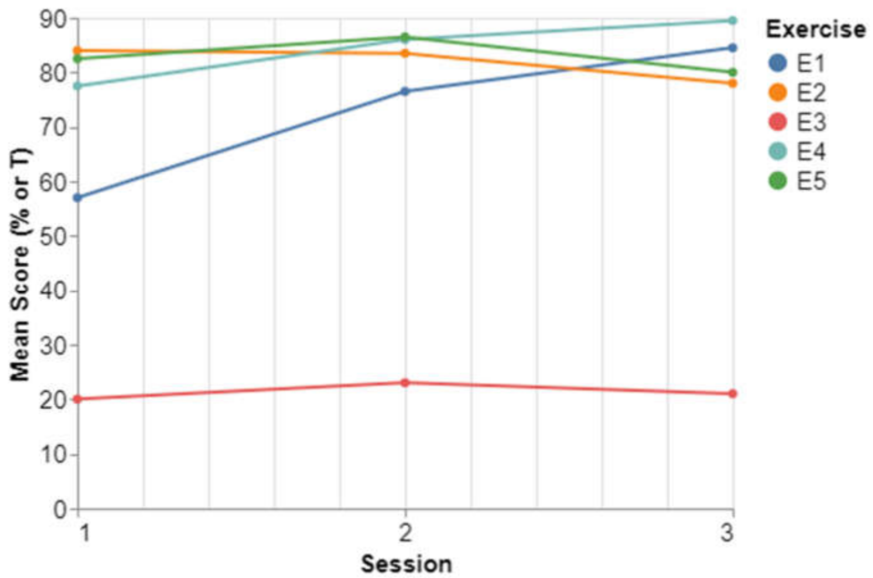



**Figure 55 Progression of the mean score (Percentage or amount of Trophies (E3)) from the two noted repetitions per exercise and training session of D.P. from ASV Montan**

### 4.5.2 Testing scenario 2 with a participant from FC Südtirol

With the awareness that the application works as part of a rehabilitation process, the application was tested in a second and more professional scenario. When the project started, it was planned to test the serious game in an early phase of rehabilitation together with exponents from the F.C. Südtirol, but due to the sensitivity and the importance of these early rehabilitation moments and due to the timing, the application was tested in a later phase. In a first meeting, the system was presented to Gabriele Vanzetta, another physiotherapist of F.C. Südtirol and the involved patient. V.V. is twenty-one years old and plays in the youth sector of F.C. Südtirol since 2018. The actual injury happened around three weeks earlier to this meeting. It was a non-contact inversion movement of the right foot that happened during training camp. Since it was not the first ankle injury for V.V., he already sprained both his ankles in the past few years, the medical staff of the F.C. Südtirol decided for a longer and more conservative rehabilitation. In fact, he stayed away from practice three weeks earlier to this testing phase, the two weeks the testing phase spanned and after that another week. In total therefore he completely stayed away six weeks from regular practices before even starting the on-the-field recovery. This duration is clear above average, but it definitely was necessary because he already suffered multiple ankle injuries before and because the ankle was still unstable and swollen at the start of the testing phase. Since the youth team trained every day, he also came every day for his rehabilitation session. Even though he was followed during his rehabilitation process, the physiotherapists were not able to be present for him at every session, therefore he was told to perform a series of exercises alone and then to have a ride on the stationary bicycle.

Given these starting situations, the first meeting was used to show the setup and function of the serious game to both the physiotherapists and the involved athlete. From the implemented movements different exercises were tried, in combination with elastic bands and other techniques in order to identify those exercises that should be performed in the next sessions. The images in Figure 56 and the videos attached in the additional materials, show the tested exercises and movements together with the exponents of F.C. Südtirol. From these exercises 6 exercises were chosen to be part of the training program, they were:

- E1) Sensor is placed on the injured foot; user is laying; user spans an elastic band around the feet. The registered movements are inversion and eversion of the injured foot (see Figure 57a)
- E2) Same as exercise one, but registered movements are dorsi- and plantarflexions of the injured foot (see Figure 57a)

E3) Sensor is placed on the injured foot; user is sitting with both feet on the ground; an elastic band is attached at the injured foot, span around the other foot and hold in the hand. The registered movements are inversion and eversion movements of the foot (see Figure 57b)

E4) Sensor is placed on the injured foot; user is sitting; user holds up the knee in front with both hands; an elastic band is placed around the injured foot and fixed under the other foot. The game with two degrees of freedom is played, therefore both inversion and eversions and dorsi- and plantarflexions are registered (see Figure 57c)

E5) Sensor is placed on the injured foot; user is standing; an elastic band is placed around the ankle and fixed by a second person. The registered movements are toe and heel rises (see Figure 57d)

E6) Sensor is placed under the knee of the leg with the injured ankle; that leg should be placed higher than the other one; an elastic band is spanned between the ankle of the injured foot and fixed under the other foot. The registered movement is a front and back movement of the higher placed leg (see Figure 57e)

E7) Additional exercise (see Figure 57f), not included in the training program but performed in the second week. The registered movement was the forward and backward movement of the whole leg that was destabilized with an elastic band and by placing an elevation under the heel of the user

It was furthermore chosen to perform each exercise only with one game mode but with longer repetitions of 90 seconds each, by switching the games at each session. With the definition of this training program, four sessions over the span of two weeks were done. The results are shown in Table 5.

**Figure 56 Images from the first meeting with exponents from the F.C. Südtirol where the system and the setup was presented and the training program was defined (Further images and videos in the additional materials)**

**Figure 57 Images from the selected exercises for the training program (Further videos and images in the additional materials)**

**Table 5 Results of the four training sessions with V.V. from F.C. Südtirol**

| Exer-cise | Repe-tition | Dura-tion | Session 1 | | Session 2 | | Session 3 | | Session 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Range | Score | Range | Score | Range | Score | Range | Score |
| E1 | Rep 1 | 90s | 18° | 69% | 20° | 71% | 21° | 84% | 24° | 85% |
| | Rep2 | 90s | 15° | 85% | 19° | 78% | 22° | 83% | 22° | 89% |
| | Rep 3 | 90s | 22° | 78% | 20° | 80% | 22° | 80% | 22° | 90% |
| E2 | Rep 1 | 90s | 52° | 90% | 55° | 89% | 55° | 90% | 59° | 89% |
| | Rep2 | 90s | 51° | 87% | 58° | 95% | 59° | 91% | 58° | 95% |
| | Rep 3 | 90s | 54° | 89% | 49° | 89% | 60° | 92% | 61° | 96% |
| E3 | Rep 1 | 90s | 54° | 76% | 49° | 77% | 53° | 90% | 55° | 92% |
| | Rep2 | 90s | 47° | 75% | 50° | 80% | 58° | 83% | 55° | 97% |
| | Rep 3 | 90s | 59° | 80% | 59° | 81% | 59° | 87% | 56° | 86% |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| E4 | Rep 1 | 90s | 54° | 31T | 53° | 32T | 55° | 31T | 63° | 34T |
| | Rep2 | 90s | 52° | 31T | 54° | 34T | 61° | 33T | 64° | 33T |
| | Rep 3 | 90s | 49° | 29T | 55° | 28T | 62° | 32T | 60° | 31T |
| E5 | Rep 1 | 90s | 39° | 90% | 40° | 91% | 51° | 92% | 50° | 94% |
| | Rep2 | 90s | 45° | 89% | 45° | 86% | 46° | 89% | 49° | 91% |
| | Rep 3 | 90s | 48° | 95% | 44° | 89% | 47° | 88% | 51° | 95% |
| E6 | Rep 1 | 90s | 13° | 65% | 14° | 81% | 18° | 79% | 20° | 90% |
| | Rep2 | 90s | 12° | 70% | 18° | 82% | 19° | 86% | 19° | 85% |
| | Rep 3 | 90s | 15° | 70% | 20° | 86% | 18° | 83% | 23° | 89% |

As it was in the first testing scenario, also with V.V. the performance was better after every session, see Figure 58 and Figure 59. The means of the range show an increase from 38.3° to 45° and the means of the scores an increase from 81% to 91%. Even though these are very satisfying results, what again was the most important aspect was the time spent doing these exercises. Per session, a total of 27 minutes of activation time was achieved and in total 1 hour and 52 minutes were spent with exercises. Especially at this specific moment of the rehabilitation process, the time spent with such strength and balance exercises is fundamental for a better recovery and to minimize the risk of re-injuries when the athlete return to sport.

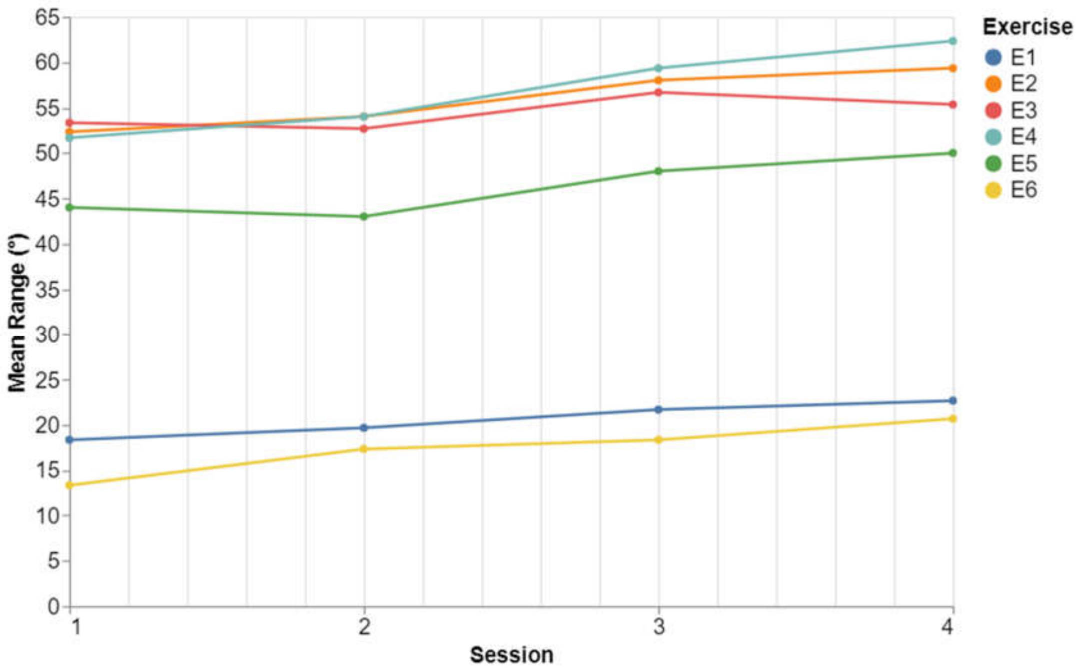



**Figure 58 Progression of the mean range from the three repetitions per exercise and training session of V.V. from F.C. Südtirol**

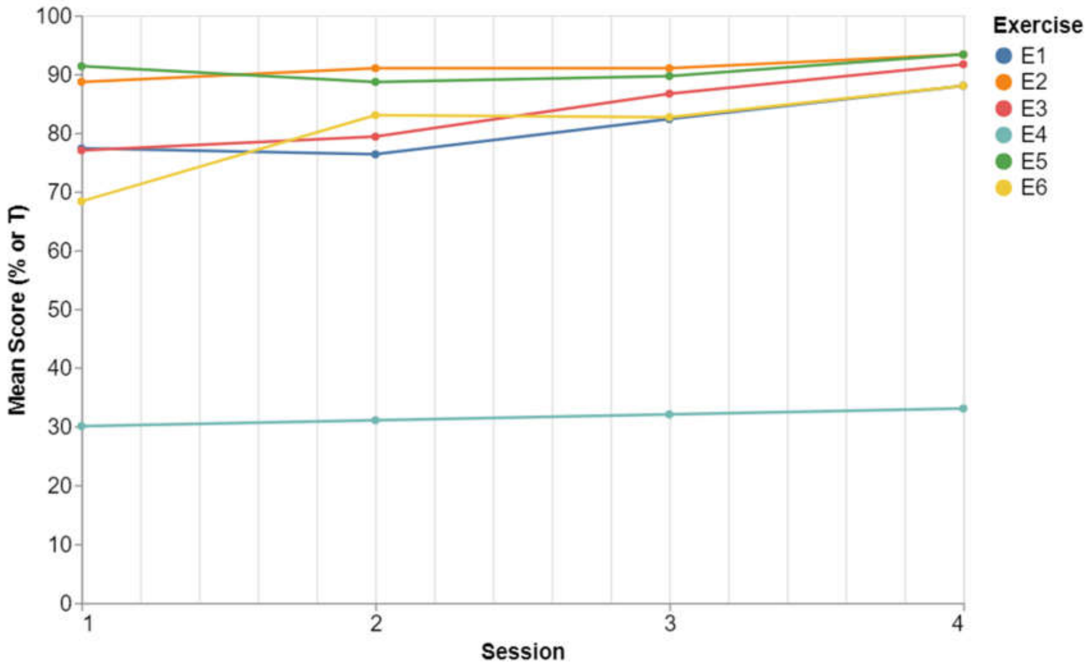



**Figure 59 Progression of the mean score (Percentage or amount of Trophies (E4)) from the three repetitions per exercise and training session of V.V. from F.C. Südtirol**

### 4.5.3 Evaluation and Feedback

The strict analysis of the results of the two testing scenarios already showed that the application of the serious game in a rehabilitation process increased drastically the time spent with rehabilitation exercises compared to normal training sessions and that the performance became better after each session. Furthermore, the feedback from the involved players and physiotherapists also resulted to be very good. The players' response was excellent since they were followed respectively for one and for two weeks and they were able to perform precise exercises that enjoyably strengthened their ankle musculature. In normal circumstances, they would never have spent so much time doing specific rehabilitation exercises. Also the fact that at the end of the session they felt some sort of exhaustion on the lower limb musculature showed the effectiveness and consequence of the exercises. Other very positive aspects were the ones regarding the motivation, concentration and dedication in overall towards the exercises. In fact, the high activation time was perceived as much shorter than it actually was, leading to the conclusion that the time spent with the exercises passed quickly and in an entertainable way. The concentration, driven by the own ambition to become better, was at the maximum while the exercises were performed leading to a very high dedication and consequentially to a high adherence towards the exercises and the proposed system. Finally, both players, when asked if they would continue to perform such exercises

together with the application of the serious game, agreed that it would be beneficial for them and that they enjoyed the rehabilitation sessions.
When the feedback of the involved athletes was good, also the feedback of the involved physiotherapists was positive. Nearby the definition of future steps and what should be modified on the game, Gabriele Vanzetta, who followed the process of the creation of this diploma thesis from the beginning, was asked to evaluate the concepts of the serious game by filling out a system usability scale (SUS), attached in the Additional Materials, and by giving his personal final considerations. To cite Gabriele Vanzetta, his final considerations were:

*"The system, presented as a prototype, does not yet meet the requirements necessary for an application in everyday-life clinical practices. In fact, a rehabilitation instrument must be easy, intuitive and "practical" in order for the patient to gain the desired benefits. However, the idea of combining rehabilitation exercises, often rather boring, with a digital interface can play an important role in increasing the patients' adherence to treatment. Often in fact, especially when it comes to ankle sprains, patients (as well as healthcare professionals) tend to minimize the problem. Having a tool that allows you to visualize and monitor the progress would allow the physiotherapist to have a history and understand if the patient is improving by objectifying the results obtained from the rehabilitation."*

# 5 Discussion

The objectives of the diploma thesis were, first, the assessment of the theory regarding the incidences of ankle injuries in different sports and the elaboration of both the theoretical and the practical concepts regarding the rehabilitation after such injuries. Then, together with the analysis of best-practice examples and the analysis of already published systems and methods, the requirements towards a serious game-based for rehabilitation purposes were identified. From these requirements, the serious game application was idealized, implemented, tested, improved and finally applied in two rehabilitation scenarios to evaluate the usability and the acceptance of the system on the field by the involved participants.

With the work of this diploma thesis it was possible to elaborate all the previously identified objectives and to confirm, on one hand side, the problematic situation regarding ankle injuries, but on the other hand, also the potential and importance of digital rehabilitation tools in order to increase the adherence of the patients towards the therapy.

## 5.1 Theory Assessment and Requirements

The problematic situation is characterized by a very high incidence, around 13-20% of the injuries happening in sports are ankle injuries, by a high re-injury rate of nearly 10% and the increment of the risk of chronic ankle instabilities with repetitive injuries caused by a low acceptance and adherence towards the therapy and by the too subjective and influenced by too many extern pressures but highly sensible and delicate return to sport decision. With the creation and evaluation of a survey, this situation was confirmed and, in some cases, resulted to be even more problematic. In fact, the ankle resulted to be amongst the most injured body parts in the majority of the involved sports and a possibly even higher re-injury rate was estimated from the answers of the participants, where already in around 7% of the cases a forced comeback or a too fast return to sport caused a further injury. In contrast to most of the analysed papers, where high professional situations were analysed, the majority of the participants of the studies, even though they play and perform at a high level, did not come close to the standards of such first-class organisations. Furthermore, only a very small portion of the involved participants are full-time athletes. This fact has huge consequences on the time that can be spent with rehabilitation exercises, the motivation, concentration and dedication towards these exercises, the received attention from a physiotherapist and consequentially on the outcome of the therapy. Therefore, despite the fact that the workload may be lower than for professional athletes, the long-term effects due to a suboptimal rehabilitation for non-professional athletes could be even worse. A possible solution towards more efficient treatment methods is the inclusion of serious games during the rehabilitation process in order to increase the adherence and the acceptance from the patients towards the therapy. From a series of already published systems and methods, it was possible to study the process that is involved with such projects and to collect responses and feedbacks from the study designs. These projects show that if it is possible to integrate conventional exercises into a game-like scenario, the motivation and the concentration increase and that the users are much more entertained while doing the exercises. Though, a very important point and also one of the main reasons that led to the idealization of this diploma thesis is the fact that the serious game needs to be adapted to the situation in which it is used to maintain a high level of motivation and acceptance. This means, that the game situation and the gaming context need to be close to the situation and the circumstances of the involved users and this is something that was missing in the analysed projects in the state-of-the-Art-Research. Given the high incidence of ankle sprains in all kinds of sports, the goal of the diploma thesis was to identify the potential of serious games in this specific context and since none of the identified projects and systems was idealized for this context, it was implemented for the sake of the diploma thesis. Nearby the adherence to the world of sport, and soccer in particular, and nearby general requirements such as an easy and quick setup and the recreation of conventional exercises other identified requirements were the possibility to integrate different kinds of exercises, to foresee the utilization of medical equipment such as balance boards and elastic bands and to have different game scenarios for a more entertaining game.

## 5.2 Practical application

The final prototype of the game was tested and evaluated inside two rehabilitation processes of two young soccer athletes. The two guys were followed respectively for one and for two weeks with a total of seven rehabilitation sessions where the serious game was used. When the overall mood and the feedback were good, what really stood out was the achieved activation time. But since the time spent while doing these exercises was time spent with a videogame, it was not perceived to be that long by the involved users. This is a very good indication of the fact that the serious game distracted them from the actual situation and that they were fully concentrated on the outcome of the game. The enjoyment of the situation was evincible also from the feedback after the utilization of the game and the admission that they would have continued to use the serious game application. With the final prototype, it was possible to recreate six different exercises, but the system can easily be adapted to include even more exercises and movements. When the overall acceptance by the involved players was really good, also the feedback and the acceptance by the involved physiotherapists was good. According to them, a further implementation of the prototype into a final product would really have positive influences on the mood and the motivation of the patients towards these exercises and consequentially increase the time spent doing these exercises and consequentially affect the outcome of the physiotherapy in a positive way. For reasons of sensibility of the situation the serious game was applied in a later rehabilitation phase where the main goal is to build up musculature and to give stability to the ankle, but of how the game was implemented it would be perfect for early rehabilitation exercises where a protected range of motion needs to be identified and where the observation of the progression is essential. With this application, both would be possible because before every exercise the user needs to define its range of motion and since it is given by the combination of different angles, and the values of these angles are registered by the sensor, the range of motion can be tracked over different training sessions. This is a very important factor because it firstly brings objectivity to the evaluation of the process and second because both the physiotherapist and the patient can interpret and see the results of the rehabilitation process. As already mentioned, this allows an objective and evidence-based evaluation of the actual situation and progress and it gives an extra motivation to the involved athlete by comparing the results of different sessions. Anyways, the application of the serious game as it was for the scenarios for this diploma thesis showed that the utilization worked in later rehabilitation phases indicating that the serious game could also be used for prevention exercises. This is possible due to a very flexible and adaptable setup where the user itself defines the difficulty of the game by defining a greater or smaller range of motion and by including more or less additional items such as different elastic bands or balance boards. Especially in a younger target group, the utilization as prevention exercises could have a huge effect on reducing the number of ankle injuries and increasing the sensibility towards the importance of these exercises, not only during a rehabilitation process but also as prevention exercises.

To conclude, the work of this diploma thesis confirmed all the positive aspects regarding the utilization of serious games for rehabilitation purposes and showed that further implementations of the proposed system could support both physiotherapists and patients for a better, more objective and definitely more enjoyable rehabilitation.

# 6 Future work

The outcomes of the diploma thesis evidenced the potential that is still hidden behind the application of serious games in the medical sector and in particular for rehabilitation exercises. As part of the implementation and evaluation process, the system was tested together with two participants that were recovering after a serious ankle sprain. These testing scenarios showed that it definitely was possible to utilize the serious game application in the context of a rehabilitation, but that there are still improvements that should be considered in future versions of the game. Nearby these technical improvements, during the whole process of the creation of the serious game and especially during the testing scenarios the potential of such application became even bigger and there are almost unlimited possibilities that can be integrated into such systems. This was summarized also by an involved physiotherapist that supervised the implementation of the serious game. He said that the actual system yet did not satisfy the necessities for the utilization in everyday-life medical scenarios, but that an implementation into a final finite product would bring significant improvements into rehabilitation processes. In fact, the actual system needs to be improved in order to allow an easy and quick setup. Nearby the efficiency of the exercises, this is the most important aspect when it comes to final products because if the system is too complex it will never be used regularly. What this means, is to have an application that can be started in one click, the sensor can be attached easily and after a short calibration, the game starts. In order to bring the actual system to such a state, the receiving of the data from the sensor needs to be integrated into the game script and definitely into just one notebook. For the sake of simplicity and because at that point it was seen as the best solution two notebooks were used, but in a future version, the system should run just on one hardware device.

With this improvement and with the guarantee of a stable connection and a stable and smooth game scenario, the system can already be defined as a product that easily can be used for rehabilitation purposes. But, as already mentioned, the system can always be expanded in order to include even more functionalities and possibilities. Starting from the inclusion of even more exercises, movements and game scenarios a what was already included in the first versions of the prototype but then not finished to implemented is the creation of training programs where the physiotherapist can define a series of exercises, game levels and the duration of each exercise and the relaxation time between the exercises that are then played one after another. This should then automatically create an output file where the achieved results and the playing time is listed. This could be very useful for exercises where the physiotherapist cannot be present, for example for exercises that should be performed at home, but also in order to track the achieved results across the different rehabilitation sessions. Another important feature that should be implemented in future versions is the possibility to regulate the difficulties of the different levels. At the moment the user defines the difficulty itself by defining the range of motion, but in future versions, the speed of the player the spawning intervals and the structure of the game scenario should be adjustable. Two other interesting improvements to let the system be even more portable are the implementation of the serious game on mobile devices and the possibility to use the mobile device as the sensor for the registration of the movement to include into the serious game. This would not work for every exercise, due to the size of the mobile phone in contrast to a smaller sensor, but for a part of the exercises, it would work as well as with the smaller sensor. A last possible improvement would be the autonomous and independent registration of a new movement.

As seen, there are quite endless possibilities that can be used to improve such a system and that evidence, even more, the potential that can be exploited with a further implementation of the "Ankle Runner".

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# Additional Materials

### AM1: Filled out System Usability Questionnaire by Gabriele Vanzetta

| | Strongly Disagree | Somewhat Disagree | Neutral | Somewhat Agree | Strongly Agree |
|---|---|---|---|---|---|
| 1. I think I would like to use this tool frequently. | ☐ | ☐ | ☐ | X | ☐ |
| 2. I found the tool unnecessarily complex. | ☐ | ☐ | X | ☐ | ☐ |
| 3. I thought the tool was easy to use. | ☐ | ☐ | X | ☐ | ☐ |
| 4. I think that I would need the support of a technical person to be able to use this system. | ☐ | X | ☐ | ☐ | ☐ |
| 5. I found the various functions in this tool were well integrated. | ☐ | ☐ | ☐ | X | ☐ |
| 6. I thought there was too much inconsistency in this tool. | ☐ | X | ☐ | ☐ | ☐ |
| 7. I would imagine that most people would learn to use this tool very quickly. | ☐ | ☐ | ☐ | X | ☐ |
| 8. I found the tool very cumbersome to use. | ☐ | X | ☐ | ☐ | ☐ |
| 9. I felt very confident using the tool. | ☐ | ☐ | ☐ | X | ☐ |
| 10. I needed to learn a lot of things before I could get going with this tool. | ☐ | ☐ | X | ☐ | ☐ |

**AM2: Link to the video of the demonstration of the serious game**
**https://drive.google.com/drive/folders/12jSmpB6uwOeOyP_mGP8hl1KYht3UTOcg?usp=sharing**

**AM3: Link to the survey**
**https://drive.google.com/file/d/1DGtYaqKj164bTfeMHzIWQKkQkNWZdNok/view?usp=sharing**

**AM4: Link to the videos and images from the first meeting with exponents from the F.C. Südtirol**
**https://drive.google.com/drive/folders/132dCg8jwtJ-lVP_PC4-3cjJDeYcvpXEb?usp=sharing**

**Folder with all Additional Materials:**
**https://drive.google.com/drive/folders/1EzMKQmxlbKoZ_cFEjiot9XYiwycTDPMQ?usp=sharing**