Faculdade de Engenharia da Universidade do Porto

Anthropometric Thermal Assessment Method for Early Injuries in Athletes

Filipa Andreia Pinto Barbosa

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Supervisor: Ricardo Vardasca, PhD AMBCS
Co-Supervisor: Eduardo Marques, MSc

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Abstract

Currently, the major concern in physically demanding sports and with frequent competition is the high incidence of injuries. These have as consequences, health complications, decreased performance and increased costs associated with rehabilitation.

The regular monitoring of the athlete can be fundamental to detect potential risks and early abnormalities, reducing the incidence of those injuries. However, the majority of existing methods are subjective, and the few objective available are financially unaffordable, which triggers the interest of research in the application of low cost monitoring methods.

The infrared thermography arises in this project as a method of identification and tracking of early lesions through the assessment of the distribution of the skin surface temperature (providing real time physiological information). For the analysis of health and nutrition condition of the subject, the applicability of a method for automatic extraction of anthropometric measurements was also studied, including body dimensions and weight, through the Microsoft Kinect sensor.

Regarding the thermographic results, repeatable and sensitive methodology for the identification of pathological conditions was developed. Objective assessments were applied to the lower limbs, demonstrating good discrimination between groups of healthy controls and pathological subjects, namely in the frontal regions of the knee and ankle, but not the in the lateral regions. Additionally, thermography shown to be a promising technique, mainly in the follow-up, assessing the progression or regression of the injury event among the trainings. With respect to anthropometry, a method for automatic extraction of body measures were designed and implemented. The results presented a mean accuracy of 91.01% in the extraction of body dimensions and 93.41% in the weight estimation.

In this exploratory work, it was possible to verify that thermography and automatic extraction of anthropometric measures are a powerful contribution in this area, allowing a decrease in practice absence caused by injury and consequently leading to the associated costs reduction.

Resumo

Actualmente, a grande preocupação nos desportos fisicamente exigentes e com competição frequente é a elevada incidência de lesões. Estas trazem como consequências, complicações de saúde, decréscimo do desempenho e aumento dos custos associados à reabilitação.

Tendo em conta este cenário, o acompanhamento periódico do atleta pode ser primordial para detetar potenciais riscos e anormalidades precoces, diminuindo a incidência dessas lesões. Contudo, os métodos existentes são subjetivos, e os poucos objetivos disponíveis, são financeiramente incomportáveis, o que desencadeia o interesse da investigação na aplicação de métodos de monitorização de baixo custo.

A termografia por infravermelhos surge neste projeto como um método de identificação e acompanhamento de lesões através da avaliação da distribuição da temperatura na superfície da pele. Para a análise da condição geral de saúde e nutrição, foi ainda estudada a aplicabilidade de um método de extração automática de medidas antropométricas através do sensor Microsoft Kinect.

No que diz respeito aos resultados termográficos, foi desenvolvida uma metodologia repetível e sensível à identificação de situações patológicas. Testes objectivos foram aplicados na região dos membros inferiores, demonstrando boa discriminação entre grupos de controlos saudáveis e grupos patológicos, nomeadamente nas regiões frontais do joelho e tornozelo, mas não nas regiões laterais dos mesmos. Adicionalmente, a termografia demonstrou ser uma técnica promissora no que diz respeito ao acompanhamento do sujeito antes do treino, permitindo avaliar a progressão ou regressão de situação de lesão. Relativamente à antropometria, foi desenhada e implementada uma metodologia para extração automática das medidas corporais. Os resultados obtidos apresentaram uma precisão média de 91.01% no cálculo de medidas corporais e de 93.41% no cálculo do peso.

Neste trabalho exploratório, foi possível verificar que a termografia e a extração automática de medidas antropométricas são contribuições poderosas nesta área, reduzindo as ausências causadas por lesão e os custos a elas associados.

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Abbreviations

2D	*Two Dimensions*
3D	*Three Dimensions*
AAT	*American Association of Thermology*
BMI	*Body Mass Index*
df	*Degree of freedom*
FN	*False Negative*
FP	*False Positive*
IR	*Infra-red*
IRT	*Infra-red Thermography*
ISAK	*International Society for the Advancement of Kinanthropometry*
LDL	*Left Dorsal Leg*
LFA	*Left Frontal Ankle*
LFK	*Left Frontal Knee*
LFL	*Left Frontal Leg*
LLA	*Left Lateral Ankle*
LLK	*Left Lateral Knee*
OpenNI	*Open Natural Interface*
NAIRS	*National Athletic Injury/Illness Registration System*
NHANES	*National Health and Nutrition Examination Survey*
PBC	*Percentage of Bad Classifications*
RDL	*Right Dorsal Leg*
RFA	*Right Frontal Ankle*
RFK	*Right Frontal Knee*
RFL	*Right Frontal Leg*
RGB	*Red-Green-Blue*
RGBD	*Red-Green-Blue-Depth*
RLA	*Right Lateral Ankle*
RLK	*Right Lateral Knee*
ROI	*Region of Interest*

SD	*Standard Deviation*
TN	*True Negative*
TP	*True Positive*

Chapter 1

Introduction

The benefits on the physical, psychological and social development as a result of physical activity have been widely studied and characterized. Among the positive effects, the physical activity prevents and reduces numerous diseases such as, obesity, diabetes and hypertension [1, 2]. Nevertheless, high performance training combined with frequent competition, pushes the anatomical and physiological systems to its limits, increasing an inherent risk of injury [3, 4].

National Athletic Injury/Illness Registration System (NAIRS) of the United States [5] defined sport injuries as the *limit of athletic participation for at least the day after the day of the onset*, and that, in accordance with the Council of Europe, it has the consequence, the reduction in the level of physical activity or the need for advice or healthcare [6].

According to Fuller *et.al.* [7] the rugby has an incidence of 89.1/1000 player hours, being the sport with the highest incidence in injury due to its high physical demanding, with physical contact with adversary teams and frequent bouts of high intensity such as running, sprinting, rucking, mauling and tacking, intercalated by phases of low intensity, like walking and jogging [8, 9]. Several studies [7–9] suggest that, in all sports but especially in the rugby, lower limb is the body location where the major percentage of injuries (55%) happens, mainly on the ankle/heel and knee. The joint ligament and muscle/tendon are the most common types of injury, with 50% and 20% respectively and the origin of the lesion is mostly traumatic (consequence of a single incident of macro-trauma; it is usually unpredictable) representing 70% of the incidence rate, in contrast to the overuse injuries (consequence of repetitive micro-traumas) with only 30% [6, 8–10].

1.1 - Motivation

The high risk of injury in a sport such as rugby, suggests that, periodic monitoring of each athlete can be fundamental to minimize the incidence of injuries and to ensure the good performance of the team. For this reason, the design of the athlete's profile can be an effective way of tracking and evaluating the potential risks and abnormalities, highlighting two main components: the first is related to the characterization of early lesions and their follow-up during the workouts, and the second component is related to the characterization of the overall health and nutrition condition of the athlete.

Nowadays, the components previously mentioned can be obtained using simple measures, such as temperature, which is one of the main consequences of the inflammatory process triggered by tissue damage, and also the body measures, named anthropometry (body weight, body height and length, breadth and girth of body parts), which are essential to determine other parameters such as body mass index (BMI), body symmetries, among others, used to evaluate the physical health and nutrition of the subject.

However, the measurement of these simple parameters is not always within the reach of some associations, either for financial or for accessibility reasons. In the case of the early injuries, the increase of skin temperature can be readily detected by touch, but when the temperature variations are very subtle, the injury is not easily identified. [2, 11]. Additionally, the available solutions for the determination of the body measurements include manual marking of the anatomical points and the use of appropriate materials, implying therefore, a time-loss, existence of advanced knowledge of human anatomy and/or money expenditure.

For all of those reasons, the research for a simple and accurate method becomes essential for a sports association, which wants to maintain their performance or improve it.

1.2. Objectives

The aim of this dissertation is to design, implement and evaluate thermal and anthropometric measures, as part of the athlete's profile, which allow the monitoring and assessment of potential risks and abnormalities among the trainings.

In addition to the main objective, secondary objectives were also established, in accordance with each of the different topics of this work: thermal and anthropometric assessment.

For thermal imaging:

- Design a protocol of identification, tracking and monitoring of early injuries (new or recurrent) among the trainings;
- Implement and evaluate the application of infrared thermography technique as a complementary mean of identification of sports injuries;

- Evaluate the infrared thermography results as sport injury continuous assessment tool;

For anthropometric assessment:

- Implement a methodology to improve the body silhouette coming from Microsoft Kinect;
- Implement a methodology for the determination of the anatomical points and for the extraction of the anthropometric measures;
- Evaluate the accuracy of the developed method and its viability by comparing the results with a system whose error is known and precise.

Despite not being an objective, an attempt was made for automatically draw regions of interest (ROIs) in thermal images of full body using the developed methodology for anthropometry.

1.3. Document Outline

This document is organized in six sections:

The first introduces the theme and characterizes the problem and its context. In addition, the motivation behind the development of the project is presented, as well as its main objectives.

The next section, Literature Review, addresses several topics found in the literature that are relevant for the present work. It describes the two approaches followed to complete the athlete profile: the thermology as a means of injury diagnosis, and anthropometry as a means of monitoring the health and nutrition status.

In the third section, Methodology, the materials and methods used in this research work are reported. For each one of the approaches, the design of experiments and methods of analysis are included.

The fourth section, Results, describes the outcomes of the experiments and tests performed, and its interpretation.

The fifth section, Discussion, analyzes the significance of findings and analyses error sources.

Finally, in Section 6, Conclusion, the main results of this project are discussed, and then, the proposals for future work to improve this project are presented.

The structure of the dissertation and the links between different parts of this document can be visualized in Figure 1.

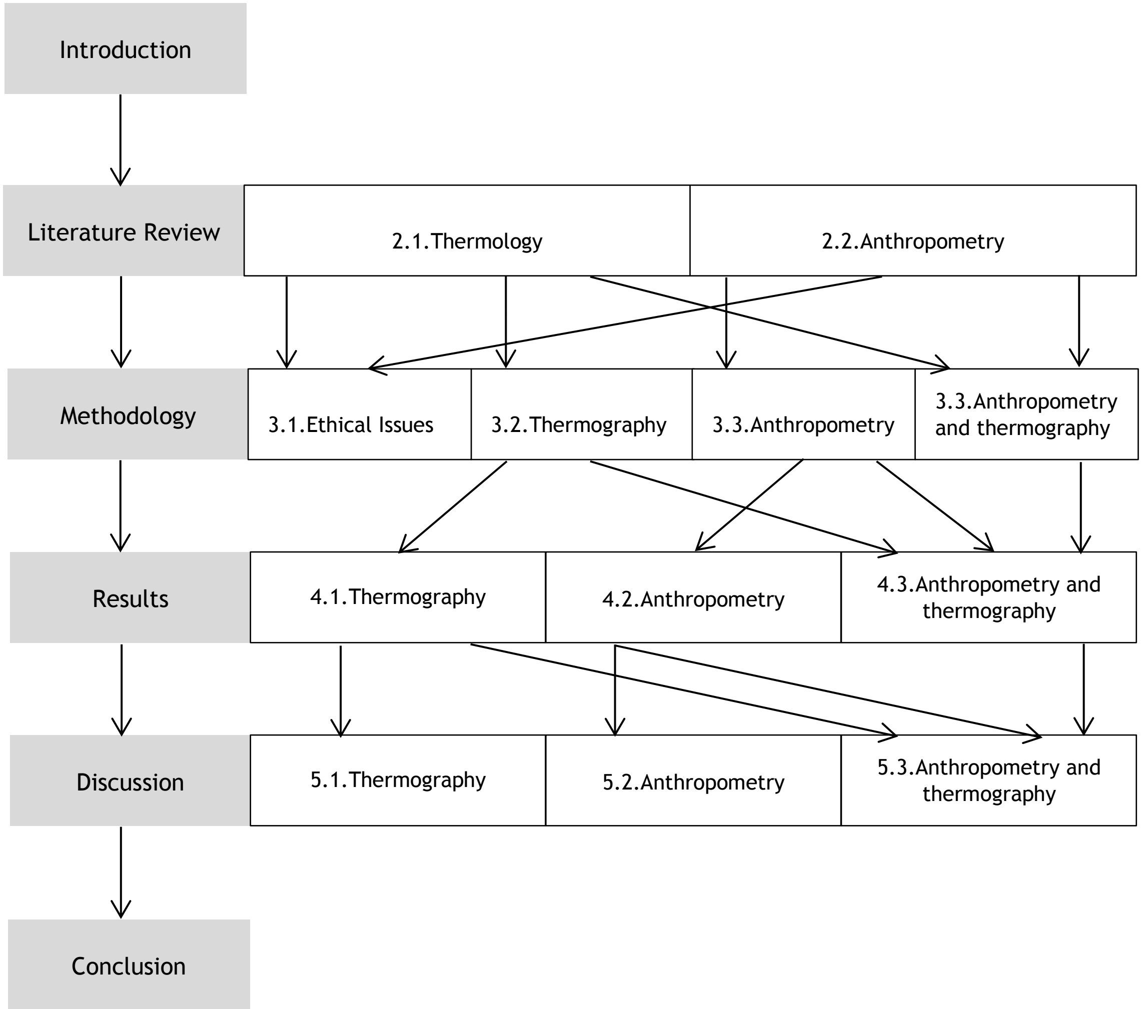

Figure 1 – Diagram of the document outline

Chapter 2

Literature Review

2.1. Thermology

Thermology is defined in the clinical context, as the science that studies the biothermal processes to access health or disease. Since 400BC, the temperature has been widely studied as health indicator in a variety of medical and sport contexts. Hippocrates was the first to document this phenomenon in his work, *Corpus Hippocraticum*: "should one part of the body be hotter or colder than the rest, disease is present in that part". To date, the temperature transfer between the body and the environment has been studied to understand the physiological processes resulting from an injury. [12–16]

2.1.1. Physiology of an injury

When an injury occurs, the information of the sensorial system located in all layers of the skin is transmitted to the brain throughout the nervous system, triggering an immediate inflammatory response in the damaged tissues. This inflammatory response, that aims to benefit recovery, mobilizes the body's defenses, isolates and destroys microorganisms and other harmful agents and it removes foreign material and damaged cells so that tissue repair can occur. Chemical substances called mediators of inflammation are released or activated in the tissues and adjacent blood vessels, inducing dilation of blood vessels to transport more quickly white blood cells, and other substances to fight infection and repair the injury [17, 18].

This mechanism manifests five immediate consequences: heat, pain, redness, swelling and disturbance of function. Temperature is usually the first signaling, due to the metabolic rate increase and the vasodilatation, that alters the temperature gradient between the body and its environment, and produces accelerated heat loss from the skin in order to maintain and regulate the core body temperature [18].

2.1.2. Mechanisms of heat transfer

The temperature of the deep tissues of the human body, core body temperature, normally remains at constant levels (36ºC to 37.5ºC). In contrast, the temperature of the skin is extremely influenced by the environment. [12, 17].

This ability to maintain and regulate the core body temperature in a narrow range of values is called thermoregulation and it is essential to the normal function of human body. The skin operates here, as an interface with the external environment, it has thermoreceptors, which together with the autonomic nervous system, activates mechanism of heat loss, when is perceived a high temperature, or activates mechanism of heat production in case of the acknowledgment of lower temperature [13, 19].

Most of the heat produced by the body is generated in the main organs, liver, brain and heart, and through the muscles during physical activity. Thereafter, heat is transferred from the deep tissues and organs to the skin, where it is lost to the air and environment [17].

The mechanisms of heat transfer (Figure 2) with external environment [13, 17] are:

• Conduction: where the heat is loss through direct conduction from the body surface to solid objects. In an unclothed resting state, about 3% of heat is dissipated by this mean in the study state.

• Convection: effect of the movement of the fluid or gas between areas of different temperature. The heat removed from an unclothed human body by convection is about 15%.

• Radiation: radiation is emitted in the form of electromagnetic waves between two objects without physical contact, when a change in the electronic configuration of the atoms/molecules occurs. All objects at a temperature above absolute zero emit and absorb electromagnetic radiation. An object that absorbs all incident electromagnetic radiation is called a blackbody, since it absorbs the same amount of thermal radiation that it is emitted. This mechanism at resting is about of 60% of the heat transfer.

• Evaporation: it occurs when heat transforms a liquid into a gas. This is a mechanism of cooling required in high air temperatures. When the ambient temperature becomes higher than the skin, instead of losing heat, the body gains heat and therefore, under these circumstances, the only means of body heat is lost through evaporation. Under resting conditions the unclothed human body loses in average 22% of heat by evaporation.

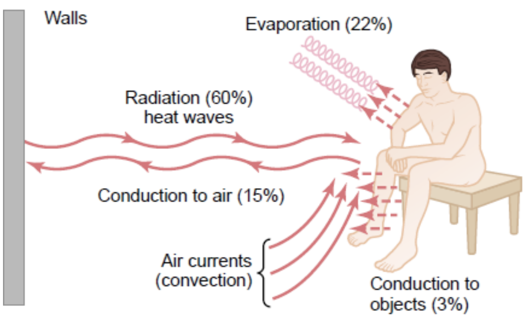

Figure 2 – Mechanisms of heat transfer. (From [17])

2.1.3. Measurement of heat transfer

The temperature of the human body can be measured quantitatively by different mechanisms of heat transfer. For example, most thermometers and thermoscopes are based on mechanism of thermal transfer by conduction, i.e., through the contact between the bodies, the heat flows from the body with higher temperature to the body with lower temperature, until both bodies reach thermal equilibrium.

However, the study of techniques that use perceived radiation is promising, due to the large amount of energy that is released by this mechanism in the human body. In addition, such techniques do not require direct contact between the bodies and therefore can be used when the body is in motion or at a distance. Thermography is an example of application of radiation for temperature measurement, becoming a technique with great potential and which has been widely studied over the last decades, since it allows the temperature measurement of larger areas of skin surface.

2.1.4. Thermography

Infrared Thermography (IRT) is a medical imaging method that detects thermal radiation (infrared radiation) emitted from objects surface and produce 2D visible images, called thermograms. This technique enables a quantitative and accurate analysis of the spatial distribution of the temperature. Its first medical application was in 1956, by Ray Lawson, through an evaporograph system to look at temperature distribution of a breast cancer malignant tumor tissue [13].

Thermography is a complimentary diagnostic tool, being noninvasive, non-ionizing, fast, objective and capable of monitoring a large area of interest in real time. Furthermore, IRT records only natural radiation emitted from the surface skin and has no harmful radiation effects [3, 12, 20]. Nevertheless, it is important to note that the IRT does not provide anatomical information, but only physiological information, which may limit the interpretation of results [21].

2.1.4.1. Thermal physics

Infrared band is part of the electromagnetic spectrum with a wavelength between 0.75-1000μm (Figure 3). The range of infrared radiation can be divided into three categories according to wavelength:

- Near infrared: 0,7-3μm
- Middle infrared: 3-8μm
- Long (far) infrared: 8-12μm

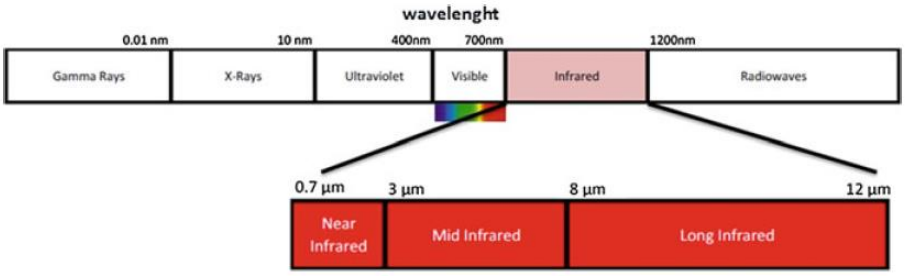

Figure 3- The electromagnetic spectrum. (From [13])

The thermal image cameras record the temperature of the object without any surface contact by detecting infrared radiation emitted. All objects with a temperature above zero emit electromagnetic radiation [13]. Moreover, the radiation measured does not depend only on the body surface temperature; it depends also on the emissivity and on the environment [3]. Emissivity is the ratio between the energy radiated by an object and the energy radiated by a blackbody, at the same temperature. A blackbody is a physical object that absorbs all incident electromagnetic radiation, and therefore has an emissivity value of 1. In contrast, for reflective materials the emissivity value approach zero [13].

The radiation emitted from a blackbody can be described by three expressions: Planck's radiation law, Wien's displacement and Stefan-Boltzmann equation. Plank's law describes the spectral shape of the source as a function of wavelength and it shows that human skin emits infrared radiation mainly in the wavelength range of 2-20µm with an average peak of 9-10µm. Since that 90% of the emitted infrared radiation in humans is between 8-15µm, human skin is considered a blackbody radiator with an emissivity factor of 0.98, a perfect radiator at room temperature. The Wien's displacement law exemplifies how the spectrum of blackbody, at any temperature, is related to the spectrum at any other temperature. Finally, the Stefan-Boltzmann equation provides the amount of energy emitted by a blackbody of a specific spectral unit (wavelength, frequency or wavenumber), and through the comparison of the perceived radiation value with this reference, a temperature value is obtained [3, 22].

2.1.4.2. History and applications of Infrared Thermography

The history of thermography started in 1800, when William Herschel discovered infrared radiation [23].

Thermography was used for military applications, especially during the two World Wars, becoming a powerful tool in thermal sensing (e.g. night vision) [23].

As a diagnostic method for diseases and injuries, thermography has only become known in the 70s. Several studies were conducted in the medical field; however, the past infrared cameras were primitive, and so, this technique was deprecated by others with high accuracy and precision, such as, x-ray, ultrasound devices and magnetic resonance imaging [24].

Currently, thermographic cameras have improved considerably in thermal and spatial resolution as in thermal sensitivity, along with became more affordable. Other aspect contributing for a wider usage are the development of recording protocols, proving to be sufficiently accurate and reliable to be used as a complementary diagnostic and treatment method [25].

2.1.4.2.1. Applications of IRT in medicine and sport injuries

Thermography has been used to study various diseases where the temperature of the skin surface may reflect the presence of inflammation in the underlying tissues or where the blood flow reflects any physiological problem.

The applications and advantages of thermography in medicine have been widely studied in the last 50 years. Some of these studies include the application of IRT in neurological disorders [26, 27], open-heart surgeries [28], vascular diseases [29], reflex sympathetic dystrophy syndrome [30], urology problems [31] and fever screening [32–34].

In the sports context, few studies [3, 21, 35–37] arose in the 80s with the purpose of diagnose injuries. Later, studies in this area declined considerably and only returned around 2007, having proved that it is a very promising technique and a powerful tool in the analysis of performance and diagnosis of pathologies in sport. All these studies follow the assumption that, in healthy athletes, the temperature of the skin surface follows a symmetric distribution [38] and this parameter is affected when injury occurs [35] (this issue will be addressed in section 3.1.3.). The most relevant researches in the area are:

- Hildebrandt *et.al.* [35] addressed the most common injuries in various sports. In running, the most commonly injury is Achiles tendinosis. The study was performed on a runner with 22 years old and at the time of exam, he had a small pain, no swelling, but the asymmetry was quite noticeable in the thermogram. The temperature difference between the two sides was 1.6ºC.
- Later, in another study, Hildebrandt *et.al.* [21] conducted a research with 35 female and 52 male junior alpine ski racers, to assess the patellae tendinopathy, an overuse injury, which is characterized by swelling, pain and tenderness. The results shown that the symptomatic athletes had a mean side temperature differences of 1.4ºC (±0.58°C) whereas the non-injured athletes revealed a side-to-side variation of 0.3°C (±0.61°C). Furthermore, physical examination of the knee shows that hyperthermia was associated with a low threshold for pressure pain, indicating a good detection for early injuries.
- Selfe *et.al.* [36] performed a quantitative analysis and showed that the difference of more than one degree centigrade between the sides of the body was enough to distinguish subclinical problems before they are clinically relevant.
- Arfaoui *et.al.* [3] studied the application of thermography for the detection of osteoarthritis of the knee related to the sport, a traumatic injury. Osteoarthritis

is characterized by a degeneration of cartilage which subsequently invades the articular pocket, resulting in the trigger of inflammation and thus increasing the temperature. The study was made on 10 pathological and 12 healthy athletes. The results demonstrated that it was possible to detect a significant asymmetric behavior in the color of the thermograms of both knees, making the IRT a new diagnostic tool to characterize osteoarthritis of the knee.

- Finally, Carmona [37] conducted a study in the professional football team of the Spanish league during the preseason of 2008 (N = 24) and 2009 (n = 24), whose main objective was the monitoring and prevention of injuries. The thermographic images were collected every day before training and in case of an asymmetry greater than 0.3°C, a protocol of post-exercise was implemented for prevention.

2.2. Anthropometry

Anthropometry (from the Greek *Anthropos,* a man, and *metron,* a measure) is defined as the science that describes the measurements of the human body, such as height, weight and body dimensions (lengths, breadths and girths of body parts) to access and study variation and differences of the human body [39–41, 42–44].

It is considered a method of universal application and non-invasive, which reflects the health and nutrition status and also provides the performance, health and survival [45]. For these reasons, the anthropometric variable has been tested in sport together with other variables, to evaluate the effects to distinguish among different competition levels, and to predict performance [46, 47].

On the other hand, anthropometry can be used as biometric identification: universal feature, quantitatively measurable and with medium/high distinctiveness [48]. This feature can be inserted in "soft biometrics", a branch of biometrics that is able to distinguish individuals through the acquiring non-intrusively of individual physical characteristics. Alphonse Bertillon was the first to devise a method which involved several body measures to identify criminals [49]. Later, anthropometry was replaced by a more reliable method based on fingerprints; however, for certain contexts such as medicine and sports, anthropometry still has a lot of potential [48, 50].

2.2.1. Anthropometric data

In anthropometry, the body dimensions are obtained through several types of measures: lengths, breadths, girths (circumferences) and skinfold thickness [47]. To obtain each of these measures, specific anatomical landmarks should be marked on the body, in order to identify the exact anatomical location of the start and end of each segment.

The identification, location and description of each landmark were standardized by the International Society for the Advancement of Kinanthropometry (ISAK) [51]. The most common anatomical points were presented in Figure 4.

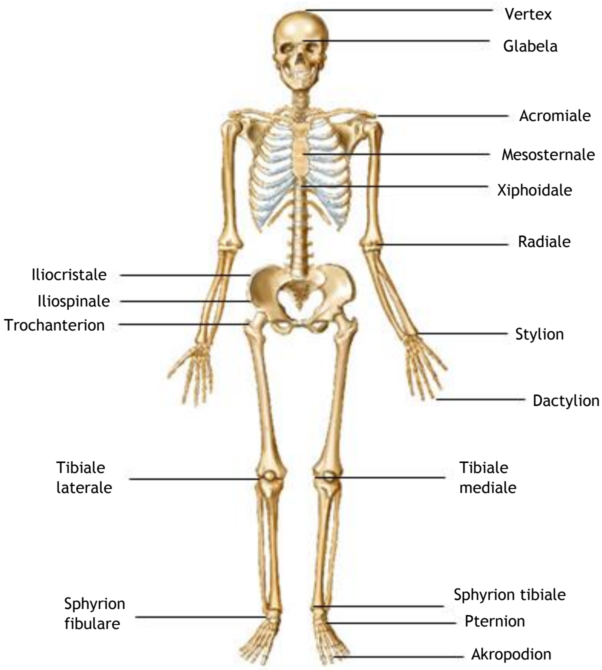

Figure 4 - Representation of the anatomical landmarks (Adapted from [51])

2.2.2. Anthropometrical methods

The body dimensions extraction can be divided in two main essential components: the anatomical points marking (landmarking) and the quantitative calculation of the segments dimension. Both components are extremely important in this process and can be performed through traditional, semi-automated or automated methods, further discussed in this section.

2.2.2.1. Traditional landmarking methods

In traditional methods, the presence of an anthropometrist is essential for marking the anatomical points, which are identified by palpation of the human body, and measurements are taken using traditional tools. Among the various equipment highlights stadiometer and anthropometric box for measuring stature and sitting height, caliper for measuring large bone breadths, anthropometric tape for measuring girths, anthropometer or segmometer for measuring heights and lengths, and weighing scale for measuring weight [51, 52].

The manually measure of human variations have as strengths its lower cost and simplicity of application. However, traditional methods present several disadvantages. Among them, can be highlighted the time-consuming to complete measurements for each person, the contact with the subject for landmarking and for extraction of measures and also, the errors associated to the intra and inter-users [53].

2.2.2.2. Semi-automated landmarking methods

More recently, systems that allow the calculation of anthropometric measurements through semi-automated systems were developed. This kind of products requires manual landmarking, but the measurement between anatomical points is done automatically.

The Qualisys system is an example of this type of equipment [54], it comprises several infrared cameras surrounding the subject which emit a beam of infrared light. Retro-reflective markers are placed on the anatomical points, which in turn reflect infrared light back to the camera sensor. The information from the markers allows calculating the position of each one, with high spatial resolution [55, 56].

These methods reduce the time spent and increase the simplicity of implementation; however, they still require a technical expert for marking landmarks and the equipment is more expensive [54].

2.2.2.3. Automated landmarking methods

In the last few years, there has been an active development of automated landmarking methods, an approach aiming completely replace the manual measurements. Automated landmarking methods have sparked a new concept: digital anthropometry, that in accordance to the American Society of Anthropometry, it is defined as “the technology to obtain reliable information of the physical objects or the environment through the recording of images, its measurement or interpretation” [57]. In other words, these products are based entirely on image analysis, not requiring any placement of markers on the body.

Automated landmarking methods can be divided in two main groups: 2D and 3D measurements.

In the first one, a two-dimensional image is taken, with a digital camera perfectly calibrated, in order to successfully transform the 2D image values (pixels) in real values (e.g. millimeters) through the triangulation method. To this end, this technique still requires the cooperation of a technician capable of controlling some crucial factors, such as the placing of the subject in parallel and at an exact distance from the camera, to ensure that the triangulation method is reliable. Several studies on the 2D measurements have already been performed [58–64]. However, they imply a very high image resolution and a controlled environment (both in lighting and in the background).

The second method is based on a fully automatic system that does not require any cooperation at technical level. The most popular examples on the market are 3D systems that scan the person and create the 3D model. These systems may be based on light (such as “2T4”, “TriForm”, “SYMCAD” and “Puls”), infrared light (such as “Body lines scanner”) or laser (such as “WBX and WB4”, “Vitus Pro”, “Vitro 3D” and “Voxelan”), all of them present accurate results [53]. Nonetheless, their disadvantages are the high price and the need for a specific scene with particular illumination conditions and background [57, 65].

Nowadays, the research for effective and competitive solutions has increased. One example of this is the Kinect™, originally launched by Microsoft® in 2010 as a game purpose interface device for the Xbox360 console [66]. The Kinect is a cheap multisensory device which combines a color camera with a depth sensor, capturing visual depth data (RGB-Depth technology) without any ambient light interference [66–68].

Studies that use the Kinect platform to extract anthropometric measurements are still few, however, they already provide promising results.

One of the main studies was conducted by Samejima *et.al.* [66], it suggested a process for determining the anthropometric measures using the Kinect sensor, a database with 52 body dimensions and 83 subjects. Four body dimensions were selected by linear multiple regression, and with those, the authors estimated the others dimensions using a regression formula based in a principal component analysis.. The errors obtained, in the measures estimation were inferior to 16%.

Araújo *et.al.* [69] also used Microsoft Kinect for extracting anatomical points. From this, the lengths of several body parts were inferred from the extracted points and training a model for posterior classification and training examples. However, the method demonstrates an inconsistency in the identification of skeletal points, since the method showed a pose dependency.

Nevertheless, these studies are still preliminary studies, presenting high errors. For this reason, further research of this tool is required in order to improve results and to present it as an alternative to traditional and automated methods previously referred.

2.2.3. Weight estimation from body dimensions

In addition to the body dimensions, the weight parameter is essential to complement the information of the health and nutrition condition of the subject [70].

Traditionally, these values are measured with calibrated weighing scales [51]. However, the interest in the development of automated systems, which do not require the subject cooperation, enforcing reduction in the time to collect all anthropometric measures has grown in last years.

Recently, some studies [48, 65, 70, 71] focused in studying the calculation of weight from body dimensions as an alternative to traditional weighting scales:

According to Velardo *et.al.*[48, 65, 70] the weight can be feasibility estimated from anthropometric data directly accessible from the available visual appearance (image or video). The same authors have used a database of known data, National Athletic Injury/Illness Registration System (NHANES), which includes several anthropometric measures for more than 28,000 people from the United States population. With these values, a linear regression, able to correlate the dimensions of bodies with weight, was calculated, and then, tested for the study data (n = 20), obtaining prosperous data. In this study, only were considered weight data with values between 35 and 130 kg.

Buckley *et.al.* [71] pretended to find a reliable solution to calculate the weight of patients in hospitals, which may have difficulty in standing on a weighing scale. A model for calculating weight through body dimensions were proposed, starting from the estimation of the weight information provided by patients, doctors and nurses (n = 208; 121 males, 87 females). The created model has the advantage of differentiating the calculation of the weight between different genres, using only two body measurements (waist circumference and thigh circumference) however, the conclusions of the work does not report the errors to the actual values, but the values of opinion of the hospital staff.

Chapter 3

Methodology

This chapter outlines the methodology used throughout this research work. Describing the selection of platforms, software and techniques used to obtain the results.

The thermographic and anthropometric components, as integral characteristics of the athlete's profile, will be addressed separately. At the end of this chapter, a methodology that correlates these two aspects will be presented attempting to establish complementarity between them.

3.1. Ethical Issues

The present study ensures the compliance with the ethical principles for medical research involving human subjects of the World Medical Association Declaration of Helsinki (2013) [72], and is in accordance with the law n º21/2014 that regulates the clinical research in Portugal [73].

3.2. Thermography

Thermography arises in this project with the main objective of characterizing the skin surface temperature for the identification and the evaluation of early injuries in rugby athletes.

For this purpose, the recording and evaluation of thermal images of the human body follow the standard guidelines defined by the Glamorgan Protocol and American Association of Thermology (AAT) [74, 75]. The athletes who participated in this study and the technical team were previously informed about the characteristics of this research.

3.2.1. Study Sample

The sample under study is divided mainly in two groups:

The first group comprises 15 male rugby athletes, belonging to under 18, under 23 and senior teams of a Portuguese club – CDUP (Centro de Desporto da Universidade do Porto). This group contains 9 injured athletes and 6 healthy athletes (controls) to whom were recorded data before training, in order to assess the thermal progress or regression between workouts. The lesions considered in this project focus mainly on the knee, ankle and legs, which are areas where injuries were more predominant (section 1.1). The characterization of the rugby athletes sample are summarized in Table I.

Table I - Descriptive data of the male rugby athletes

Sample data	*Pathological (mean±SD)*	*Non-pathological (mean±SD)*
n	9	6
Age	20.0±2.2	19.3±1.9
Weight (kg)	93±11.7	80.3±1.6
Height (m)	1.8±0.1	1.8±0.1
Body mass index	28.3±3.9	25.6±4.6

The second group comprises 10 non-athletes (Table II), without any injury on the lower limb (EUROQOL score = 0, Appendix D). The analysis of this group is intended to help in identifying the values used for the control population, as well as to understand if there is any difference between the two types of controls (athletes and non-athletes) that may compromise or change the data analysis. It is also important to note that the monitoring and follow-up of this group is not the purpose of this study, and therefore the thermographic images were collected only once for each subject.

Table II – Descriptive data of the non-athletes (all non-pathological)

Sample data	*Males (mean±SD)*	*Females (mean±SD)*
n	5	5
Age	24,.6±4.8	23.0±0.6
Weight (kg)	80.2±13.0	60.0±4.8
Height (m)	1.8±0.0	1.6±0.0
Body mass index	24.9±3.5	22.4±1.8

3.2.2. Equipment and software

Data collections were performed using specialized equipment. This equipment ensures the gathering of thermographic images and monitoring of the external variables that can affect the results, such as ambient temperature and relative humidity.

- Thermal images were recorded with an infrared camera A325 SC (FLIR® Systems, Sweden) (Figure 5). The main features of this IRT camera are shown in Table III.

Figure 5 - IRT camera A325 SC (FLIR® Systems, Sweden)

Table III – Characteristics of IRT camera A325 SC (FLIR® Systems, Sweden)

Spatial Resolution	320 x 240 pixels
Field of view (FOV)	25° × 18.8°
Minimum distance focus	0.4 m
Image frequency	60 Hz
Thermal Sensitivity	< 0.05°C at +30°C / 50 mK
Accuracy	± 2% of overall reading
Focal Plane Array	Uncooled microbolometer
Focus	Automatic
Measurement analysis correction	Automatic, based on inputs for ROI distance, room temperature and relative humidity

- In order to control the influence of the room temperature and relative humidity on skin temperature, these two parameters should be monitored in all thermographic collections. A combined device (Testo Go) has a thermometer for measuring the room temperature and a hygrometer for measuring the relative humidity.

Regarding the software, different platforms are used at different stages of the project:

- The image capture was made by FLIR® ThermaCAM Researcher v2.10, a software package, developed by the manufacturer.

- The temperature data were extracted by the same software, which provides the temperature information for each ROI drawn by the user.
- The data was organized in Microsoft Excel 2010® for subsequent statistical processing with SPSS (Statistical Package for the Social Sciences) v21 for Windows®.

3.2.3. Thermographic record evaluation

All parameters and procedures for collection and analysis of thermographic images are explained in detail in a protocol designed specifically for this project (Appendix A). It specifies the subject preparation, the room conditions and the capture procedure, taking in account the standard recommendations defined by the Glamorgan Protocol [74].

For thermographic record and evaluation:

- The thermal collections were performed with the informed consent of the subjects (Appendix B);
- The subject was previously informed, both oral and written, about the research, being advised to avoid a list of factors that can influence the skin temperature, such as, topical applications, physical effort, methods of therapy, heavy meals, energy drinks, alcohol, tobacco intake, or any other type of vasodilator (Appendix C);
- Thermographic collections are carried out before each workout, in order to avoid the variation of body temperature by performing physical activity. This procedure was made before every training session (Mondays, Tuesdays and Fridays);
- The subject fulfills an acclimatization period of approximately 10 minutes for achieving thermal equilibrium, with the lower limbs disrobed and without any contact between any part of the body;
- In each session, the athletes complete a questionnaire to find out if they used some factor that may influence the assessment of thermographic images (Appendix D);
- The room temperature and relative humidity are recorded in each collection. The temperature values should be between 18ºC and 24ºC and the relative humidity of the room should be lower than 50%. These values were fulfilled in the case of the temperature parameter (20.0±3.1ºC), however, due to a recording location limitation, the relative humidity of the room exceeded the recommended values (69.4±8.5%);The values of ambient temperature, relative humidity and distance between the camera and the body should be inserted into the capture software to rectify the calculated temperature;
- The standard views and respective ROIs for recording and evaluation of thermal images of knees, ankles and legs are shown in Figure 6. Once again, these views were chosen taking in account the Glamorgan Protocol [74, 76].

The regions of interest presented in the Figure 6 have the following designation: LFK: lateral frontal knee; RFK: right frontal knee; LLK: left lateral knee; RLF: right lateral knee; LFA: left frontal ankle; RFA: right frontal ankle; LLA: left lateral ankle; RLA: right lateral ankle; LFL: left frontal leg; RFL: right frontal leg; LDL: left dorsal leg; RDL: right dorsal leg.

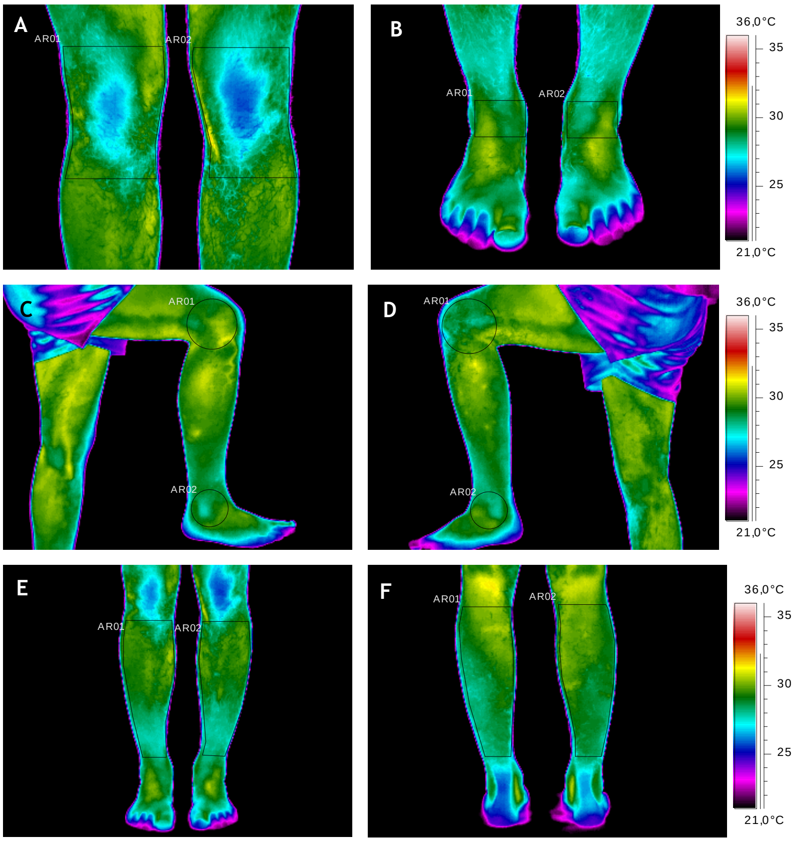

Figure 6 - Regions of Interest (ROI) for each view (pallet: rain): A) Both Knees (anterior view) - AR01: RFK, AR02: LFK; B) Both Ankles (anterior view) - AR01: RFA, AR02: LFA ; C) Right Leg (lateral view) - AR01: RLK, AR02: RLA; D) Left Leg (lateral view) - AR01: LLK, AR02: LLA; E) Lower Legs (anterior view) - AR01: RFL, AR02: LFL; F) Lower Legs (dorsal view) - AR01: LDL, AR02: RDL.

- For the thermographic collection (Figure 7), two setups were performed. For frontal views of the knee and ankle (Figures 6A and 6B), thermographic camera was placed at 0.90m from the subject and at 0.70m of the ground. For the remaining views (Figures 6C, 6D, 6E and 6F), thermographic camera was placed at 1.30m from the subject and 1.10m of the ground.

Figure 7 – Representation of thermographic setup

- In this study, the presence or absence of a lesion was evaluated by thermal symmetry value, i.e., to assess whether there is a bilateral difference in temperature when the region is compared with its contralateral region. According to Vardasca *et.al.* [38], thermal symmetry is defined as the 'degree of similarity' between two regions, which in turn are mirrored across the human longitudinal main axis and that are identical in shape, size and with approximate position.
  The thermal symmetry is calculated from the absolute difference between the mean temperatures of the contralateral ROIs;
- The validation of the results was performed according to the information provided by the subject. The athletes were considered pathological when they claimed pain in the regions to be analyzed, or when they were to reintegrate the team after a period of physical therapy or post-surgery. Similarly, they were considered non-pathological when they stated not feeling any kind of pain in the lower limbs.

3.2.4. Statistical analysis

From the results of temperature and thermal symmetry collected for each ROI, the Shapiro-Wilk test was performed in order to verify the adherence to normality of each of these variables. However, since the dimension sample is small, the non-parametric tests were performed for both distributions (normal and non-normal distribution).

The Mann-Whitney U test was the selected non-parametric test to compare the skin temperature in pathological and non-pathological groups. Significance level was set at $p \leq 0.05$ [77].

3.2.5. Follow-up

After the identification of the pathological subjects, they were followed among several sessions in order to monitor the progression or regression of the injury. For this follow-up, the values of thermal symmetry in each session were calculated and compared with the values of the previous sessions.

In addition, the thermal symmetry values were correlated with the information provided by the athlete in terms of severity (mild, moderate or strong, Appendix D) to assess whether the infrared thermography is also able to reflect the intensity of pain.

3.3. Anthropometry

Anthropometry arises in this project with the aim of completing the athlete's profile. In this section, the algorithms for automatic identification of anatomical points and anthropometric measurement will be addressed. Thereafter, these anthropometric measurements are compared with a semi-automated method and the errors associated with the literature results.

3.3.1. Study Sample

This study was conducted with a different dataset of thermography due to a practical limitation. This dataset comprises 12 healthy subjects, 6 females and 6 males. The characterization of the sample is summarized in Table IV.

Table IV – Descriptive data of the subjects

Sample data	*Male (mean±SD)*	*Female (mean±SD)*
n	6	6
Age	24.3±2.6	23.0±0.6
Weight (kg)	77.5±6.0	61.5±1.1
Height (m)	1.8±0.1	1.6±0.0
Body mass index	24.2±2.2	22.8±2.4

3.3.2. Equipment

The development of this work was divided into two main parts which are performed separately: data acquisition and post-image-processing.

The data acquisition was performed using the Kinect^{TM}, a portable multisensory device that does not require markers placed on the patients for silhouette recognition, being completely based on gestures and voice interaction [67, 78]. For that, Kinect comprises a RGB camera and an IR emitter and sensor (Figure 8), useful for capturing color images and depth of each pixel of the scene. This technology, called RGB-D technology, combines three color channels and another for the depth data, which works in all lighting situations and computes the depth values through triangulation method [66–68].

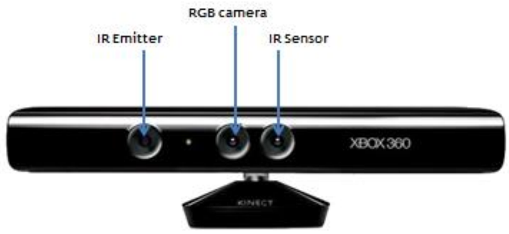

Figure 8 - Kinect components (Adapted from [79])

The RGB camera operates at 30fps and it can push images at 640x480 pixels with 8-bit depth per channel (capable to represent 256 colors each one). The IR camera operates at

30fps creating images with resolution of 1200x960 pixels. These images are downsampled to 640x480 with 11-bits, which results in a sensibility of 2^{11} = 2048 levels. The depth information can be represented in pixels or in millimeters. In pixels is merely representative, i.e., the pixels do not have real depth values, but the relative depth among them. Furthermore, the pixels exhibit black color (value equal to zero) when there is no depth information (when the points are not within the field of view of Kinect or when the object reflects inefficiently the infrared light, as is the case of the mirrors or hair) [78].

According to angle of vision, the system has an angular field of view of 57° horizontally, 43° vertically and 70° diagonally. The accurate distance range is between 0.8 meters and 4 meters [66, 78, 79].

3.3.3. Anthropometric record

Taking into account all of characteristics presented in previous section, the experimental setup was designed (Figure 9A). For the image collection, the Kinect sensor was placed on a tripod, 0.9 meters from the ground and 2.40m from the subject, so that the device can extract information without losing resolution. The subject must perform the position shown in Figure 9B, parallel to the camera and standing, during 3 seconds. The same procedure was carried out for the lateral view (Figure 9C)

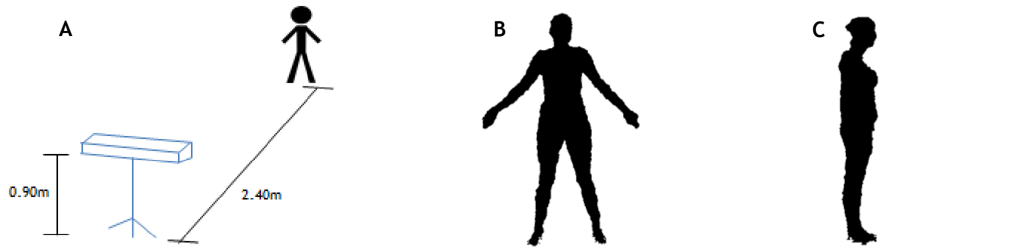

Figure 9 – Anthropometric record. A) Kinect experimental setup; B) Frontal position; C) Lateral position

This capture follows the standard recommendations of the Windows Human Interface Guidelines [79], ensuring the correct data collection (recommended distances, position, among others). This information is described in detail in Appendix F.

3.3.4. Selection of landmarks

According to Norton *et.al.* [51] and the previous studies [66, 67, 69], there are several anthropometric measures to describe the human body. The measures chosen for the development of this project, and most common, can be visualized in Figure 10.

Thus, among the existing landmarks (Figure 4) and body dimensions, this study aims the computation of following measures: height, acromiale height, iliocristale height, patellar height, lower leg length, upper leg length, upper arm length, forearm length, hand length, biacromiale breadth and bitrochanterion breadth. Detailed information about the location of each of the anatomical points can be found in Appendix E.

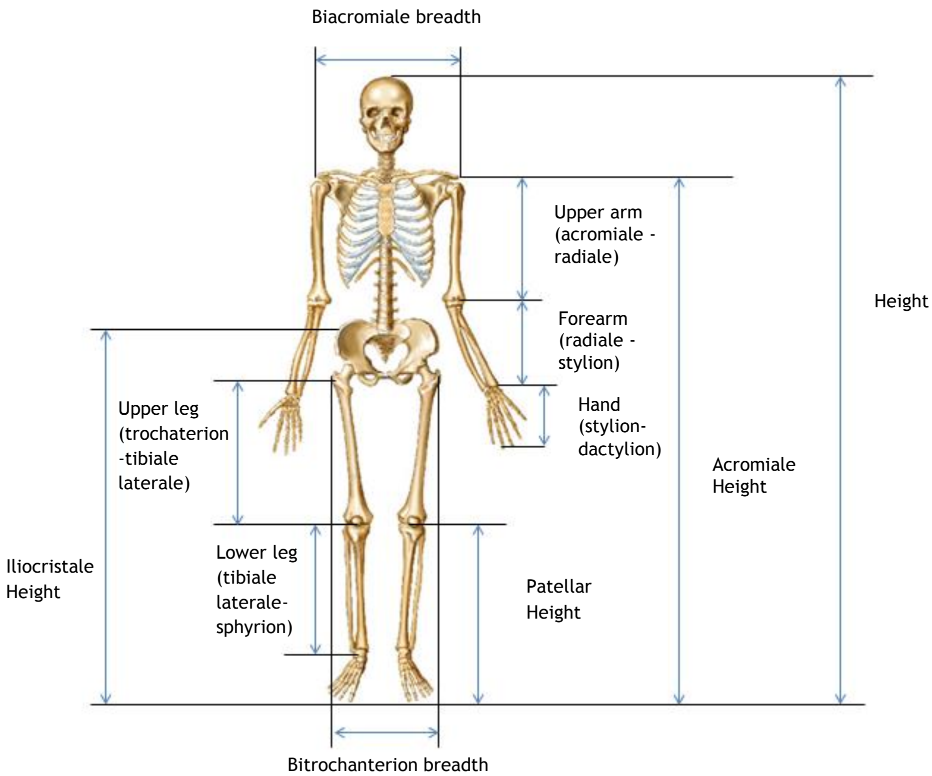

Figure 10 – Anthropometrical measures

3.3.5. Data processing for landmarking

In this project, a platform was developed for processing and extracting the information from the Kinect, using OpenNI (an open source project available for most languages, compatible with any Operating System and which supports skeleton tracking) [80, 81].

After capturing images, four types of information can be extracted directly from the platform. The first one corresponds to the color information (Figure 11A), the second corresponds to the depth information in pixels and in millimeters (Figure 11B), the third corresponds to the information of the skeleton of the body translated into 15 representative joints in 2D or 3D (Figure 11C), and lastly, the fourth corresponds to the mask, i.e., a gross segmentation of the individual silhouette (Figure 11D).

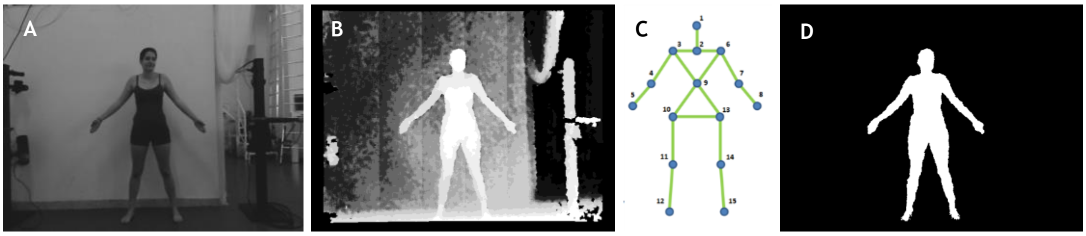

Figure 11 – Information extracted from the developed platform: A) Color image (RGB); B) Depth image; C) Skeleton representation joints (1-head, 2-neck, 3-right shoulder, 4-right elbow, 5-right hand, 6-left shoulder, 7-left elbow, 8-left hand, 9-torso, 10-right hip, 11-right knee, 12-right foot, 13-left hip, 14-left knee, 15-left foot); D) Subject mask.

3.3.5.1. Algorithm for landmarking

Considering that the anatomical points were marked on the outline of the subject and that the silhouette and depth information coming from the Kinect presents noise and poorly defines these regions, it was necessary to perform an image processing technique to obtain landmarking detection robustly. Thus, this process can be divided in 3 main steps:

1 - detection of the real silhouette of the subject;

2 - reconstruction of the depth values for the new silhouette;

3 - detection of the landmarks and calculation of the anthropometric measures.

3.3.5.1.1. Detection of the real silhouette of the subject

For the detection of real contour of the silhouette, the use of the color images were the best alternative. Nonetheless, all objects belonging to the background, as well as the interior of the subject, were also detected, called over detection (Figure 12A). To solve this situation, a new mask is created from the Kinect mask by performing a subtraction between a dilation and erosion of the same mask. The extremities of the body have a larger area since they are most susceptible to poor detection by Kinect (Figure 12B). The combination of these two images is shown in Figure 12C. Note that generally, the contour was not closed.

For the refinement of silhouette, the feet were not considered, since they are poorly detected by Kinect, being a source of a considerable amount of noise.

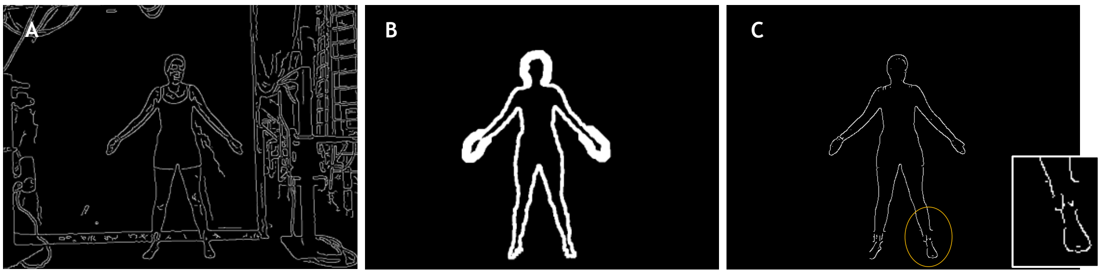

Figure 12 – Detection of the real silhouette of the subject (part I). A) Edge detection from color image (canny algorithm); B) New mask - the white areas are the result of the subtraction between the dilation and erosion of the mask Kinect and where it could be the outline of the subject; C) Combination of figures A and B. The right image shows, in more detail, that the contours detected by this method are not closed.

In order to obtain a closed contour, it was necessary to link the objects to each other. However, due to the over detection, there were ends that were outliers, not belonging to the object. To remove some of these outliers, some considerations were applied, such as:

- very small objects were considered noise (Figure 13A);
- extremities of the objects whose orientations were very different of the total average orientation were removed (Figure 13B).

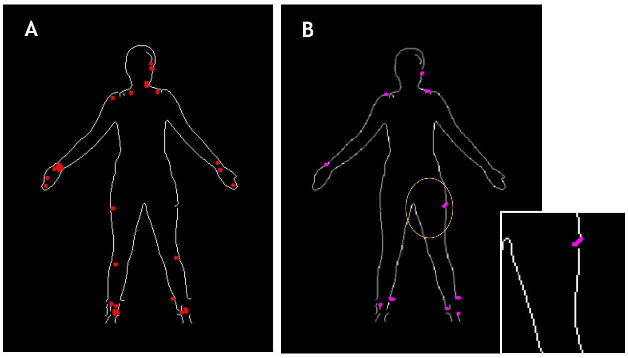

Figure 13 - Detection of the real silhouette of the subject (part II). A) Pixels that are marked in red color are considered noise and therefore, they are deleted; B) Pixels that are marked in magenta are the extremities of the object with very different orientation. The right image shows, in more detail, the result of this procedure

To remove noise, which was within the silhouette, the information of the human body location (region) must be known in advance, to address it independently (Figure 14A). Then, a line was drawn, which divided the region in two parts, and if there were more than one point between this line and contour, the innermost point was removed (Figure 14B).

After removing the maximum possible outliers, the connection of objects became easier. For each end of any object (each contour segment uninterrupted) it was evaluated the presence of neighbors in a 35x35 window, and with restrictions according to body region. These restrictions involve: the knowledge of the region to which the neighbor point belongs (for example, if the point was in the arm, the point can only connect to neighbors who belong to the hand or shoulder) and the knowledge of the side of the joint to which actual point and neighbor point belong (noted that this type of restriction cannot be applied to the body's extremities such as hands, feet and tip of the head). This last spatial constraint is represented in Figure 14C.

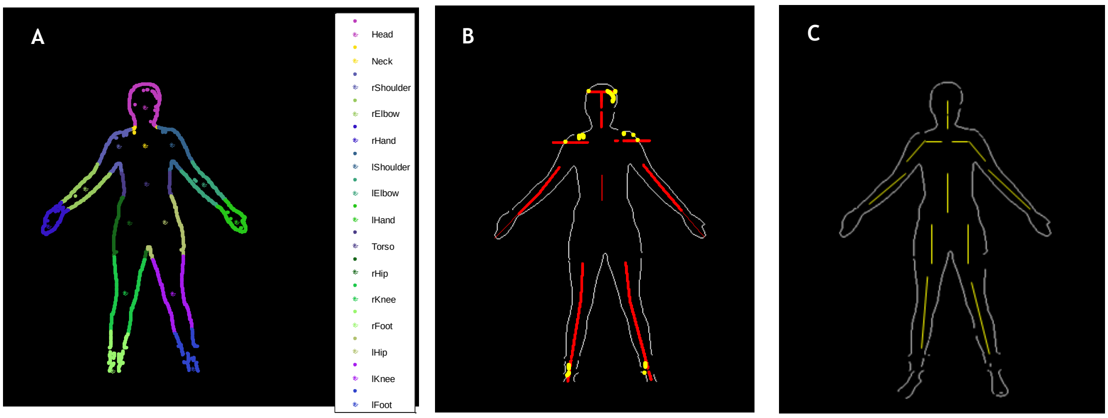

Figure 14 - Detection of the real silhouette of the subject (part III). A) Representation of the information of the human body location. For each pixel, the region to which it belongs is known. B) Removal noise within the silhouette. Red lines represent the lines which divides the region and the yellow pixels are the outliers; C) Spatial constraint to the choice of neighbors (yellow lines)

Finally, prospective neighbors are weighted according to a number of parameters, and the point with lowest sum was chosen as a neighbor. The weights assigned to each region were determined from the visual analysis of the study sample (Table V). The parameters include the euclidean distance between the end point and the prospective neighbor; the tendency of the bond, the object length (neighbor objects with greater length, have greater relevance) and distance to the joint (in many cases, the contour must follow the furthest path, giving greater emphasis to higher values). The selected neighbor consists in the value that present the lowest sum.

Table V - Weights attributed depending on the parameters and depending on the region of the human body.

	Euclidean distance	Tendency of the bond	Object length	Distance to the joint
Head, neck	0.5	0	0.2	0.3
Shoulders (upper shoulder)	1.0	0	0	0
Armpit (lower shoulder)	0.8	0.2	0	0
Elbows, torso, knees, hip	0.8	0.1	0.1	0
Hands	0.7	0	0	0.3

After choosing the neighbor of each object, a spline interpolation was performed in order to close the contour (Figure 15A) and then, a contour smoothing was applied (Figure 15B). Final mask can be visualized in Figure 15C.

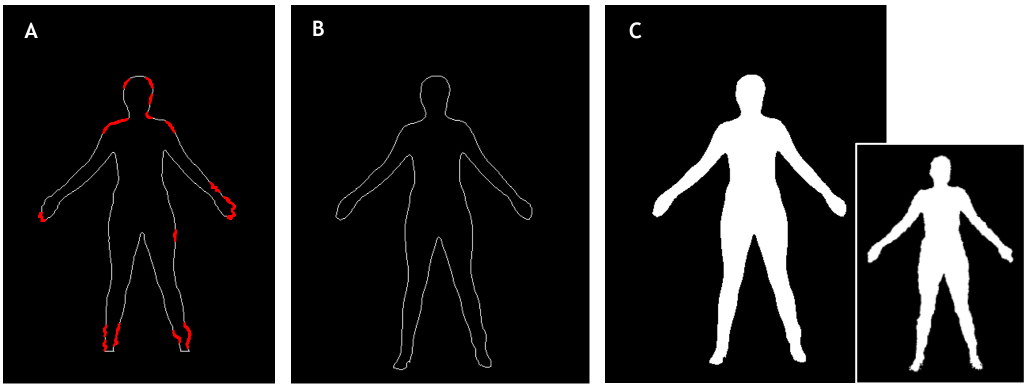

Figure 15 - Detection of the real silhouette of the subject (part IV). A) Spline interpolation is represented in red lines; B) Smooth contour; C) Filling the contour to obtain the new silhouette. The right image shows the original mask from Kinect

3.3.5.1.2. Reconstruction of the depth values for the new silhouette

Since the mask has already been refined, it may be combined with depth image. Firstly, the data was smoothed with a median filter (4x4 window) in order to remove the noise [82].

Thereafter, these previous values were multiplied with the new mask, to get only the depth values corresponding to the silhouette. Nonetheless, the depth on contour silhouette was not accurately detected (Figure 16A) and, therefore, this values need to be rebuilt. The reconstruction of the depth image was made through a median filter with a window of a variable size, i.e., the window size increase until have at least 25 pixels with a nonzero value. Result can be shown in Figure 16B.

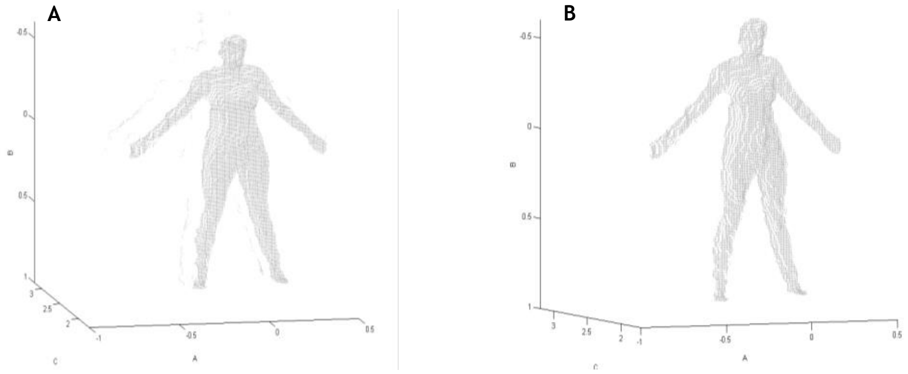

Figure 16 - Reconstruction of the depth image. A) Point cloud before the reconstruction of depth values belonging to the new silhouette; B) Point cloud after reconstruction of the depth values of the new silhouette with a median filter.

3.3.5.1.2.1. Comparison of the silhouettes with the groundtruth

To verify whether the silhouette obtained through the developed method (2D mask improved, Figure 17A) was better than the original silhouette from the Kinect (2D mask raw, Figure 17B), metrics were calculated, namely precision, recall and PBC (percentage of bad classifications). For these calculations, both silhouettes were compared with the groundtruth mask (Figure 17C), which was obtained by manual segmentation.

These metrics require the distinction between the silhouette, named foreground (usually considered as positive) and the background (negative). Through these considerations, the common terminology can be used, as True Positive (TP), True Negative (TN), False Positive (FP) and False Negative (FN). The equations for these metrics calculation are:

$$Precision = \frac{TP}{TP+FP} \quad (1)$$

$$Recall = \frac{TP}{TP+FN} \quad (2)$$

$$PBC(\%) = \frac{FN+FP}{TP+FN+FP+TN} \times 100 \quad (3)$$

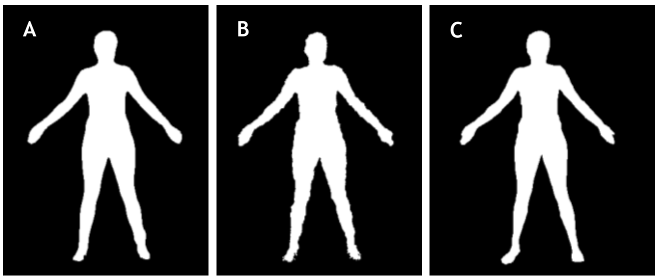

Figure 17 – Representation of different masks: A) 2D mask improved; B) 2D mask raw; C) Groundtruth mask

3.3.5.1.3. Landmarking

Finally, with the refined silhouette and correct depth values, the position of the landmarks can be estimated. The determination of each anatomical point tries to follow the recommendations defined by the ISAK protocol, however, when this was not possible, approximations are made based on anatomical proportions or based on testing the study sample.

- The vertex corresponds to the highest vertical point of the silhouette (Figure 18A).
- The right and left dactylion correspond to the intersection between the contour and the straight line formed by correspondents hand joint and elbow joint (Figure 18B).
- The right and left stylion are the points where there is an opening contour, i.e., it is the point of intersection between two segments that have an opening angle (Figure 18C).
- The right and left elbow are anatomical points where it was difficult to identify by direction changes of the contour. Thus, the best way to determine this point was through anatomical proportions. According to [83], elbow corresponds to the point whose distance from the stylon is one head (Figure 18D).
- The left and right acromiale are the points of intersection between the silhouette and the straight line formed by torso joint and correspondent shoulder joint (Figure 18E)
- The right and left iliocristal points were also calculated from anatomical proportions [83] (a half head from the trochanterion, which in turn was the most lateral point of the hip joint) – Figure 18F
- The right and left tibiale laterale correspond to the outermost point of the correspondent knee joint (Figure 18G).
- The right and left sphyrion fibulare correspond to the outermost point of the correspondent foot joint (Figure 18H)

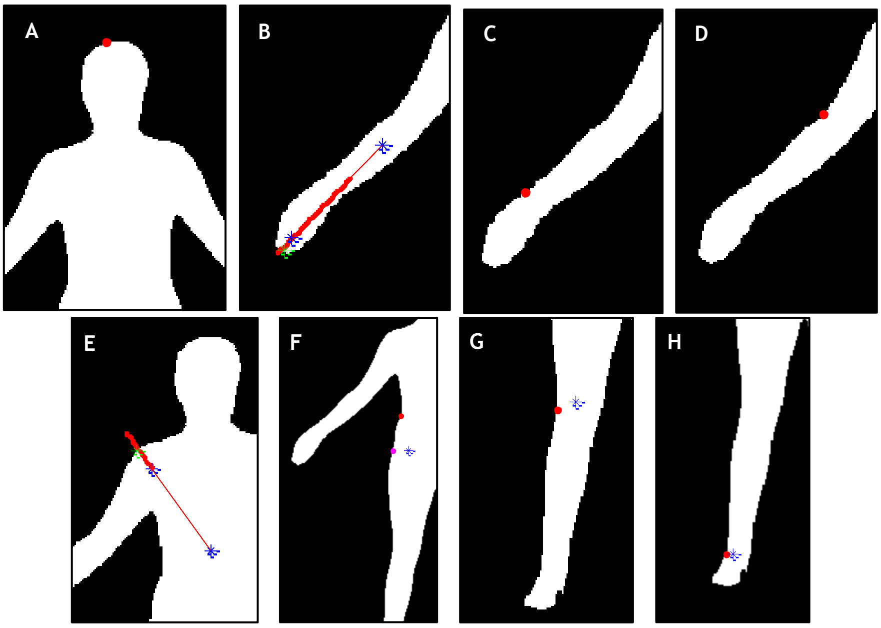

Figure 18 - Landmarks position. A) Vertex (red point); B) Right dactylion (red line is the straight line formed by correspondents hand joint and elbow joint, which are marked in blue; green point is the dactylion point); C) Right wrist (red point); D) Right radiale (red point); E) Right acromiale (red line is the straight line formed by correspondents torso joint and shoulder joint, which are marked in blue; green point is the acromiale point); F) Trochanterion (hip joint is the blue point; trochanterion is the magenta point); iliocristale I the red point); G) Tibiale laterale (knee joint is the blue point; tibiale laterale is the red point); H) Sphyrion (foot joint is the blue point; sphyrion is the red point);

3.3.5.2. Algorithm for weight estimation

Several studies [48, 65, 70, 71] have tried to determine the value of the subject's weight (body mass) by anthropometric measures.

Usually, these studies rely to databases having several body measures trying to correlate different variables in order to reach an ideal formula. As the population of this study was very small, this kind of study was not possible. However, the formula obtained by these studies can be tested, evaluating combinations of these parameters and trying to adapt it to the population under study.

Thus, this study will be based on the formula given by the study of Velardo *et.al.*[48], which uses a database widely known, NHANES:

$$weight\ (kg) = -122.27 + 0.48 \times f1 - 0.17 \times f2 + 0.52 \times f3 + 0.16 \times f4 + 0.77 \times f5 + 0.49 \times f6 + 0.58 \times f7,$$

where f1 corresponds to the height, f2 to the upper leg length, f3 to the calf circumference, f4 to upper arm length, f5 to upper arm circumference, f6 to waist circumference and f7 to upper leg circumference.

The length measures were calculated using the previous method, but circumference measures have to be calculated from the scratch. For these measures, some assumptions were need, particularly if the circumference would be approximated to a circle, or an ellipse. When they were approximated to an ellipse, it was necessary to read the side images of the subjects captured by the Kinect (Figures 19A and 19B).

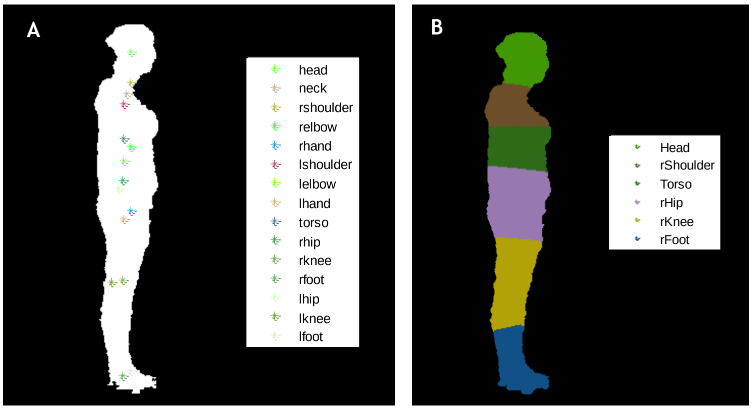

Figure 19 – Information from the side view of the human body. A) Joints representation in a mask of side view. B) Segmentation mask according to the joints of the right side

3.3.5.2.1. Landmarking

The determination of each new anatomical point, tries to follow the recommendations defined by the ISAK protocol, making the following approaches:

- The upper arm point corresponds to the midpoint between the shoulder joint and elbow joint. This circumference was approximated to the perimeter of a circle: it is only considered the front view of the subject (Figure 20A)
- The waist was approximated to the closest point of the iliocristale. This circumference was approximated to the perimeter of an ellipse: the front view gives the largest radius, and the side view gives the smaller radius (Figures 20B and 20C respectively).
- The thigh point corresponds to the midpoint between the hip joint and knee joint. This circumference was approximated to the perimeter of an ellipse: the front view gives the largest radius, and the side view gives the smaller radius (Figures 20D and 20E respectively).
- The calf point corresponds to the midpoint between the knee joint and foot joint. This circumference was approximated to the perimeter of an circle: it is only considered the front view of the subject (Figure 20F)

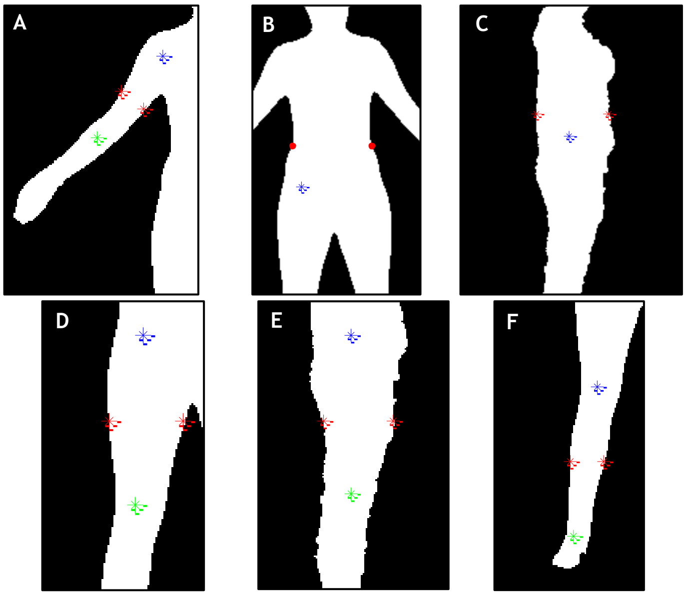

Figure 20 - Landmarks position for weight estimation. A) Upper arm – frontal view (extremities of the radius of upper arm are represented in red; shoulder and elbow joints are marked in blue and green respectively); B) Waist – frontal view (extremities of the major radius of the waist are represented in red; right hip joint is marked in blue); C) Waist – lateral view (extremities of the minor radius of the waist are represented in red; right hip joint is marked in blue); D) Thigh – frontal view (extremities of the major radius of the thigh are represented in red; hip and knee joints are marked in blue and green respectively); E) Thigh – lateral view (extremities of the minor radius of the thigh are represented in red; hip and knee joints are marked in blue and green respectively); F) Calf – frontal view (extremities of the radius of calf are represented in red; knee and foot joints are marked in blue and green respectively);

3.4. Anthropometry and thermography

Since the drawing of ROIs in thermographic images is performed manually, it might be interesting to combine the anthropometric information with thermographic data in order to draw those regions automatically.

This is a preliminary work that does not intent to be fully developed, because it is not the purpose of this dissertation. The idea of this section is only to show the potential of this approach.

Accordingly, the thermographic image segmentation as well as the obtaining of the skeleton provided by Kinect was not performed automatically, being a proposal for the future work (Figures 21A, 21B and 21C).

With these data, the code developed in the anthropometry section, for obtaining the landmarks, was applied here, showing that it was possible to segment the thermographic images by drawing ROIs automatically (Figure 21D).

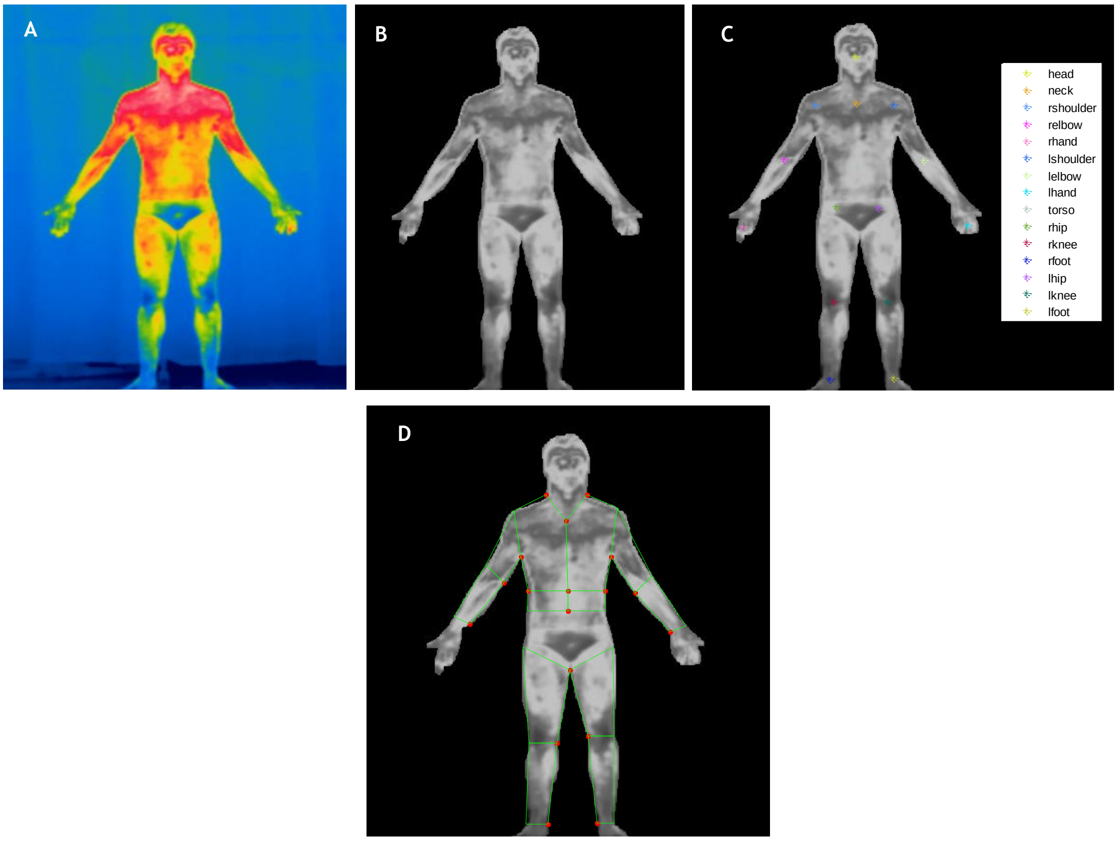

Figure 21 – Input data (data already acquired) and the result. A) Original thermogram; B) Segmented image; C) Representation of joints; D) Result of the image segmentation by ROIs

The anthropometric data processing will mark the relevant anatomical points and relevant areas in the thermographic images in a (semi) automatic way.

Chapter 4

Results

In this chapter, the thermal and anthropometric experimental results arising from the implementation of the methodology mentioned in Chapter 3 will be detailed.

4.1. Thermography

Regarding the characterization of sports injuries, thermographic images were collected in accordance with the capture protocol defined in the methodology section. For each sample, 12 regions of interest were collected and analyzed. These regions belong to the lower limbs, in particular, on the knees, legs and ankles.

Throughout this study, 34 samples were collected, comprising 8 knee pathologies, 9 ankle pathologies and 17 healthy cases. The values of the mean temperature of each ROI for each group are summarized in Table VI.

Table VI – Mean temperatures of each ROI for each group (LFK: lateral frontal knee; RFK: right frontal knee; LLK: left lateral knee; RLF: right lateral knee; LFA: left frontal ankle; RFA: right frontal ankle; LLA: left lateral ankle; RLA: right lateral ankle; LFL: left frontal leg; RFL: right frontal leg; LDL: left dorsal leg; RDL: right dorsal leg)

	LFK	RFK	LLK	RLK	LFA	RFA	LLA	RLA	LFL	RFL	LDL	RDL
Pathological (knee injury) n=8	29.7 ±0.9	29.7 ±1.1	30.6 ±1.0	30.8 ±0.9	29.1 ±1.8	29.1 ±1.7	29.1 ±1.5	28.9 ±1.5	29.9 ±0.8	29.9 ±0.8	30.0 ±0.8	30.0 ±0.7
Pathological (ankle injury) n=9	28.3 ±0.7	28.2 ±0.8	29.4 ±0.9	29.1 ±0.9	28.1 ±1.0	28.4 ±1.0	28.0 ±1.2	28.0 ±1.3	29.6 ±0.9	29.6 ±1.0	29.9 ±0.9	29.9 ±0.8
Non-pathological n=17	29.7 ±1.5	29.7 ±1.5	30.7 ±1.2	30.5 ±1.3	29.8 ±1.9	29.8 ±1.8	29.5 ±1.8	29.5 ±1.7	30.8 ±1.4	30.8 ±1.4	30.6 ±1.3	30.5 ±1.4

For each of the considered anatomical regions, the thermal symmetry is calculated from the absolute difference between the mean temperatures of the contralateral ROIs (section 3.2.3), in order to assess the potential of infrared thermography in this study. Firstly, statistical tests were performed for distinguishing between pathological and non-pathological group, and then, the identified injury is monitored through a follow-up.

Since no injuries were reported in the legs regions (frontal and dorsal view), these collections was not used for the remaining statistical tests.

4.1.1. Validation of the study

Prior to performing any statistical test for the study of the relevance of using infrared thermography for the injuries characterization, it is necessary to check if it is possible to distinguish the different control groups (athletes and non-athletes) that may compromise or change the data analysis (section 3.2.1).

A non-parametric test was applied (Mann-Whitney U test) to investigate this assumption. The adherence to normality (Shapiro-Wilk) was also used to corroborate the hypothesis test chosen (Table VII).

Table VII – Test of Normality for thermal symmetry parameter – Shapiro-Wilk test (n=34 for frontal knee, frontal ankle and lateral ankle; n=29 for lateral knee)

	statistic	df	p-value
Frontal knee symmetry	0.626	34	0.000
Lateral knee symmetry	0.926	29	0.043
Frontal ankle symmetry	0.882	34	0.002
Lateral ankle symmetry	0.849	34	0.000

The normality test demonstrates that the collected values of thermal symmetry follows a non-normal distribution (Shapiro-Wilk test, p-value<0.5, Table VII), and therefore, the non-parametric tests are the most appropriate to evaluate the statistical difference between the different groups.

Applying a non-parametric test, the controls of each group were compared, showing no statistical evidence for the distinction between them (Mann-Whitney U test, p-value>0.05, Table VIII).

Table VIII – Non-parametric test for thermal symmetry parameter (controls) - Mann-Whitney U test - (n=17 for frontal knee, frontal ankle and lateral ankle; n=15 for lateral knee)

	U	Z	p-value
Frontal knee symmetry	29.500	-0.572	0.567
Lateral knee symmetry	17.500	-0.944	0.345
Frontal ankle symmetry	22.500	-1.249	0.212
Lateral ankle symmetry	24.000	-1.092	0.315

The results of the non-parametric test validate the achievement of this study, and is in line with literature values [38, 84].

4.1.2. Injury identification

In infrared thermography the presence or absence of pathologies is commonly identified through the thermal symmetry value (see section 3.2.3) [3, 21, 35–37].

For that reason, the thermal symmetry values of each region were statistically analyzed (Table IX).

Table IX - Non-parametric test for thermal symmetry parameter - Mann-Whitney U test – (n=34 for frontal knee, frontal ankle and lateral ankle; n=29 for lateral knee)

	U	Z	p-value
Frontal knee symmetry	53.000	-2.109	0.035
Lateral knee symmetry	57.000	-0.659	0.510
Frontal ankle symmetry	56.000	-2.234	0.025
Lateral ankle symmetry	64.000	-1.917	0.055

The results of the nonparametric test present statistical evidence to distinguish pathological and non-pathological groups from the frontal regions of the knee and ankle (Mann-Whitney U test, $p\text{-value}<0.05$, Table IX). However, the same is not true for the lateral regions (Mann-Whitney U test, $p\text{-value}>0.05$, Table IX).

These non-concordant results can be associated with the inflammation process resulting from the injury, being only visible in the frontal views. This attribution of state of pathology by area of interest (knee or ankle) instead of view (frontal knee, lateral knee, frontal ankle or lateral ankle) may distort the outcomes. An example of an injury that is detectable only in one of the views is represented in Figure 22.

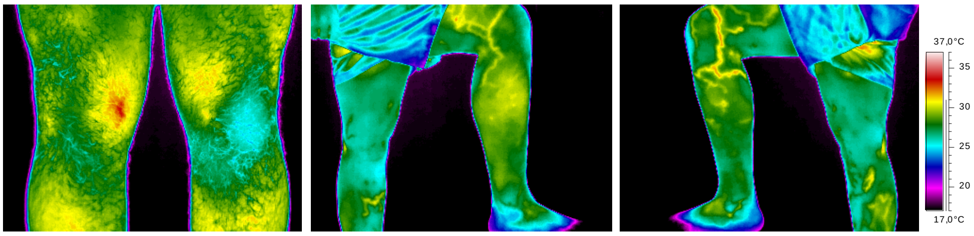

Figure 22 - Example of thermograms of a right knee injury (lesion in an internal meniscus). A) Frontal view (injury is detectable); B) Lateral view (injury is not detectable)

Assessing the value of mean temperature of each ROI to distinguish between pathological and controls, it was found that this parameter did not present statistical evidence for this distinction (Mann-Whitney U test, p-value>0.05, Table X). Although the temperature values follow a normal distribution, a non-parametric test was performed (see section 3.2.4).

Table X - Non-parametric test for temperature parameter - Mann-Whitney U test – (n=34 for frontal knee, frontal ankle and lateral ankle; n=29 for lateral knee)

	U	Z	p-value
Left frontal knee	38.500	-0.486	0.627
Right frontal knee	41.000	-1.532	0.125
Left lateral knee	21.000	-0.517	0.605
Right lateral knee	13.500	-1.786	0.074
Left frontal ankle	15.500	-1.884	0.060
Right frontal ankle	51.500	-1.022	0.307
Left lateral ankle	16.000	-1.854	0.064
Right lateral ankle	54.000	-0.900	0.368

4.1.3. Follow-up

Beyond the identification of pathological cases, follow-up is essential for monitoring and tracking the progression or regression of an injury. This monitoring allows the comparison of the thermal symmetry values among the several sessions, and therefore is able to identify the evolution of the detected abnormality, which in case of a progress can constitute a risk for the athlete.

This component of the study was assessed graphically with visual support (thermograms) and with support of the athlete's symptoms in terms of severity (with a scale with 3 levels: mild, moderate or strong, Appendix D). Additionally, this analysis was performed in order to obtain the spatial information of the injury (left or right knee/ankle), i.e., the thermal symmetry was calculated according to a fixed rule (through the difference between left and right ROI).

The first example corresponds to a pathological athlete with a lesion in the right knee (internal meniscus injury) who returned to training after a period of physiotherapy. The athlete was followed over a period of 20 days, having completed 4 collections. The quantitative and qualitative results of the knee regions are presented in Figures 23 and 24 and in Table XI.

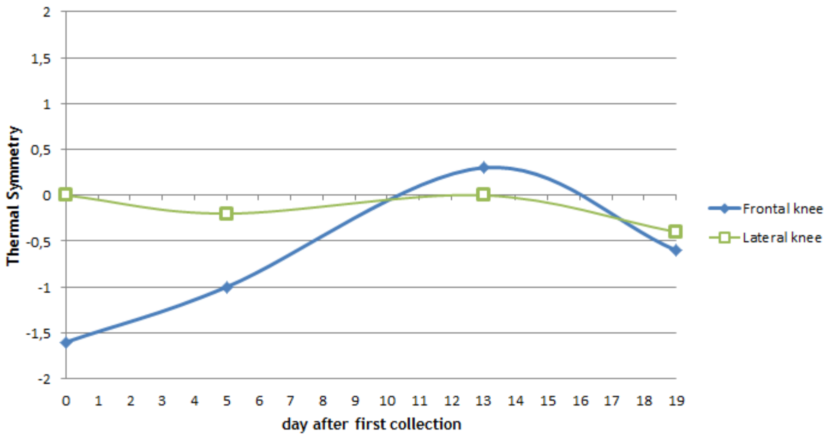

Figure 23 - Results of thermal symmetry during follow-up of the athlete (knee regions)

Table XI - Degree of severity reported by athlete during follow-up (knee injury)

Session	Session 1	Session 2	Session 3	Session 4
Degree of severity	3	2	1	2

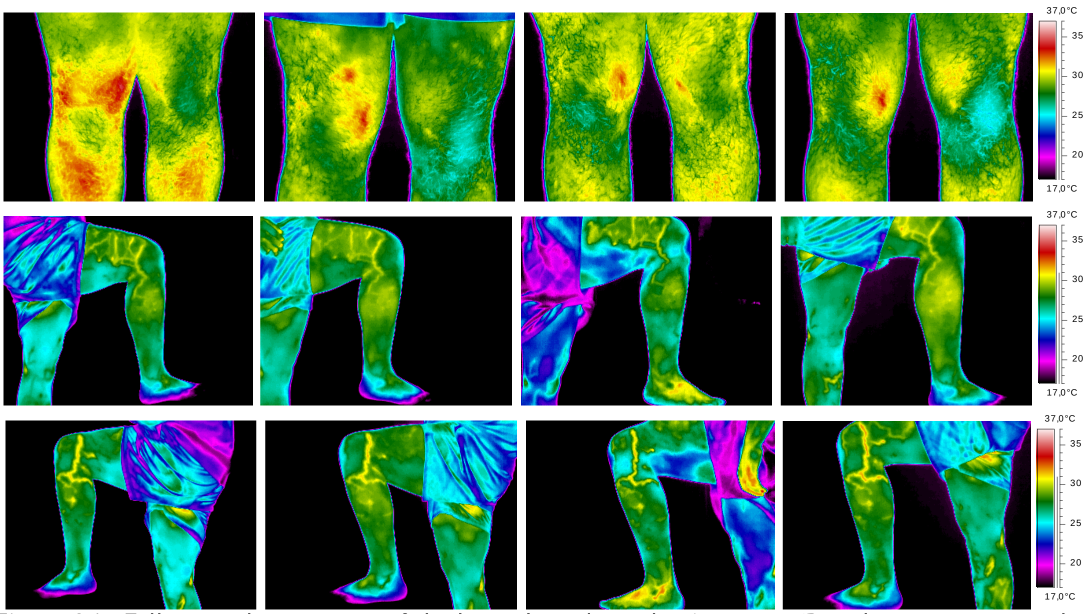

Figure 24 - Follow-up thermograms of the knee throughout the 4 sessions (By column: session number; By row: 1-frontal knee, 2-right lateral knee, 3-left lateral knee)

From the obtained results, it is possible to verify that, either quantitatively or qualitatively, there are noticeable asymmetries in the frontal knee region, demonstrating an abnormality in the right knee (negative thermal symmetry). Furthermore, it is visible the difference between several sessions and how they are correlated, by comparison, with the degree of severity (intensity of pain) assigned by the athlete.

This section in particular proved once again that an injury in the frontal view may not be observable in lateral view (or vice versa), corroborating the ideas outlined in section 4.1.2.

The second example corresponds to a pathological athlete with an injury in the right ankle. This athlete was followed over a period of 7 days, having completed 2 collections. The quantitative and qualitative results of the ankle regions can be observed in Figures 25 and 26 and in Table XII.

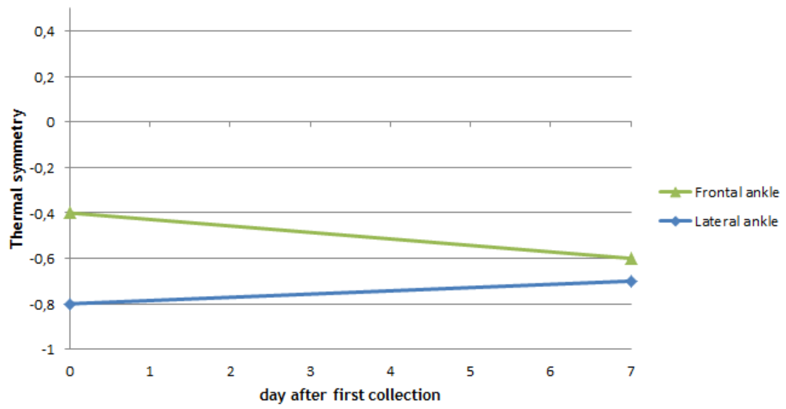

Figure 25 - Results of thermal symmetry during the follow-up of the athlete (ankle regions)

Table XII - Degree of severity reported by athlete during follow-up (ankle injury)

Session	Session 1	Session 2
Degree of severity	1	1

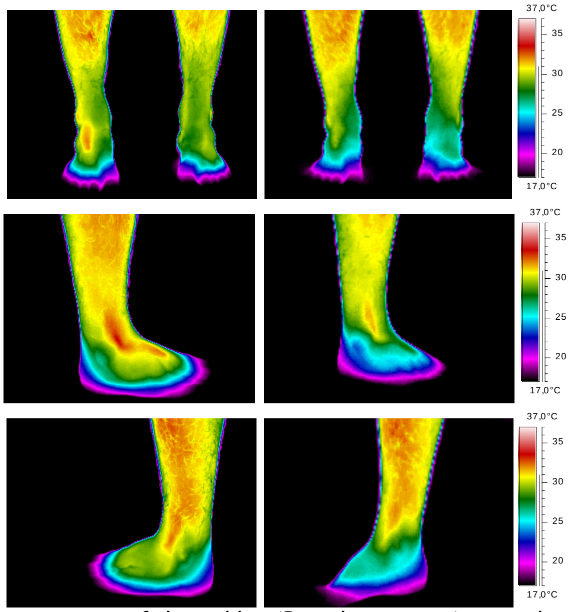

Figure 26 - Follow-up thermograms of the ankles (By column: session number; By row: 1-frontal ankle, 2-right side of ankle, 3-left side of ankle)

Either quantitatively or qualitatively, there were visible the asymmetries in the ankle regions. These results corroborate with the physical condition of the athlete.

Finally, only for confirming the results, a non-pathological athlete was followed during 3 sessions in 14 days. The results are presented in Figures 27 and 28, showing that there are not noticeable asymmetries in the knee, ankle or leg regions. These results corroborate with the physical condition of the athlete and is in line with literature values (|thermal symmetry|≤0.5ºC) [38, 84].

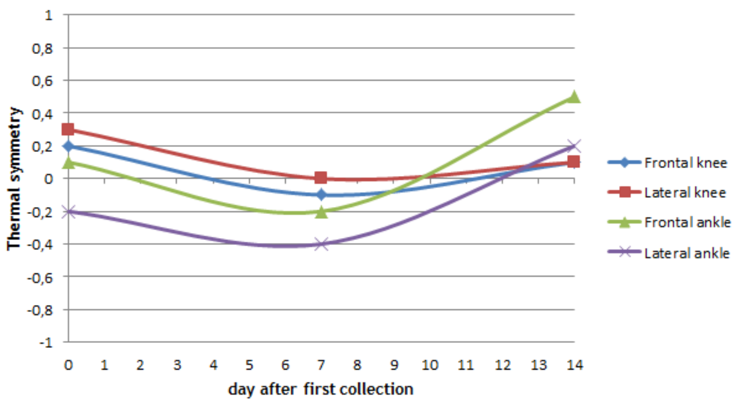

Figure 27 - Results of thermal symmetry during the follow-up of the athlete (knee, leg and ankle regions)

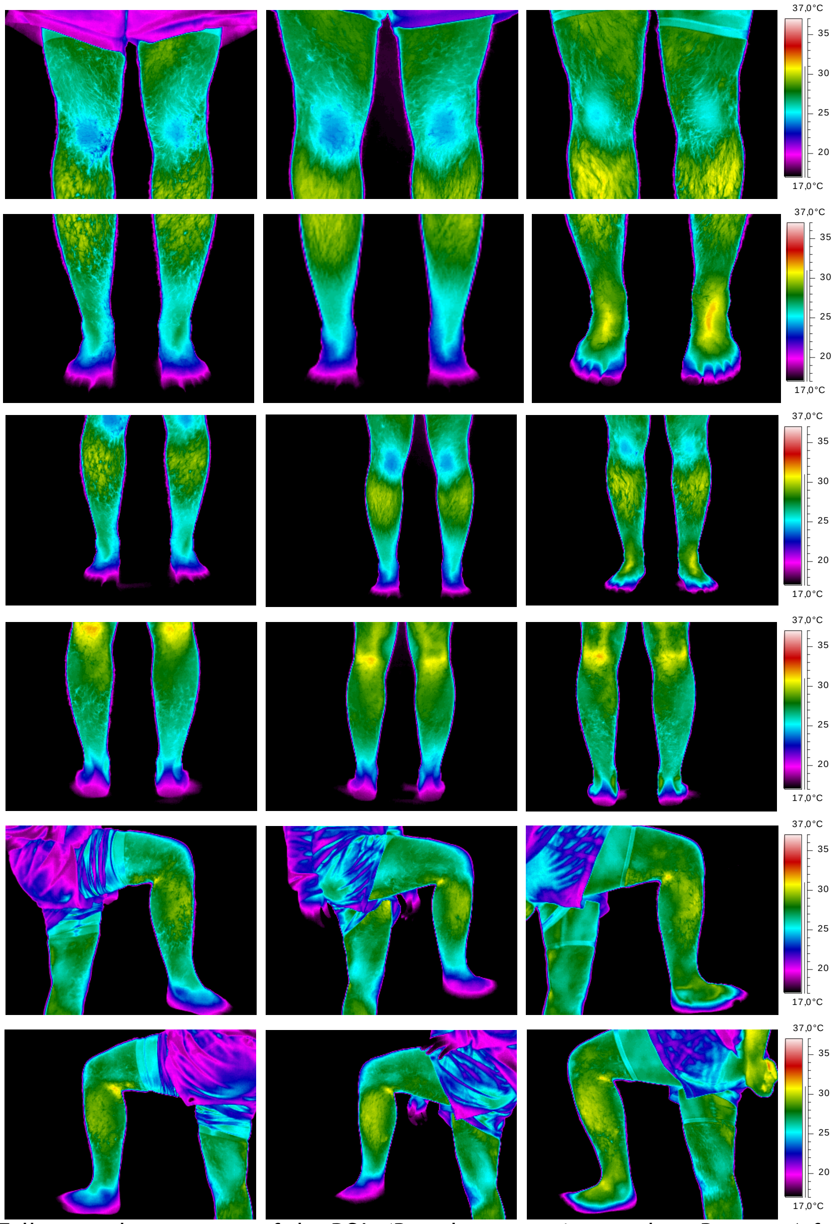

Figure 28 - Follow-up thermograms of the ROIs (By column: session number; By row: 1-frontal knee, 2-frontal ankle, 3-frontal leg, 4-dorsal leg, 5-right side of the knee and ankle, 6-left side of the knee and ankle)

4.2. Anthropometry

After the data collection with Kinect, the image processing was applied in order to mark the anatomical points in silhouette and then extract anthropometric measurements, such as body parts sizes and body weight.

4.2.1. Comparison of the silhouettes with the groundtruth

After obtaining the silhouette through the developed method (2D mask improved), this and the original mask from the Kinect (2D mask raw) were both compared with the groundtruth mask. The results of measurements of precision, recall and PBC are presented in Table XIII.

Table XIII – Values of precision, recall and PBC metrics, for 2D mask improved and 2D mask raw

Metric		Values	Ratio (pixels)
Precision	2D mask improved	0.95	$\frac{27155.3}{28489}$
	2D mask raw	0.95	$\frac{26889}{28207.7}$
Recall	2D mask improved	0.96	$\frac{27155.3}{28200}$
	2D mask raw	0.95	$\frac{26889}{28200}$
PBC (%)	2D mask improved	0.78%	$\frac{2378.3}{306541.3}$
	2D mask raw	0.79%	$\frac{2436.7}{306541.3}$

In terms of precision (percentage of pixels correctly identified as silhouette), the values obtained for the two masks were similar. This value can be explained by the large number of pixels in the silhouette on both masks. Regarding the recall (percentage of pixels of the silhouette correctly identified), the value for the refined mask is superior, showing that, in the improved mask, there are more points belonging to the silhouette that are correctly identified as silhouette. Finally, PBC (percentage of pixels wrongly identified) is inferior in refined mask, which proves once again, that the developed method is better than 2D mask raw.

4.2.2. Data processing for landmarking

At the end of the developed algorithm, the spatial location of each of the landmarks is extracted, from which it is possible to calculate the anthropometric measures previously defined (Figure 10). The whole procedure of reconstruction of the silhouette, marking the anatomical points and extraction of body measurements is performed for each frame that was collected from the Kinect. The final landmarking in 2D and 3D silhouettes are represented in Figures 29A and 29B respectively.

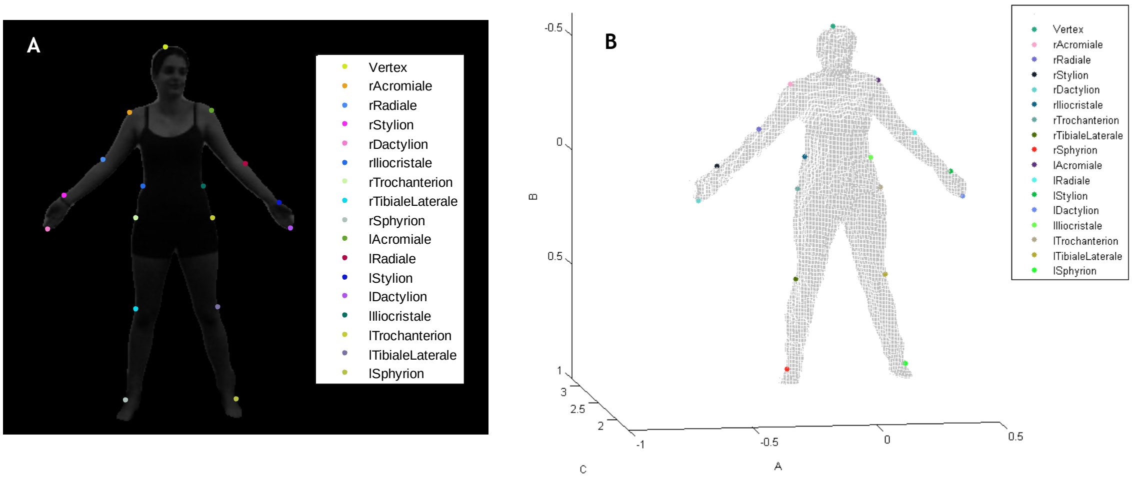

Figure 29 - Final landmarking in 2D and 3D silhouettes (A and B respectively)

4.2.2.1. Validation of landmarking results

The validation of the landmarking data involves the comparison with results of the direct measurement or with a system whose error is known and precise, such as Qualisys, a tested system, which has a very low error (0.6mm for these collections). In this system, landmarks are labelled on the subject using specialized markers, taking about 20 minutes.

Anthropometric measurements are performed by 7 to 12 Oqus cameras that capture the position of landmarks from different angles (the acquisition protocol is in Appendix G).

Thus, each body measure for each frame of each subject is compared with the same measurement extracted by Qualisys, calculating an error.

Table XIV summarizes the average error of each measure for the study sample. Thereafter, the obtained errors are then compared with the errors found in the literature [66].

Table XIV - Measurement error for each anthropometric measure

	Mean (mm)	Mean (%)	SD (%)	Literature Mean (%)
Lower leg	36.01	8.69	6.97	-
Upper leg	22.36	5.27	3.40	-
Iliocristale - trochanterion	11.39	9.48	10.41	-
Hand length	30.35	16.04	4.68	-
Forearm	16.64	**6.64**	4.42	6.68
Upper arm	63.40	20.10	9.62	**12.76**
Biacromiale breadth	28.80	**7.87**	6.02	13.99
Bitrochanterion breadth	55.61	**14.29**	3.25	15.64
Height	75.20	4.40	1.70	**3.31**
Acromiale height	72.14	5.16	1.99	**3.69**
Iliocristale height	25.96	**2.53**	1.62	7.72
Patellar height	33.14	7.36	3.62	**6.58**
Mean	**39.25**	**8.99**	**4.81**	-

Based on the values extracted from the Qualisys, the developed method had an error of 8.99% (accuracy of 91.01%). Generally, the obtained errors have variability between different body measurements and between subjects (higher SD), which does not set a consistent pattern.

The upper arm and hand lengths are the measures most susceptible to error. These values were expected, since the stylion is the most difficult to identify using the developed algorithm, and therefore the same happens with radiale (which is calculated from the stylion by anatomical proportions). In addition, the dactylion is not well identified, because it belongs to a region poorly detected by Kinect.

Compared with the literature [66], the developed method has four measures with higher values (iliocristale height, forearm, biacromiale breadth and bitrochanterion breadth). The worst result recorded is once again the upper arm length, while the others are very close to the literature ones, which suggests that this method is promising.

4.2.3. Weight estimation

As mentioned above, to calculate the weight, it is necessary to determine the spatial location of more anatomical points.

Among the anthropometric measures required and those already calculated, it is only necessary to determine: upper arm circumference, upper leg circumference, waist circumference and calf circumference. As all of them are circumferences, some approximations are required, i.e., for the upper leg and waist, the circumference may be approximated to the perimeter of an ellipse, since there is side information of the subject from Kinect; however, for the upper arm and calf, this is not possible, since the mask is wider due to other body structures that are behind. In the latter case, the respective circumferences are approximated to the perimeter of a circle (with the radius from the front view).

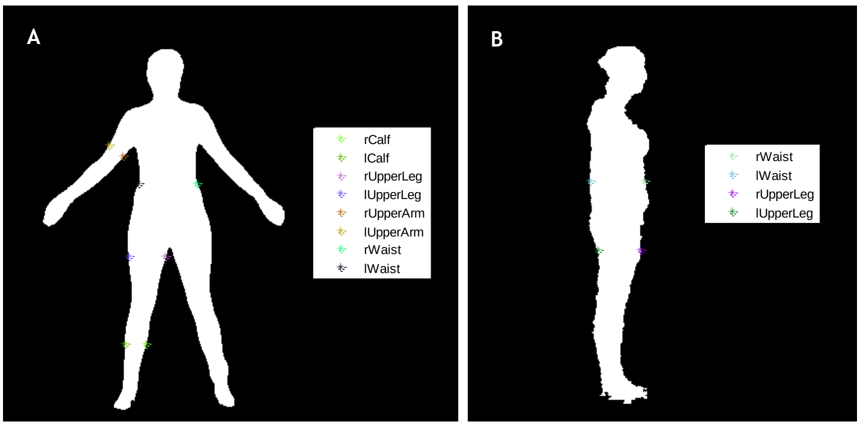

Figure 30 – New anatomical points computed to estimate the weight. A) Frontal view; B) Lateral view

With measures already determined, the weight is estimated according to the formula previously presented. For the sample belonging to this work, the average error associated with the measurements is 14.38% (accuracy of 85.62%).

Nevertheless, the weight formula was obtained from measurements coming from a database with an accuracy that the method developed in this study does not present.

Thus, it is necessary to perform an additional study to evaluate the loss of performance that can be expected in this method. To this end, all the combinations of features present in the theoretical model were tested (127 combinations), showing that for the sample considered, the results considerably improves its performance when all the features are considered less the leg length information (f2):

$$weight\ (kg) = -122.27 + 0.48 \times f1 + 0.52 \times f3 + 0.16 \times f4 + 0.77 \times f5 + 0.49 \times f6 + 0.58 \times f7$$

The associated error with these measurements was lowered to 6.59% (accuracy of 93.41%), still higher than the reference literature (4.3%). However, it is important to note that this formula contains the upper arm measure, and therefore this value will adversely affect the result (since it has a high error). In addition, the circumferences previously mentioned, used for the calculation of the weight, were obtained through mathematical approximations (circles or ellipses), which may compromise the results.

4.2.4. Anthropometry and thermography

The use of anthropometric data to identify human body ROIs in thermographic images can be a good solution to automate this method. Thus, starting from the already segmented image and skeleton information (data that was not automatically obtained in this part of the work), it is possible to segment the thermographic images by drawing regions of interest automatically.

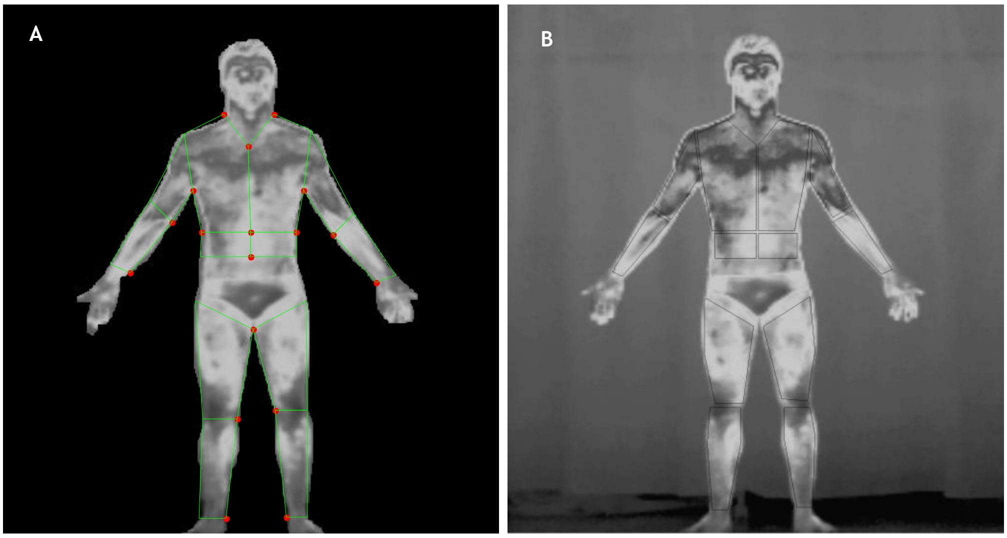

Figure 31 – Thermographic segmentation. A) Automatic segmentation of the thermogram; B) Manual segmentation of the thermogram

The results of automatic segmentation can be visualized in Figure 31A. Then, they can be qualitatively compared with the manual segmentation, which is shown in Figure 31B.

Chapter 5

Discussion

5.1. Thermography

5.1.1. Capture protocols

Due to contradictory results presented by the lack of methodological standards and by the limitation imposed by the equipment, the IRT lost interest in the end of 70's, being replaced by emerging technologies such as radiography, ultrasound or magnetic resonance. However, the technological improvements of IRT in the last years (in terms of resolution, sensitivity, specificity and reproducibility), as well as the advances in thermal image processing and the increase in the number of standard recording procedures, combined with the substantial reduction of prices of the equipment, have made possible a resurgence of this technique, restoring the lost credibility of the technique for medical use.

The proposed protocol for capturing thermograms of the knee, ankle and leg, are based on the Glamorgan and AAT protocols [74, 75], where all factors are described: patient pre-examination preparation, examination room preparation and temperature control. All these factors are addressed in the present study, and when properly applied, avoid a major source of error and unreliability.

5.1.2. Injury identification

When an injury occurs, an inflammatory response is triggered, increasing the local temperature and consequently, the heat transfer from the skin surface to the outside, in order to maintain and regulate the body core temperature. This process of heat transfer is mainly carried out by radiation mechanism (60%), and for this reason, the interest of use of techniques that detect radiation, such as the case of the infrared thermography, has emerged.

For the injury identification through IRT, several studies [38, 84, 85] indicate that the temperature parameter should be analyzed according to the bilateral imbalances (temperature difference between symmetrical ROIs) instead of the analysis of the temperature of each region independently. Throughout this work, these two types of evaluation were carried out.

As expected, regarding the temperature parameter, there is no statistical evidence to distinguish pathological subjects and non-pathological subjects, since these values alone (temperature of the skin surface) do not provide sufficient information about the human health status [38].

With respect to thermal symmetry parameter, it does present some conclusive outcomes. The statistical distinction between healthy controls and pathological subject groups is observable for frontal regions of the knee and ankle, but not for the lateral regions. This may be caused through the inflammatory process resultant from the injury presented a manifestation only in the frontal part of the area of interest. These findings, in frontal views, highlight the potential of the thermal symmetry in injury identification, however for more reliable conclusions, it is necessary:

- Consider a sample of larger dimension for future research. Among the considered sample, there are only 8 samples with knee pathology, 9 with ankle pathology and 0 with leg pathology.
- For the validation of the method, it is important to know the history of the anatomical injury, i.e., to know the exact location of the lesion and if it affects the two views of the area concerned. Further research is needed to identify whether the signs of injury are only identified in frontal views and not lateral views.
- Regarding the anatomical aspect, it would be important to consider smaller regions within the region concerned, since, for each region, only the mean values of temperature are calculated, and therefore, the adjacent regions to the lesion can camouflage the pathology. Nevertheless, the regions cannot have an area smaller than 25 pixels (Glamorgan Protocol recommendation) [74] because it would increase the changes of producing reading errors.
- Another clinic method (ultrasound, for example) should be considered in order to validate the results obtained. This study was conducted only with information from the player and without any reliable confirmation, which makes the results fairly subjective.

5.1.3. Follow-up

The follow-up and monitoring of injuries before training allows assessing pathological events, following its progression or regression. In this study, athletes belonging to different groups (controls, with pathology in the knee and with pathology in the ankle) were followed.

There were no strict time intervals within collection due to absence of those athletes in the training sessions. This is not relevant for this study because the aim is to assess the implementation of the developed methodology.

From the results obtained, it was possible to verify the relation between the degree of severity assigned by the athlete and the value of asymmetry, demonstrating that, the infrared thermography has potential to monitor and assess the condition of the athlete.

Thus, infrared thermography has proven to be, not only a tool in helping the diagnosis, but also an ideal tool for monitoring the evolution of the injury (progress or regression). With this information, the training reintegration of the player can be programmed with greater confidence and objectivity.

5.1.4. Final considerations

The use of thermography as a diagnostic and treatment complementary method has only been used in sports context as research tool. To date, there are few studies on this topic, especially with regard to the characterization of early sports injuries. For this reason, the present study aimed to explore the several aspects and necessary conditions for the analysis of thermal images.

The introduction of thermal imaging in medical and sports context does not suggest the replacement of existing methods at the clinic, but their combination, being a powerful tool to enhance and support it, mainly on the follow-up of the athlete throughout its practice.

Nevertheless, the injury characterization can only be performed when there is at least one healthy limb, because pathology identification is carried out through the thermal symmetry parameter. This assumption is a limitation of the technique.

5.2. Anthropometry

Anthropometry has proven to be a very important parameter in the design of the athlete's profile, both as an indicator of health and nutrition status or as a biometric identifier.

In view of existing solutions, it becomes crucial to develop an automatic method, fast, inexpensive, effective and which can be operated by anyone and anywhere, without the need for specialized technicians.

The Kinect as an automated method presents several advantages over the traditional methods. Among them, this method does not require a specialist technician to perform the collection, since it does not need calibration procedures, placement of markers and/or measurement. Regarding the 2D cameras, Kinect has as advantages the ability to operate at low light levels and the ability to resolve ambiguities in silhouette. In addition, and as Kinect provides depth value for each pixel, different structures at different distances from the camera were not ignored, unlike what happens in 2D methods [78]. Finally, compared to the 3D methods, the Kinect presents worse results; however, 3D methods are not accessible to any sport institution, and require a specific scene, with particular illumination conditions and background [57, 65].

5.2.1. Landmarking and anthropometric measures extraction

The automatic marking of anatomical points from RGB-D images was one of the biggest challenges of this work.

The whole preceding process to the detection of landmarks, either the removal of outliers or the reconstruction of a new silhouette, was fairly detailed, since the image processing has been performed at the pixel level. The spatial position of the landmarks was estimated by various methods, mostly: using similarities between the skeleton and the silhouette contour or through anatomical proportions.

Anthropometric measurements performed in this study showed an error of 8.99%. The upper arm and hand lengths presented the highest errors (20.1% and 16.04%, respectively), whereas, the lowest error values correspond to height of iliocristale and full body (with 2.53% and 4.4%, respectively). These errors are most often associated with an incorrect marking of the anatomical points, such as dactylion, stylion and radiale, previously mentioned.

Another important issue is related to the position of the landmarks when Qualisys collections are made. Once the Kinect places all landmarks on the contour of the silhouette, the Qualisys landmarks should be placed, as far as possible, also on the side of the subject. For the radiale landmark, this procedure was not carried out, increasing measurement errors involving these landmarks.

Comparing the results obtained with the work of Samejima *et.al.* [66], it is possible to observe that, the 8 measures in common with this literature, the developed method has four measures with lower errors. The worst result recorded is once again the upper arm length, while the others are very close to the literature ones.

It is important to note that, although the study conducted by Samejima [66] also uses the Kinect as a means of obtaining anthropometric measurements, the method is completely different. Samejima [66] uses only four measurements taken from Kinect and all others are estimated from a linear regression, which in turn is taken from a different anthropometric database (Japanese).

Therefore, the proposed methodology of the present study could be improved in the future, with the use of an appropriate anthropometric database.

5.2.2. Weight estimation

The body dimensions may also be used to estimate the weight of a subject. The present work was based on a formula proposed by Velardo and Dugelay [70], which use a set of body measurements that cover the whole body (top and bottom) to estimate the weight.

After marking of new anatomical points on the silhouette and extracting the corresponding body measurements, the formula was applied to the sample, showing an error of approximately 14,38%. However, the authors claim that, in real cases where it is not always possible to take direct measurements, this formula is not a good alternative. Thus, an additional study was performed to estimate what the best combination of features in the data collection to compute the weight. The best performance of this study was considering all the features less the upper leg length information (f2). The average error for the weight calculation with the new formula is 6.59%, showing close results to the literature (4.3%).

Nevertheless, some aspects must also be considered in this study: firstly, the formula proposed by Velardo and Dugeley [70] is based on a well-known database but concerns the American population and therefore may not be adequate to the Portuguese population; secondly, this formula could be recalculated for the different age groups, since the physical conditions are different between them; and finally, the error associated with these measurements can be a consequence of the anthropometric measurements of the errors calculated in the previous section, especially with regard to the upper arm length (error=20.1%).

5.2.3. Final considerations

The existing studies for the calculation of body sizes or the calculation of the weight from methods that use the Kinect, remains subtle. Thus, the method presented can be an important tool in such studies, since it has reasonable and promising results. In terms of limitations, it is important to note that the method developed is still very dependent on posture and clothing used (the thickness of clothing is not taken into account for the detection of the silhouette), being an important aspect to improve in the future.

5.3. Anthropometry and thermography

The preliminary study to combining anthropometric information with thermographic images aims to automate the process of ROIs delimitation in thermographic images, whose actual process is manual and time consuming.

Relevant and interesting results can be obtained through the identification of anatomical points from anthropometry, in the thermographic images.

In the future, new anatomical points are needed to enhance the results obtained for each ROI (to ensure that the drawing of the regions is performed only within the silhouette), as well as, for the delimitation of different regions.

Chapter 6

Conclusion

The purpose of this dissertation included the design, implementation and evaluation of thermal and anthropometric measurements as part of the athlete's profile, and which allows the monitoring and assessment of potential risks and abnormalities among the trainings.

Concerning the thermal perspective of the athlete, repeatable and sensitive methodology for the identification of pathological conditions was developed. Objective assessments were applied to the lower limbs, demonstrating good discrimination between groups of healthy controls and pathological subjects, namely in the frontal regions of the knee and ankle, but not the in the lateral regions.

The infrared thermography proved to be a potential method to enhance and support the existing methods in clinical area, mainly in the follow-up of the athlete, since the athlete does not perform clinical examinations so often during this period of time. It is a prospective tool to avoid player absence due to injury and consequently leading to the reduction of the associated costs. In addition, a standard capture protocol was designed, implemented and proposed for future work.

Regarding the anthropometry, the developed method used in this study, proved to be useful for silhouette detection and depth values reconstruction, showing that, with affordable equipment, such as Microsoft Kinect, the identification of the subject is quite reasonable. In the application of the anatomical points detection and consequent anthropometric measures extraction (body dimensions and weight), the obtained results were promising, being object of enhancement in future studies.

In conclusion, both methods discussed throughout this study are still exploratory, being recommended a larger dimension study for better characterization to be used in the future, however, they already present powerful contributions in this area.

6.1. Proposed future work

For further work, regarding thermography, the following aspects should be considered:

- Clinical methods (ultrasound, for example) should be used to corroborate the finding in thermographic images, once the pain scale used is subjective;
- To acknowledge the anatomical location precision and not only the anatomical region for the method validation;
- Consider the hypothesis of pinpointing smaller regions inside the regions proposed by the Glamorgan protocol;
- Evaluate if different pathologies could be distinguished by thermography.
- Apply the method to a larger dimension sample, to obtain more reliable results

Regarding anthropometry:

- Improve the method to the point that anthropometric measures extraction may not be dependent of the subject posture;
- Assess the possibility of studying/analyzing dressed subject.
- Apply the method to a larger dimension sample, to obtain more reliable results

With regard to combination of anthropometry and thermography information, the preliminary study carried out in this project can be improved through:

- the segmentation of thermographic image;
- the skeleton coming from the Kinect should be provided to the thermographic image.

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Appendix A

Thermographic image capture protocol

The standard procedures for recording the thermograms of the human body are based on the guidelines of the “Glamorgan Protocol”. This protocol divides the recommendations into three major sections: the subject, the room and the image recording process.

Subject

Subject should be advised to:

- Avoid all topical applications such as ointments and cosmetics, on the day of the exam for all areas of interest;
- Avoid heavy meals and intake of tea or coffee until 2 hours before the exam;
- Avoid smoking for a minimum of 2 hours before the exam;
- Avoid tight fitting clothing;
- Avoid physical effort and methods of therapy such as electrotherapy, ultrasound, heat treatment, cryotherapy, massage and hydrotherapy. In case of physical effort or physical therapy, wait at least 6 hours to perform the test;
- Avoid the use of steroids, sympathetic blockers or vasoactive medications for 24 hours before to the thermographic examination. Exceptions should be noted.

On arrival:

- The subject should be informed about the whole examination procedure;
- The subject should be asked to assume the pre-defined positions;
- The subject should remove the clothes and jewelry;
- The subject should be asked to sit and or rest in order to achieve thermal equilibrium with the ambient conditions. The time required for the stability is usually 10 minutes.
- The subject should avoid any contact between any parts of the body.

On scanning:

- Should be avoided any comparisons of results in different conditions;
- Should be guaranteed the confidentiality of the subject. The identification of the subject will be carried out using a code;
- The distance between the camera and the patient should be previously calculated and recorded in order to reliably compare different thermograms;
- The date and time of the examination shall also be recorded.

Room

Room measures:

- To capture thermal images of the human body, should be considered a minimum distance between the camera and the subject (usually 1 meter), as previously mentioned. This means that the size of the room should be at least 2x3 meters;
- The room should include only the necessary material for the exam, i.e. all unnecessary equipment and material must be removed from the room, to avoid thermal reflections.

Ambient temperature control:

- The room temperature must be maintained for at least one hour at a constant value between 18 - 24°C, usually 22 ± 1°C. At lower temperatures, the subject is susceptible to shiver, and over 24ºC, room temperature will cause sweating;
- For inflammatory lesions, the appropriate temperature is 20°C ± 1°C;
- The ultraviolet radiation should be avoided. All windows and doors must be securely closed;
- The relative humidity of the room should be lower than 50%;
- Air conditioning equipment should be addicted, in order to compensate the ambient temperature;
- The flow of air from the air conditioning equipment should never be directed to the patient and the air speed must be kept as low as possible [<5m / s];
- The image processing equipment should be located outside the area of the patient, to prevent disturbances.
- It is recommended a cubicle inside the examination room with the same environmental conditions to provide privacy to the subject;
- Incident illumination in the subject should be avoided;
- Should be avoided incidence of light on the voluntary, in order to avoid reflections in thermal images collected.

Thermal image capture

- The infrared camera must have been initialized at least 60 minutes before image capture;
- The equipment should provide an automatic or manual focus;
- Tripods that tilt the camera at obtuse angles should be avoided;
- Each image must be labeled the false color code. The rainbow scale is the most widely used for medical applications. The scale should have pre-defined intervals. For investigation in humans it is recommended the range 23-37°C.

Appendix B

Consent Form

As a participant, I agree to collaborate in this study, having knowledge of the objectives, tests and examinations that will be performed. I was informed about all aspects that I consider important.

The researchers will provide clarification to any questions that may arise at any time during the research process, through the following contacts:

- Filipa Barbosa – bio09038@fe.up.pt

- Dr. Ricardo Vardasca – ricardo.vardasca@fe.up.pt

Telephone number: 220424741 (Laboratory L003 FEUP)

At any time, I can refuse my participation in the study, without thereby bring losses to me. For the procedures, there are no kinds of damages, risks and / or discomforts to my person. It was further safeguarded that all data to be collected will be for the exclusive use of the respective research, and that I will be maintained on condition of anonymity.

Porto, ________ de ____________ de 2014.

______________________________	______________________________
The participant	Signature of participant
______________________________	______________________________
The investigator	Signature of the investigator

Appendix C

Information for participants

Objective of the study

This study has as main objective to verify the viability of using thermography as a means of identification, tracking and monitoring of early lesions (new or recurrent) over the trainings.

What is infrared thermography?

The infrared thermography is a technique that allows quantitative and accurate analysis of the temperature distribution of the skin surface.

This technique uses the infrared radiation that is emitted by the human body, i.e., it is a non-invasive method, which captures the natural infrared energy that is released by the body surface and that presents no health risk for the subject.

What is the relation between the infrared thermography and injuries?

The temperature increase in tissue is an inherent consequence of inflammation, which in turn can be an indicative of a lesion. Therefore, the infrared thermography, as method of quantification of skin surface temperature, can be a good alternative for the detection of early injuries.

What should I do?

- Avoid all topical applications such as ointments and cosmetics, on the day of the exam;
- Avoid heavy meals and intake of tea or coffee until 2 hours before the exam;
- Avoid smoking for a minimum of 2 hours before the exam;
- Avoid tight fitting clothing;
- Avoid physical effort and methods of therapy such as electrotherapy, ultrasound, heat treatment, cryotherapy, massage and hydrotherapy. In case of physical effort or physical therapy, wait at least 6 hours to perform the test;
- Avoid the use of steroids, sympathetic blockers or vasoactive medications for 24 hours before to the thermographic examination.

On arrival:

- It is necessary that before participating in this project, you answer an inquiry and sign the consent form.
- Before the exam, it is necessary that you carry out a thermal acclimatization over 10 minutes.

Duration of exam:

The whole process will take approximately 15 minutes.

What will happen to the information from my exam?

Captured images will only be used for this investigation. The identification of the subject will be securely stored and it is strictly confidential.

Contacts:

Filipa Barbosa – bio09038@fe.up.pt

Appendix D

Questionnaire

First collection:

Personal Information:

Name:
Age:
Genre: M ○ F ○
Height (m):
Weight (Kg):
BMI:
Lower limb dominance:
Time experience in rugby:
Position on the rugby field:

Injuries:

Do you have any symptoms of injury?	*Yes* ○ *No* ○ If yes: 1 - Where? 2 - Please rate the pain: Mild ○ Moderate ○ Strong ○
Did you have an injury in the last 6 months?	Yes ○ No ○ If yes, where?
Did you perform a surgery in the last 6 months?	Yes ○ No ○ If yes, where?

Please, tick appropriate boxes:

	No Problems	*Some Problems*	*Many Problems*
Mobility			
Self-care			
Usual activities			
Pain or discomfort			
Anxiety or depression			
EUROCOL score: (To be completed by the investigator)			

Daily information:

Meal in the last 2 hours	*Yes* ○ *No* ○ If yes, what?
Medication in the last 24 hours	Yes ○ No ○ If yes, what?
Energy drinks in the last 2 hours	Yes ○ No ○ If yes, what?
Tobacco in the last 2 hours	Yes ○ No ○
Creams or ointments on the lower limbs?	Yes ○ No ○

To be completed by the investigator:

Subject ID:	
Date of collection: Time of collection: Room temperature: Relative humidity:	

Questionnaire

Next collections:

Personal Information:

Name:

Injuries:

Do you have any symptoms of injury?	*Yes* ○ *No* ○ If yes: 1 - Where? 2 - Please rate the pain: Mild ○ Moderate ○ Strong ○

Daily information:

Meal in the last 2 hours	*Yes* ○ *No* ○ If yes, what?
Medication in the last 24 hours	Yes ○ No ○ If yes, what?
Energy drinks in the last 2 hours	Yes ○ No ○ If yes, what?
Tobacco in the last 2 hours	Yes ○ No ○
Creams or ointments on the lower limbs?	Yes ○ No ○

To be completed by the investigator:

Subject ID:	
Date of collection: Time of collection: Room temperature: Relative humidity:	

Appendix E

Landmarks

According to K. Norton and T. Olds [51], the landmarks selected for this project are defined as:

- Vertex - *The most superior point on the skull when the head is positioned in the Frankfort plane.*
- Acromiale - *The point on the superior part of the acromion border in line with the most lateral aspect.*
- Radiale - *The point at the proximal and lateral border of the head of the radius.*
- Stylion - *The most distal point on the lateral margin of the styloid process of the radius.*
- Dactylion – *The tip of the middle (third) finger. Finger nails should not be used as landmarks for the end of fingers.*
- Iliocristale – *The point on the most lateral aspect of the iliac tubercle, which is on the iliac crest.*
- Trochanterion – *The most superior point on the greater trochanter of the femur, not the most lateral point.*
- Tibiale laterale – *The most superior point on the lateral border of the head of the tibia.*
- Sphyrion fibulare – *The most distal tip of the malleolare lateralis (fibularis).*

Appendix F

Anthropometric image capture protocol – Kinect

The standard procedures for recording the Kinect images of the human body are based on the Windows Human Interface Guidelines v1.8.0.

On arrival:

- The subject should be informed about the whole examination procedures;
- The subject should remove the needed clothing and accessories;
- The subject should be asked to assume the pre-defined positions;

On scanning:

- The subject will remain standing at a distance of 1.5 to 2 meters from the sensor;
- The sensor should be placed at 0.6-1.8 meters above the floor;
- The room dimensions should be large enough to permit a minimum distance between The patient and the camera;
- The distance between the camera and the subject and the date of the examination should be recorded
- The sensor works in all lighting situations (even darkness). However, it works better in moderate light than in direct sunlight;
- The subject should remain (statically) in the defined position, while the procedure is being performed;
- The ideal temperature is between 5-35 ° C.
- Should be guaranteed the confidentiality of the subject. The identification of the subject will be carried out using a code;

Appendix G

Anthropometric image capture protocol – Qualisys

The assembly of the system for this project comprises 7 to 12 optical infrared cameras, Oqus, which emit a beam of infrared light. Retro-reflective markers are placed on the subject, which in turn reflect infrared light back to the camera sensor. The information from the markers allows to calculate the position of each one, with high spatial resolution.

The QTM (Qualisys track manager) is the software used to access and analyze data.

On arrival:

The use of Qualisys system for extracting anthropometric measurements requires some previous procedures:

Technician:

- The system needs to be calibrated. To this end, the specialized technician moves a wand around in the capture volume while a stationary reference object in the volume defines the lab coordinate system. This procedure takes approximately 10-20 minutes.
- The technician also needs to place markers on the subject's body, one on each anatomical point of interest. These points should be carefully found (manually) and marked accurately.

Subject:

- The subject should be informed about the whole examination procedures;
- The subject should remove the needed clothing and accessories;
- The subject should be asked to assume the pre-defined position;

On scanning:

- Measurements can be made at distances up to 25m of the subject with 19mm markers or up to 9m with 4mm markers. High-speed video can also be captured at full resolution up to 500 fps.
- The room dimensions should be large enough to permit a minimum distance between the patient and the camera;
- The ideal temperature is between 0-35 ° C.
- The subject should remain (statically) in the defined position, while the procedure is being performed;
- The date of the examination should be also recorded.

- Should be guaranteed the confidentiality of the subject. The identification of the subject will be carried out using a code;