The use of Infrared Thermography to Measure Injury Biomarkers in Lower Extremity Musculoskeletal Injuries of Professional Football Players

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ABSTRACT

The use of Infrared Thermography to Measure Injury Biomarkers in Lower Extremity Musculoskeletal Injuries of Professional Football Players

Julie Lamoureux

Musculoskeletal injuries in football (American) are common, and health-care professionals are continuously trying to find new ways to prevent, assess, and rehabilitate sports injuries. While magnetic resonance imaging is considered the gold standard in diagnosing soft tissue injuries, magnetic resonance imaging is expensive, difficult to access, and requires a qualified professional. Infrared thermography is a novel technology that is quick, non-invasive, easily accessible, and can provide a static or dynamic image. This study evaluated the use of infrared imaging as a tool to monitor the healing and rehabilitation of injured professional football athletes. The first objective was to use infrared thermography to track changes in average maximum temperature of the injured limb following an injury up until return to play. The second objective was to use infrared thermography to track the average temperature asymmetry between the injured limb and the healthy limb after injury up until return to play. The third objective was to identify the relationships between average maximum temperature, average temperature asymmetry, and LEFS scores at time of injury and return to play in football players recovering from an acute lower extremity musculoskeletal injury. Infrared imaging could measure the changes in temperature from acute inflammation all the way to increased blood flow during sport specific rehabilitation. Infrared imaging can be provided by any health care professional at any time and could improve player safety in the CFL.

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Finally, thank you to my family, especially my mom (Karen) and sister (Gab), as well as my friends for their unwaivering support and constant encouragement. I would not be where I am today without them.

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Figure 12. Above there are 7 series of avatars that display the thermal images taken at 7 timepoints between September 3rd, 2023, and September 10th, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

Figure 13. Above there are 7 series of avatars that display the thermal images taken at 7 timepoints between September 11th, 2023, and September 30th, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

Above there are 7 series of avatars that display the thermal images taken at 7 timepoints between September 11th, 2023, and September 30th, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

Figure 14. Above there are 3 series of avatars that display the thermal images taken at 3 timepoints between October 6th, 2023, and October 23rd, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

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Figure 18. We took thermal images of professional football players that suffered a lower extremity injury ($n = 9$). A repeated measures ANOVA was used to compare the mean temperature asymmetry between the injured and uninjured side at baseline, time of injury, and return to play. There was no significant difference found between the means at the three time points ($p = 0.808$).

Figure 19. Figure illustrating the relationship between the temperature asymmetry at baseline compared to return play in 9 injured professional football players. Asymmetry is the ratio between the temperature on the injured side compared to the uninjured side. A higher average

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LIST OF ABBREVIATIONS

ATFL	Anterior Talofibular Ligament
CFL	Canadian Football League
ICC	Intraclass Correlation Coefficient
FLIR	Forward Looking Infrared
IRT	Infrared Thermography
LEFS	Lower Extremity Functional Scale
MCL	Medial Collateral Ligament
MRI	Magnetic Resonance Imaging
NFL	National Football League
NSAIDs	Nonsteroidal Anti-Inflammatory Drugs
OA	Osteoarthritis
PCL	Posterior Cruciate Ligament
ROI	Region of Interest
RTP	Return to Play
TENS	Transcutaneous Electrical Nerve Stimulation
VAS	Visual Analogue Scale

LITERATURE REVIEW

Theoretical Context & Background

Injuries in Football

While musculoskeletal injuries are frequent in all sports, football (American) has some of the highest injury rates and therefore most significant repercussions. For example there are significantly more injuries in the National Football League (395.8 per 1000 athletes at risk) compared to other professional contact team sports such as rugby (121.7 per 1000 athletes at risk) and hockey (15.6 per 1000 athletes at risk).[1] Out of all the injuries in football, the most common injured site is the lower extremity including the knee (17.8%), the ankle (12.4%), the hamstrings (8.7%), compared to the shoulder (8.4%).[1] One of the significant concerns from the number of injuries is the amount of time lost competing or practicing for the player. The average amount of time loss due to lower extremity injuries in the National Football League ranges from 15 days to 279 days.[2] Because of the significant amount of injuries and time lost, player health and safety has become a priority in both the CFL[3] and NFL[4].

Musculoskeletal Injuries

Musculoskeletal injuries are injuries to bones, ligaments, muscles, tendons, and joints.[5] Examples of musculoskeletal injuries include fractures, sprains (ligaments), and strains (muscles/tendons). In sports, musculoskeletal injuries can occur during practices/training and games.[5] Injuries can be classified as either acute (traumatic), or chronic/overuse (non-traumatic). Moreover, acute injuries can be considered as direct (contact) or indirect (non-contact) injuries.[6] Musculoskeletal injuries trigger swelling, inflammation, and a change in peripheral blood flow, which affect skin temperature.[7] In the clinical setting, inflammation is mostly measured subjectively using pain rating scales, the observation of redness and swelling, as well as the subjective measurement of gross motor function.[8] Subjective measurements are subject to bias and fail to provide quantitative information that could be used to better measure and monitor inflammation.[8] Therefore, new clinical tools that provide objective measurements of inflammation and injury healing would be beneficial for both clinicians and athletes.

Current Standard Imaging Techniques

Currently, health-care professionals rely on an injury history, physical examination, and diagnostic imaging for the assessment of musculoskeletal injuries.[9,10] Common diagnostic imaging techniques presently used include computed tomography (CT) scans, x-rays, magnetic resonance imaging (MRI) and diagnostic ultrasound.[11] Magnetic resonance imaging is considered the gold standard in diagnosing soft tissue injuries and can provide an objective measurement of the damaged tissue.[11–13]3/28/2025 9:24:00 PM However, traditional imaging such as magnetic resonance imaging is expensive, difficult to access, and requires a qualified professional.[12,13] Therefore, imaging is prescribed and scheduled according to the availability of the test or doctor.

Infrared Thermography

Infrared thermography, or thermal imaging, is a novel imaging technique that maps out the temperature distribution of the object or body photographed using a specialized camera.[14] The infrared camera captures the infrared radiation of the tissue and transforms the energy into electrical signals that produce the final image, as each level of thermal energy corresponds to a different colour.[12,7,15] White and warm colours such as red, orange and yellow represent areas of higher temperatures, whereas black and cold colours like blue, green and purple are areas of cooler temperatures.

In a clinical setting, infrared thermography could be used to measure the increase in temperature caused by inflammation.[14] While infrared thermography displays heat patterns, thermal imaging does not give a precise image of anatomical landmarks or the origin of the problem. In other words, infrared thermography provides more physiological information as opposed to structural information.[7]

Figure 1. Example of a thermal image taken with the FLIR E8. The thermal image was taken three days after a professional football athlete suffered a knee contusion to the right knee. The temperature scale can be seen at the top of the image. White and red represent the hotter areas, whereas blue and purple represent cooler areas.

Advantages of Infrared Thermography

Infrared thermography has many potential advantages over current practices used in the assessment and rehabilitation of musculoskeletal injuries. Infrared thermography is quick, inexpensive, non-invasive, and can be completed by any health-care professional.[13] The infrared image is captured based on the needs of the patient, not on the availability of the treating physician. In other words, thermal imaging allows the clinician to perform imaging at the best time to measure the injury rather than obtaining the image at a time when the MRI is available. The equipment needed for infrared thermography is portable, making thermal imaging even more accessible.[11] Moreover, infrared thermography can produce a static image (picture) as well as a dynamic (video) view of the physiological response of the injured athlete which is not obtainable with most standard medical imaging, apart from diagnostic ultrasound. The thermal images and videos provide objective measurements of physiological functions such as blood flow.[8,12] Thus, the thermal scans allow the clinician to individualize the treatment for the athlete by closely monitoring the healing process of a soft tissue injury and to progress the rehabilitation program according to the athlete's individual needs.

Infrared Camera Specifications

In the biomedical setting, the main type of infrared camera used is a FLIR camera. The FLIR infrared cameras contain a focal plane array detector that measures infrared radiation through an increase in temperature.[16] The focal plane array contains micrometer size pixels that detect infrared radiation.[17] A greater amount of pixels means higher resolution, which improves the quality of the picture obtained and a greater quantity of thermal information.[18] All objects and bodies that have temperatures greater than absolute zero emit infrared radiation.[17] FLIR cameras can detect temperatures changes as little as 0.02ºC.[16] The accuracy of the camera depends on the manufacturer, and is usually $\pm$ 1 or 2ºC.[17,19] An advantage of FLIR cameras is their portability since the cameras are either standalone or smartphone-based.[16]

Factors Affecting Infrared Thermography in Humans

There are various environmental, individual, and technical factors that must be considered with infrared thermography (Figure 2). These factors were identified to increase the accuracy of infrared thermography in humans.[18] Environmental factors include room size, ambient temperature, relative humidity, atmospheric pressure, and any other sources of infrared radiation. Considering the various environmental factors that affect skin temperature, a period of acclimatization is included in most studies involving infrared imaging. However, the length of this acclimatization period varies greatly. Recent studies have suggested that a minimum acclimatization of 8 to 10 minutes is required for optimal skin temperature readings.[18] Moreover, acclimatization periods of greater than 30 minutes can potentially have negative effects on the stability of skin temperature.[18] Individual factors include both intrinsic factors and extrinsic factors. Examples of intrinsic factors are age, sex, genetics, and emotions. Examples of extrinsic factors to consider are physical activity, application factors like creams and ointments, intake factors such as medication or alcohol consumption, and therapeutic modalities like ultrasound, electrotherapy, and cryotherapy. Finally, technical factors to consider are the characteristics of the camera, the validity and reliability of the equipment, the software used to analyze the images, and the protocol selected.[18]

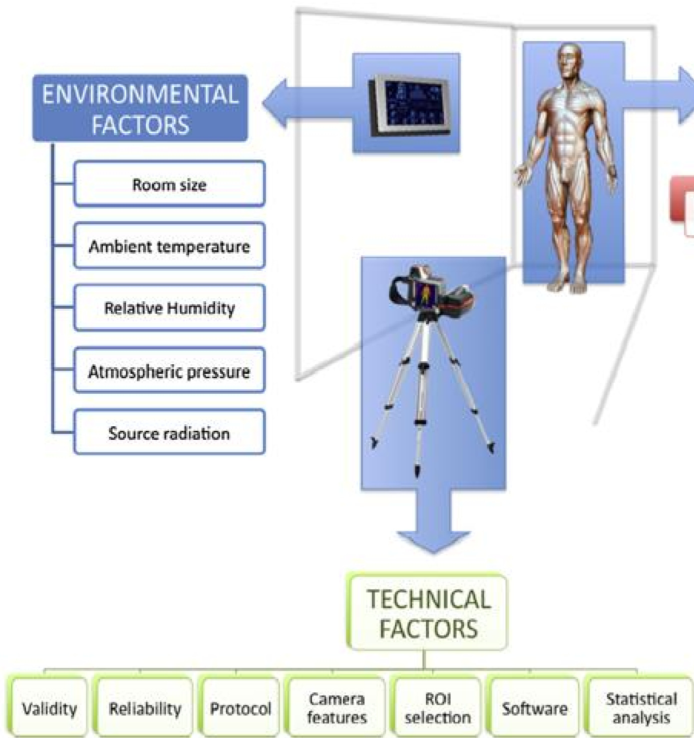

Figure 2. Factors Affecting Infrared Thermography in Humans. Image from Fernández-Cuevas et al. (reference #18)[18]

The Glamorgan Protocol

A common protocol used for infrared thermography is the Glamorgan protocol, which was created to increase the reproducibility of thermal images.[20] The Glamorgan protocol is a detailed protocol generated by a research group at the University of Glamorgan that takes into account the technical factors that influence infrared imaging.[18] The Glamorgan protocol defines 24 different body views to take infrared images.[20] To take infrared images, the protocol requires that specific landmarks are aligned with the edge of the image according to the selected body view.[20] For instance, if a larger subject is being photographed, the distance from which the picture is taken will be slightly further to ensure that all landmarks are included in the image. Therefore, the view is not affected by the size of the subject, which increases the ability to reproduce the thermal image.[20]

Current Uses of Infrared Thermography in Medicine

Infrared thermography allows for the detection of both warmer and cooler areas. Conditions resulting in inflammation as well as tumours cause an increase in skin temperature, categorized as hyperthermia.[21] A decrease in skin surface temperature, or hypothermia, can indicate a decrease in muscle activity or blood flow, as well as tissue degeneration.[21] Infrared thermography is used in various areas of medicine, such as neurological disorders, burns, tumours, fever screening, vascular disorders, and diabetes.[14]

Infrared Thermography and Injury Prevention

Infrared thermography has been used for injury prevention.[22] A study including professional soccer players evaluated the combined use of strength training and infrared thermography to prevent musculoskeletal injuries.[22] A total of 26 male soccer players participated in the study. The players participated in two 60- to 120-minute strength training sessions per week. Infrared images were taken at the beginning of the study, prior to the season, and 24-48 hours following every game.[22] If a player complained of pain or had a thermal asymmetry of > 0.7ºC, infrared images were repeated every day until the player no longer had symptoms.[22] When analyzing the infrared images, the average maximum and minimum temperatures readings of the region of interest between the affected and unaffected limb were compared. A thermal asymmetry of > 0.7ºC was considered abnormal.[22] When combining infrared thermography with strength training, the amount of injuries as well as the days missed due to injury in professional soccer players decreased throughout the season.[22] Therefore, infrared thermography is a useful adjunct to screen for participants that are at an increased risk of injury according to abnormal heat patterns, and to prevent injury.[22]

In another study, an infrared thermography prevention program was implemented during the preseason for professional soccer players.[23] The aim of the study was to create a prevention program using infrared thermography and to see if the program would entail a greater reduction in the amount of injuries occurring during the season compared to a conventional prevention program. The study took place over 2 seasons and included 33 male professional soccer players. A conventional prevention program was implemented during the first preseason, while an infrared thermography prevention program was followed during the second preseason. For the infrared thermography prevention program, thermal images of all players were taken prior to every training session. If a player had a thermal asymmetry of 0.50ºC or higher, the player followed a prevention protocol. The player's training was modified according to the affected area. Following training, the player received 10 minutes of cryotherapy. The player also received physiotherapy treatments that included mobilizations and stretching.[23] The infrared thermography prevention program was better at reducing the incidence of injuries compared to the conventional prevention program, with only 6 injuries during the second season compared to 15 injuries during the first season. The average amount of time loss due to injury during the season was also less with the infrared thermography prevention program (2.3 days per injury) compared to the conventional prevention program (10.4 days per injury).[23] Thus, using thermal imaging in combination with physiotherapy or athletic therapy treatments could assist not only in preventing musculoskeletal injuries in athletes, but also at helping with a quicker return to competition.

Infrared Thermography for the Diagnosis and Monitoring of Musculoskeletal Injuries

<u>General</u>

The evidence regarding the use of infrared thermography for the monitoring of musculoskeletal injuries is emerging and the existing literature appears promising. Prior research has found that infrared imaging displays the physiological changes that occur with musculoskeletal injury.[8] According to a review on infrared thermography and musculoskeletal injuries, infrared thermography was found to have an excellent accuracy for the diagnosis of musculoskeletal injuries.[11,24] Indeed, the area under the receiver operating characteristic curve was 0.81, where a score of 1 means that infrared thermography perfectly detects the presence or absence of a musculoskeletal injury.[11]

The differences in vascularization of different types of musculoskeletal tissues (ligaments, muscle, periosteum, bone) should be considered when using infrared thermography.[25]

For instance, a bone is highly vascularized, whereas ligaments and tendons are poorly vascularized. The higher blood flow will lead to higher temperatures on the thermal image. The thermal images of healthy participants generally display a symmetry between the right and left limbs in terms of temperature intensity and heat patterns.[26] Therefore, most studies use the contralateral limb as a comparison when diagnosing and monitoring musculoskeletal injuries.[18]

Fractures

A fracture is a break in a bone that affects the bone's continuity.[27] A fracture also affects other soft tissue surrounding the site of injury.[27] When a fracture occurs, there is an increase in inflammation that peaks within the first 24-48 hours following the injury.[28] In a clinical setting, the amount of pain reported and swelling observed are used as indicators of inflammation.[27] Inflammation is also accompanied by an increase in temperature resulting from increased cell activation, blood flow and metabolism.[28–30] This change in temperature can be objectively monitored using infrared thermography.

Infrared imaging has been applied previously for the diagnosis of fractures. A previous study used an infrared camera to measure the temperature difference between the healthy and the injured limbs of patients with a suspected fracture.[31] The aim of the study was to test the ability of infrared thermography to diagnose fractures, so that patients' exposure to the electromagnetic radiation of x-rays could be decreased. The study included 133 participants that presented at an emergency department with a suspected fracture. An infrared image of the injured limb was compared to the corresponding thermal image of the healthy limb. To determine whether a fracture was present, the researchers evaluated the difference in mean and maximum temperatures of the affected and unaffected side as well as the number of pixels in the region of interest that reached maximum temperature. Out of the 46 patients that had a confirmed fracture, infrared thermography failed to diagnose four of them. However, three of the four fractures undetected through infrared thermography were Salter-Harris type 1 fractures (mild growth plate fracture) and were also undetected through radiography.[31] Accordingly, the negative predictive value was found to be 95%, meaning that infrared thermography was good at ruling out fractures.[31] Moreover, the sensitivity and specificity of infrared thermography for the diagnosis of fractures in paediatric emergencies were 0.91 and 0.88 respectively.[31] Therefore, infrared thermography has the potential to rule out fractures and avoid exposing subjects to the ionizing radiation of x-rays.

Following a fracture, infrared thermography could also be used to monitor bone healing.[29] A pilot study on forearm fractures recorded the thermal images of the fractures at days 7, 14 and 21 post-injury. On day 7, the temperature of the injured wrist was higher than that of the uninjured wrist (0.8 to 2.0ºC).[32] On day 14, the temperature difference between the injured and uninjured wrists decreased. By day 21, there was a smaller temperature difference of 0 to 0.7ºC between the injured and uninjured wrists. The decrease in temperature difference corresponds with the remodelling phase of bone healing, which occurs around 3 weeks post-injury. Therefore, the authors state that infrared thermography could be used as a safer alternative to x-rays for fracture follow-up since thermal imaging is free of radiation.[32] Thus, thermal imaging has the potential to be used as a follow-up imaging technique for musculoskeletal injuries.

Soft Tissue Injuries

Infrared thermography can help with the diagnosis and monitoring of inflammatory knee conditions such as osteoarthritis.[25,33] A study was conducted to assess the reproducibility of thermal imaging and to compare the use of infrared thermography to radiography for determining the severity of knee osteoarthritis.[33] The study was part of a larger observational study regarding the use of magnetic resonance imaging in women with knee osteoarthritis. The participants of the study were 30 women, 15 with symptomatic knee osteoarthritis and 15 controls without knee pain or knee osteoarthritis that were matched for age. Participants underwent radiographic imaging at baseline to determine the severity of knee osteoarthritis. Infrared images were taken at 6 months for the participants with knee osteoarthritis, and at 6 and 12 months for the control group. A thermal evaluation software was used to determine the mean temperatures for the entire knee as well as 5 regions of interest. Moreover, intraclass correlation coefficients were calculated to evaluate the reproducibility of the thermal images taken at 6 and 12 months in the control group whose knee status was expected to remain the same. Results indicated that the temperature of the patellar region of interest obtained with infrared thermography showed a significant association with the severity of knee osteoarthritis determined through x-ray.[33] The reproducibility of thermal imaging for the knee was classified as good, with the lowest reproducibility occurring in the patellar region (ICC: 0.50).[33] The intraclass correlation coefficients for reproducibility of the thermal images may not be high since the images were taken 6 months apart. As mentioned previously, there are multiple environmental, technical and individual factors that can affect temperature readings.[18] The study controlled for the environmental and technical factors, as well as medication intake.[33] However, there are multiple other extrinsic factors such as physical activity, therapies, and food/beverage intake that could affect temperature readings.[18] Therefore, the superficial temperature of the participants at time points that are 6 months apart may not be the same, which would affect the results of the reproduciblity of the thermal images. Moreover, the sample size of this study (15 non-knee OA controls, 15 knee OA cases) was not large, so more studies with a higher sample size are required to increase the signficiance of the results and determine the reproducibility of infrared imaging.

Infrared imaging can help monitor temperature changes with anterior cruciate ligament injuries. Previous research found that there is a large increase in temperature (1.4 ± 0.58ºC)[25] behind the patella of the injured knee when compared to the uninjured knee in a person with a torn anterior cruciate ligament.[25,30] A thermal asymmetry was still present following six months.[30] Thermal images can show the temperature difference occurring in the knee prior to and after a six-week rehabilitation period following anterior cruciate ligament surgery.[30] Following six weeks of rehabilitation, the temperature of most regions of interest of the knee decreased, but the temperature changes were not statistically significant. The maximum temperature significantly increased in the posterior knee region of both the injured leg and the non-injured leg, potentially as a result of muscle compensation.[30] The authors hypothesize that the increase in temperature in the posterior region of both legs was due to changes in gait mechanics as a result of injury. The participants appeared to load the non-injured leg more while walking, which could have entailed the increase in temperature.[30] In most studies, the non-injured leg is used as a control or comparison. Therefore, muscle compensation in the unaffected leg is a factor that must be kept in mind when comparing the degree of thermal symmetry between the affected and unaffected limb.

Injuries to tendons can also be evaluated using infrared thermography. The thermal images of patients with patellar tendinopathy display increased temperatures at the front of the knee.[25,34] While the full-text of the study on patellar tendinopathy and infrared imaging in volleyball players is not available, the abstract is accessible.[34] The study was performed on 20 volleyball players. The players were separated into groups based on symptoms and previous tendon injuries. Infrared thermography was used to evaluate the skin temperature of the anterior aspect of the knee. The skin temperature of the anterior aspect of the knee was higher in players that presented with symptoms compared to players without symptoms, regardless of whether the players had a history of tendon injuries or not. Moreover, function was measured using the VISA-P questionnaire. There was a correlation between temperature of the anterior knee and function, where a higher temperature was associated with lower function.[34]

Thermal imaging has also been used for monitoring the progress of ankle sprains. In a patient with a lateral ankle sprain, infrared thermography tracked the change in temperature occurring as the ankle healed.[10] Infrared images were taken at days 7, 21 and 42. By day 7, there was a decrease in approximately 2ºC of the lateral ankle. The temperature of the lateral injured ankle started to return to baseline by day 21. On day 42, both the injured and non-injured ankle had symmetrical temperature readings, with the greatest temperature difference being 0.3ºC (see Figure 3).[8]

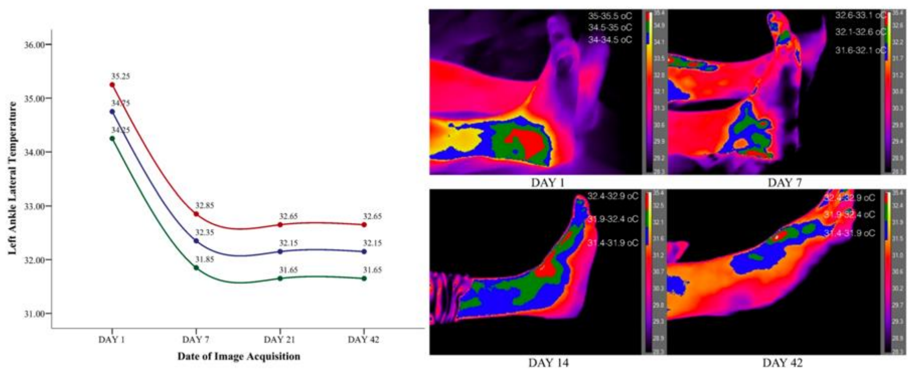

Figure 3. Progress of thermal images of an ankle sprain up until recovery.[8] Image from Ioannou. (reference #8)

In addition, a different study examining ankle sprains explored the relationship between the change in temperature and the levels of pain and function throughout rehabilitation.[35] The research included 22 patients with acute ankle sprains, with 22.73% being sports injuries. The 2-week rehabilitation program consisted of modalities such as TENS, ultrasound, cryotherapy, massage, and physical therapy individualized to each patient. The patients were assessed pre- and post-rehabilitation using the VAS scale for pain, the Foot Function Index, as well as infrared images. The thermal images were taken from an anterior view and were used to determine the functional progress of the injury according to inflammation and peripheral blood flow. The healthy limb was used as a comparison. The images were repeated at 3 time points: prior to the therapy program, at discharge, and 6 weeks following discharge. One region of interest in the anterior ankle was used for data analysis. Prior to treatment, there was a significant difference in the temperature between the affected and non-affected limb, with the injured ankle being warmer than the uninjured ankle due to increased blood flow. Following rehabilitation, the temperature of the injured ankle showed significant decrease. By the end of the rehabilitation program, there was thermal symmetry between the unaffected and affected limbs. Specifically, there was an average temperature asymmetry of 0.16 ºC at discharge, and 0.32 ºC at the 6 week follow-up. Moreover, the decrease in temperature as shown by the thermal images corresponded with higher foot function and lower pain level as per the VAS.[35] Therefore, infrared imaging has been used to objectively monitor the progression of the inflammatory process and changes in blood flow following musculoskeletal injuries.

Temperature Cut-offs for Injuries

Previous research has attempted to determine the ability of infrared imaging to detect temperature changes that are indicative of injury. Current literature reports that a temperature asymmetry of more than 0.7ºC is considered abnormal and therefore indicates an injury or inflammation.[8,21,22] However upon further review of the literature cited, there appears to be little evidence to support the 0.7ºC value for indicating injury. The references provided by the Menezes et al. study do not appear to report temperature values that suggest the presence of injury. The review paper by Szentkuti et al. also reports that 0.7ºC is considered abnormal. However, while the review references an article by Garagiola and Giani regarding the use of thermography in the management of sports injuries, the article does not report 0.7 ºC as a cut off temperature. Therefore, more studies are needed to determine the cut-off value that would indicate injury or a predisposition to injury. The goal of infrared thermography is to help clinicians manage their patients' injuries. Typically, clinicians desire a cut off or a value that indicates something is wrong and more work is needed to establish a cut off temperature for injury using infrared thermography. Generally, a temperature difference of 0.25°C is considered normal, or free of pathology.[8]

In some studies examining injury, the temperature difference can be greater that 0.7ºC. For instance, in a participant who suffered from an ankle sprain, the infrared thermal image noted an increase of 2.5ºC of the injured ankle compared to the uninjured side. Moreover, the temperature started to return to baseline on the 21st day and reached bilateral symmetry by day 42.[8] This study suggested that not only was the infrared image able to measure the change in acute inflammation, but also the resultant improvement in blood flow returning to normal in the proliferative phase (5-21 day), and the remodelling/maturation phase (day 20 and on).[36,37] There have also been case studies on alpine skiers and patella tendinopathy. The case studies included 15 alpine skiers: 7 athletes with symptoms of overuse of the patellar tendon and 8 athletes without symptoms. The case studies found that athletes with overuse injuries had an average temperature asymmetry of 1.4°C, while non-injured athletes had an average thermal asymmetry of 0.3°C.[7] Overall, more studies on infrared thermography and musculoskeletal injuries are required to determine what degree of thermal asymmetry is considered healthy or indicative of injury or risk of injury.

Potential Uses of Infrared Thermography in the Clinical Setting

Infrared thermography could help measure the change in temperature and blood flow acutely, but also throughout the process of the rehabilitation. Infrared thermography could improve the rehabilitation process by providing objective measures of tissue healing that are specific to the patient. For instance, thermal imaging has been used to assess the effects of various therapeutic modalities, such as cryotherapy, electrotherapy, and massage. The effectiveness of the modalities was determined according to skin temperature following their application, which is reflective of inflammation and the function of local blood vessels.[38] Therefore, the thermal scans can be used to determine how the injured tissue responds to treatment, allowing the clinician to develop a rehabilitation program that is tailored to the patient's individual goals and needs. Moreover, the infrared images provide the athlete with visual feedback of how their injury is healing, which could improve an athlete's accountability, motivation, and compliance with the rehabilitation program. The visual representation of the thermal symmetry between the two limbs may also increase confidence when returning to sport by showing the athlete that the injured area has returned to a pre-injury temperature reading.[12]

Infrared Thermography and Return to Play Decisions

Making the decision to return to competition for the injured athlete is difficult and there are many factors that can influence the decision. Presently, there are no standard guidelines for return to play decisions made by qualified professionals.[39] Return to play decisions currently rely mostly on subjective pain levels reported by the athlete and evaluations of strength and range of motion. Following an injury, athletes may feel pressured to return to sport, which can ultimately lead to athletes returning to play too quickly.[40] Another factor that may cause a pre-mature return to sport is that, similar to concussions, players may start to feel better, but their injury may not be fully healed yet.[41] Returning to sport pre-maturely increases the chance of re-injury and can lead to poor athletic performance.[40] For example, 38.4% of hamstring injuries in the National Football League from 2009-2020 were recurrent, and the main risk factor for the recurrence of hamstring injury was an early return to play.[42] Therefore, infrared thermography could help with return to play decisions by providing the degree of thermal asymmetry between the injured and non-injured limb.

Gap in the Literature & Significance of Research

This project aims to determine if infrared thermography could be used to monitor the rehabilitation of musculoskeletal injuries. Ultimately, infrared thermography could facilitate the tracking of healing using a novel technology, potentially decrease the time loss due to injuries, and improve player safety in the CFL.

There are a limited amount of studies that have examined the use of infrared thermography for tracking soft tissue injuries such as strains, sprains and contusions. Most previous studies have evaluated the use of infrared thermography for the diagnosis of fractures or chronic musculoskeletal injuries such as osteoarthritis and tendinopathies, as well as for the prevention of injuries. There is still limited evidence that supports a specific temperature asymmetry (cut off) that indicates an injury when comparing the injured limb to the un-injured limb. Identifying a specific temperature that would determine if a tissue is healthy, at risk of injury, or if there is the presence of an injury or pathology is needed. Moreover, in previous studies, the infrared images were not repeated on a frequent basis, but rather at pre-determined time points. One of the potential strengths of infrared imaging is that it can be repeated on a more frequent basis than other types of imaging and at the time point that is most important for the athlete like 24hrs after injury occurance or the morning of the return to competition day for example. In addition, the images could be taken at the time the injury and repeated frequently throughout the rehabilitation process to see how the tissue is healing, or which muscle groups need to be strengthened. Therefore, infrared imaging could track the physiologicial changes that occur in the tissues as the injury heals, and assist in managing and modifying the rehabilitation program based on the individual’s needs.The advantages of infrared thermography could be extremely beneficial for athletes, and especially professional athletes where the amount of time missed due to injury is critical. However, not many studies include athletes as the participants. There is a lack of literature regarding the use of infrared imaging to monitor lower extremity musculoskeletal injuries from the time of injury up until the player fully returns to play. Infrared imaging could help improve player safety in football. Therefore, the aim of this pilot study is to determine if novel infrared thermography can be used as a clinical tool to monitor the healing process of acute lower extremity musculoskeletal injuries sustained by professional football players. The study focussed on professional athletes as their time to return to play is extremely important, and they need to follow-up with the medical staff on an almost daily basis. The nearly daily follow-ups allowed us to repeat the infrared images frequently throughout the player's rehabilitation process.

Infrared thermography is an easily accessible tool that could be used to assess the physiological impact of an injury in athletes in addition to our current assessment methods (such as the orthopaedic examination, subjective medical history, and medical imaging). Thermal imaging is a new imaging technique that could facilitate the monitoring of the effectiveness of the rehabilitation programs of injured players as thermal scans can be repeated on a more frequent basis compared to other types of imaging currently available. Whereas traditional imaging such as x-ray, computed tomography (CT) scan, diagnostic ultrasound, and magnetic reasoning (MRI) is scheduled based on when an appointment is available, thermal imaging can be performed at the ideal time indicated by the injury. Therefore, infrared thermography is a great tool to include in a patient-centered health approach. For instance, thermal images could allow clinicians to provide their clients with a set of corrective exercises and rehabilitation services that are specially adapted to them based on how their body physiologically reacts over time with treatment. Eventually, standard timelines could be developed regarding the thermal progression of specific lower extremity injuries. For example, a graph displaying the average thermal asymmetry in relation to the time elapsed since the time of injury for specific injuries (type, location, severity) could indicate how an individual athlete's injury is progressing compared to the norm. As an injured athlete goes through their rehabilitation process, the graph would allow the clinician to determine if the injury healing is on track, in advance, or delayed, and adjust accordingly. The clinician would be able to individually adapt the clinical assessment and rehabilitation program according to how the injury presents itself on the thermal scans.

OBJECTIVES

The overall aim of this project was to determine if infrared thermography could monitor the healing process of acute lower extremity musculoskeletal injuries sustained by professional football players.

- **Objective 1:** To use infrared thermography to track changes in average maximum temperature of the injured limb following an injury up until return to play.
- **Objective 2:** To use infrared thermography to track the average temperature asymmetry between the injured limb and the healthy limb after injury up until return to play.
- **Objective 3:** To identify the relationships between average maximum temperature, average temperature asymmetry, and LEFS scores at time of injury and return to play in football players recovering from a lower extremity musculoskeletal injury.

HYPOTHESES

We hypothesized that:

- **Hypothesis 1:** The infrared images would display an increase in average maximum temperature of the injured limb at the time of injury compared to baseline. As the injury healed, there would be a decrease in the average maximum temperature of the injured limb from time of injury to return to play.
- **Hypothesis 2:** The infrared images would display an increase in average thermal asymmetry between the injured and uninjured limb following an acute lower extremity injury. As the healing of the injury progressed to the maturation phase, there would be a gradual return to thermal symmetry from time of injury until return to play.
- **Hypothesis 3:** We expected there to be a significant relationship between an increase in average maximum temperature, an increase average temperature asymmetry, and a decrease in LEFS score at time of injury. As the average maximum temperature and average temperature asymmetry decreased at return to play, there would be an increase in LEFS score.

METHODS

Recruitment

To be included in this study, participants had to be an active player of the Montreal Alouettes and have sustained a football-related acute musculoskeletal lower extremity injury. An injury is defined as damage to musculoskeletal tissue that causes the player to miss at least one practice or game.[43] The injured player completed his rehabilitation with the team's therapy staff for the whole rehabilitation process. The exclusion criteria included the current rehabilitation of a pre-existing injury. Some studies suggested using an exclusion criteria of an abnormal infrared thermography baseline, which would be any asymptomatic thermal symmetry higher than 0.3 ºC.[7,22] However, we did not use any baseline asymmetry value as an exclusion criterion as most of the participants of the current study demonstrated a certain level of thermal asymmetry at baseline. The thermal asymmetry present at baseline will be further addressed in the discussion. The participants were considered rehabilitated once they returned to practice or competition without any restrictions. In terms of sample size, we did not perform a power analysis to calculate a minimum sample size needed for the study since our research objective was to track injury data using infrared thermography, as opposed to performing a randomized control trial. We wanted to see if infrared thermography could monitor musculoskeletal injuries. Most previous case series were composed of about 3 participants, so our goal was to gather as much data as possible by including any player that sustained a lower extremity injury.

Measures

Infrared Camera and Setting

The FLIR E8 camera was used to capture the infrared images. The camera has a resolution of 320 x 240 pixels. The FLIR E8 camera has an accuracy of ±2ºC, a sensitivity of < 0.03ºC and contains infrared sensors that capture the infrared radiation emitted by the tissue photographed and turn the thermal energy into electrical signals to produce the final image. We used a standardized Glamorgan protocol in a controlled setting when collecting the infrared images which was suggested in a previous study.[20] The Glamorgan protocol is used to increase the reproducibility of thermal imaging by providing reference images of body positions and regions of interests that can be used for infrared imaging.[20] As mentioned previously, there are various internal and external factors that can affect infrared thermography.[18] To minimize the effects of individual factors, we used the contralateral limb as a control temperature by also looking at temperature asymmetry between the two limbs. A specific room was dedicated to the infrared thermography procedure, and the same room was used every time an image was taken. Previous studies reviewing the protocol used for thermography state that the room should be set at a constant lighting and a

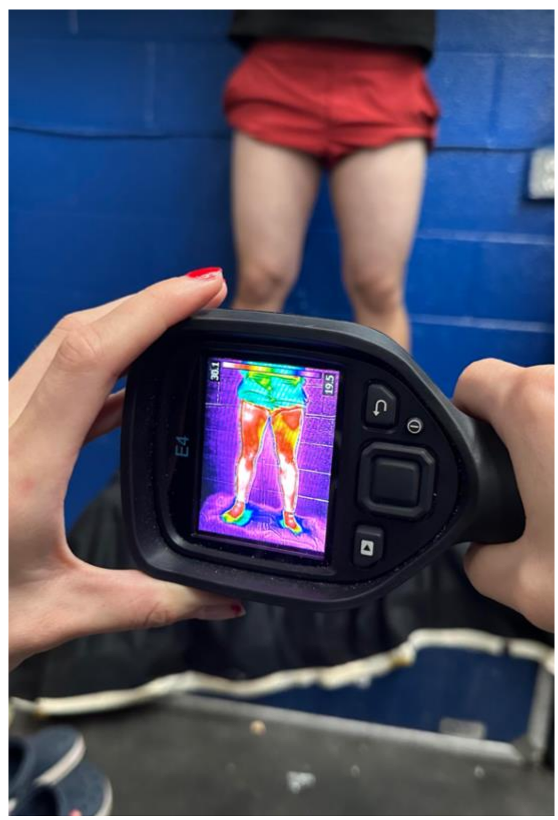

Figure 4. Taking an anterior lower extremity thermal image with the FLIR E8.

temperature of 20 ± 0.5ºC with temperature variations of ≤ 1ºC. [44] The room used for this study was a storage room that was set at a constant lighting and a temperature of 21ºC. The room temperature was required to be kept at 21ºC as items need to be stored at that specific temperature, but slight temperature variations are expected to have occurred. To take an infrared picture, the players removed all their lower extremity clothing apart from their underwear, as infrared radiation cannot go through clothing.[44] The players then stepped up on a platform since contact with the floor would affect the subject's body temperature and alter results. Prior to taking the image, we ensured that the camera was placed perpendicular to the subject being photographed.[44] We used three different field of views indicated for soft tissue injuries to the lower extremity and the knee. The field of views used included an anterior view of the lower extremity, a posterior view of the lower extremity, and a close-up anterior view of the knees.[44] The thermal images were taken from a distance that included all suggested landmarks and respects the boundaries stated in the protocol.[44] Specifically, the anterior and posterior lower extremity images show the waist of the player down to the player's feet (Figure 5). The knee images display an anterior, mid-thigh to mid-tibia horizontal view of the legs (Figure 6). All images included both limbs of the lower extremity[31]. Taking the infrared image took approximately 2 minutes. Finally, we analyzed the thermal images using the ThermoHuman ® Software to obtain more detailed and more structured approach for the readings of the thermal images[45]. For the thermal images to be uploaded to the Thermohuman ® software, the distances suggested by the previously mentioned Glamorgan protocol needed to be respected. Otherwise, the ThermoHuman ® Software was unable to process the thermal images. Once the thermal image was uploaded to the software, the software produced two results: a thermogram (Figure 7) and an avatar of the thermal image (Figure 8). The thermogram is a digitalized version of the thermal image. The avatars are a segmented version of the thermal image. Each avatar is separated into multiple temperature regions of interest. There are multiple temperature readings for each region of interest, such as maximum temperature and temperature asymmetry (Figure 9).

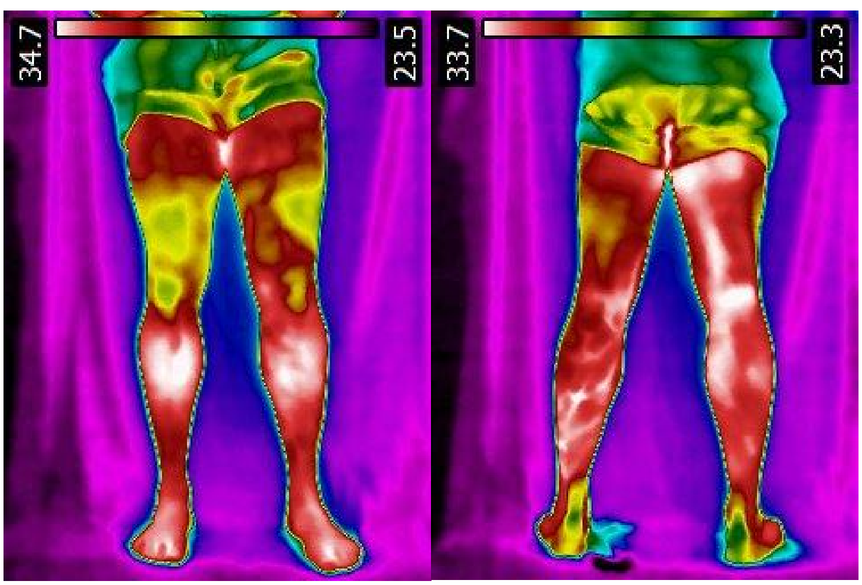

Figure 5. When taking thermal images, there is a specific framing that is required to be able to upload the images into the ThermoHuman ® Software. The above images are an example of the framing required for the thermal images displaying the temperature distribution of the anterior

(left photo) and posterior (right photo) lower extremity. Both images are limited by the waist at the top, and the toes/heels at the bottom. These are the thermal images of a professional football player that suffered a PCL sprain with tibial bone bruise and Baker's cyst rupture to the left knee. The images were taken within 48 hours of the time of injury.

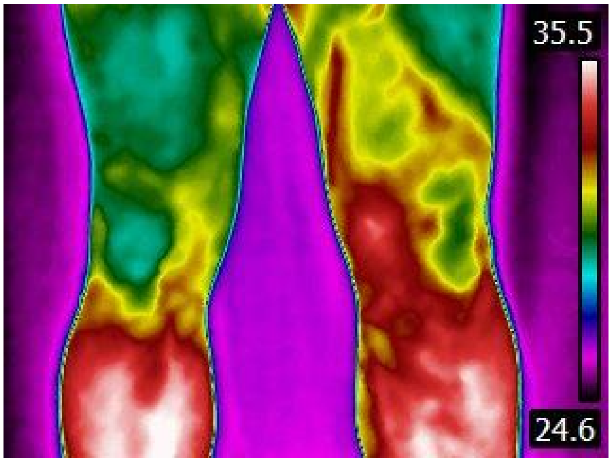

Figure 6. When taking thermal images, there is a specific framing that is required to be able to upload the images into the ThermoHuman ® Software. The above image is an example of the framing required for the thermal image displaying the close-up anterior view of the knees. The image includes the mid-thigh to mid-tibia. These are the thermal images of a professional football player that suffered a PCL sprain with tibial bone bruise and Baker's cyst rupture to the left knee. The images were taken within 48 hours of the time of injury.

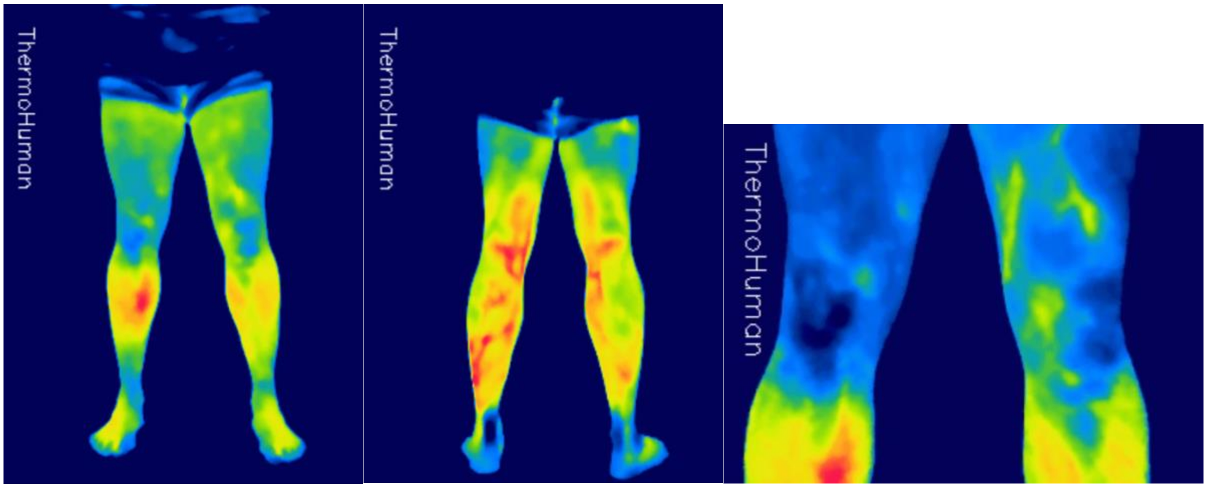

Figure 7. Here we present the thermograms produced by the ThermoHuman ® Software when the thermal images presented in figures 5 & 6 were uploaded onto the software.

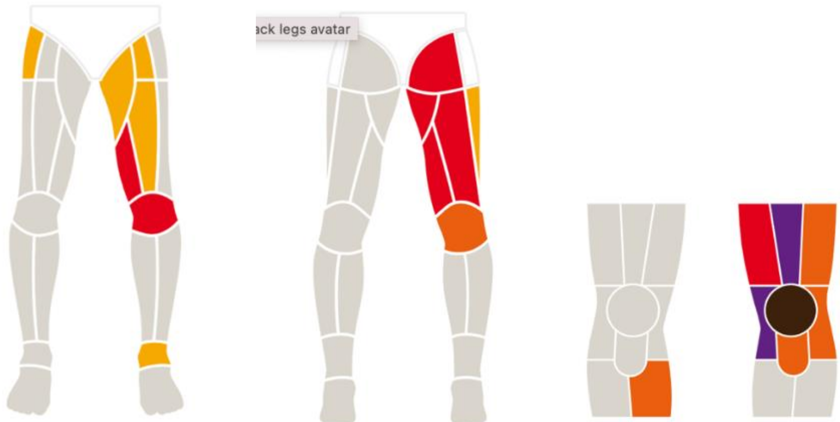

Figure 8. Here we present the avatars and regions of interest of an injured professional football athlete that had suffered a PCL tear, tibial bone bruise and a Baker's cyst rupture of the left knee. These images were taken within 48 hours of the time of injury. The raw images (see Figure 5 and 6 as an example) were uploaded to the Thermohuman ® Software and the software generates the avatar and region of interests shown here. The three protocols include the front legs (left), back legs (middle) and close-up of the knee (right). The red sections indicate a higher temperature compared to the yellow sections for example.

Knee	Right/Left	
Alarm level:	-	
Asymmetry RL:	0.41°	
Asymmetry (max):	0.42°	
Neutralized asymmetry:	0°	
Neutralized asymmetry (includes injury, pain and factors):	0°	
Avg temp:	34.33°	33.91°
Max temp:	35.37°	34.95°
Min temp:	33.32°	33.01°
Std temp:	0.5°	0.48°

Figure 9. When a thermal image is uploaded to the Thermohuman ® Software, the software generates avatars that are split into regions of interest. Each region of interest has multiple temperature readings provided by the software, as shown in the above image.

Function of the Lower Extremity

Lower extremity function was measured by having the participant complete the Lower Extremity Functional Scale (LEFS) (see Appendix). The scale is a self-reported questionnaire composed of 20 items and scored out of 80, where a higher score corresponds to higher function.[46] A 9-point difference in score represents a clinically significant change.[47] The Lower Extremity Functional Scale has been used in multiple previous studies and in a wide variety of patient populations with various musculoskeletal conditions. A previous systematic review concluded that the scale has excellent reliability, validity, and responsiveness. While the systematic review only included one study examining athletes, the lower extremity functional scale has been used in many previous studies to measure lower extremity function in athletes.[48–50] A study investigating prognostic factors in athletes with medial tibial stress syndrome found that the athletes' score on the lower extremity functional scale was significantly related to recovery time.[51] The reliability is indicated by intraclass correlation coefficients of 0.85 to 0.99. The strong validity is demonstrated by correlation coefficients greater than 0.7 when the scale is compared with other well-known self-reported scales for lower extremity function. The excellent responsiveness is reflected by effect sizes greater than 0.85.[47]

Procedure

Consent to participate in the study was obtained on the day that baselines were taken. All players on the Montreal Alouettes that provided consent underwent infrared imaging as detailed above to scan for healthy baseline temperature measurements. Baselines were taken after training camp, before the start of the regular season. Certified athletic therapists and a physiotherapist were present at every practice and game. When a player sustained an injury, a thermal scan was taken as soon as possible after an injury occurred (usually on the day of the injury or the day after the injury). The injured players also completed the Lower Extremity Function Scale as outlined previously (**Objectives 1, 2 & 3**). The players followed a usual rehabilitation program with daily follow-ups and athletic therapy and/or physiotherapy treatment. The temperature measurements were repeated as often as possible (almost daily) and function measurements every 2 weeks until the participant completed the rehabilitation program and was cleared to return to sport without any limitations according to the guidelines mentioned previously (**Objectives 1, 2 & 3)**. At the end of the player's rehabilitation, we took a final infrared scan and had them fill out the Lower Extremity Functional Scale.

Data Analysis

After a participant suffered an injury, we were interested in the changes in temperature related to the inflammation or healing phase of the injury. Therefore, we used a repeated measures ANOVA to measure the change in maximum temperature of the injured limb over time (**Hypothesis 1**). We also used a repeated measures ANOVA to measure the change in temperature difference (asymmetry) between the injured and uninjured limb over time (**Hypothesis 2**). We were also interested in the relationship between the tissue temperature and function of the athlete (**Hypothesis 3**). Accordingly, we used Pearson correlations to identify the relationships between the maximum temperature of the tissue, the temperature asymmetry and lower extremity function at each given time point. A correlation coefficient between 0.1 and 0.3 is weak, between 0.3 to 0.5 is moderate, and greater than 0.5 is categorized as strong.[52]

RESULTS

Participants

The subjects of this study consisted of 9 professional football players from the Montreal Alouettes team. Each participant sustained a lower extremity injury throughout the season that caused them to miss at least 1 practice or game. The injuries sustained by the participants included ankle sprains, an MCL sprain, a PCL sprain with a tibial bone bruise and Baker's cyst rupture, a calf strain, and knee contusions (Table 1). While the study sample consisted of only 9 participants, we still opted to use parametric tests since parametric tests are more robust and we wanted to compare our means to previous studies that used a similar type of anlaysis. Moreover, the sphericity test for both repeated ANOVAs (maximum temperature and temperature asymmetry) was non-significant, meaning that all assumptions were met.

Participant	Injury	Time to return to play	Height (cm)	Weight (kg)
1	Ankle sprain	4 days	185	105.69
2	Ankle sprain	6 days	185	94.35
3	Knee contusion	5 days	192	106.59
4	Ankle sprain	Did not RTP during season	182	117.48
5	Ankle sprain	8 days	181	87.09
6	MCL sprain	3 days	191	135.62
7	Medial gastrocnemius & soleus strain	17 days	182	104.33
8	Knee contusion	8 days	190	139.71
9	PCL sprain with tibial bone bruise and Baker's cyst rupture	67 days	191	107.96

Table 1. Injury type, demographics, and how long each athlete took to recover for all athletes who participated in this study.

Time Point Selection and Temperature Regions of Interest

Time Point Selection

For the time point selection, we initially wanted to take pictures at the time of injury, at the end of the inflammation phase, during the proliferation and remodelling phase, and at return to play to track temperatures changes during the different stages of healing. However, as observed in Table 1, the time until to return to play varied for each participant, with one participant returning to play after 4 days and another after 67 days. Therefore, we selected three time points that the participants had in common and at which we would expect a change in temperature. The three time points selected were baseline, time of injury and return to play.

Region of Interest

When uploading the thermal images on the ThermoHuman ® Software, there are various protocol options available to analyze lower body thermal images. The lower extremity protocols include "front legs", "back legs" and "knees". As mentioned in the methods, for each protocol selected, the software produces avatars that are separated into regions of interests (Figure 8). Each region of interest has a set of temperature readings for that area of the body. The temperature readings include average temperature, maximum temperature, minimum temperature, and maximum temperature asymmetry between the left and right limbs (Figure 9). As the participants sustained different injuries to the lower extremity, it was not possible to use the same region of interest for every participant. Instead, for each participant, we selected the region or regions of interest that we would analyze based on a few factors. First, we examined the avatar of the front legs, back legs, and knees and observed each region of interest for each participant. Second, we observed how the temperatures of the regions of interest near the area of injury appeared at the time of injury, and how the temperatures of each region changed over time. While keeping in mind what the injury diagnosis was, we selected the region or regions of interest that best represented the player's injury at the time of injury and throughout the healing process to be analyzed. In other words, if the injury was spread over multiple regions of interest, we chose to include the temperature readings of more than one region in our analysis. This was done to ensure that we properly captured the injury and included the main areas affected by inflammation and changes in blood flow over time. Below is an example of the images and decision process to determine the regions of interest (Figures 10 to 16).

Example of the Selection Process for the Regions of Interest

The following figures demonstrate the selection process of the regions of interest for one of the participants (Figures 10 to 16). The participant injured his left knee. Specifically, he had a PCL tear with a tibial bone bruise and a Baker's cyst rupture. The injury occurred on August 24th, 2023, and the first set of images following the injury were taken on August 26th, 2023 (due to travel and time change). The first figures demonstrate the avatars for the three different views (the anterior view of the lower extremity, the posterior view of the lower extremity, and the close-up view of the knees) over the participant's entire rehabilitation process. Each grey zone limited by white borders represents a different region of interest (ROI).

As seen in the images, there are a lot of different colours and changes in temperature. When selecting the region(s) of interest to analyze, we decided to use the "knee" region of interest from the anterior view of the left knee (top row) for this participant (Figure 15). First, the different colours observed in the posterior right leg are most likely due to compensation, as the athlete was using crutches/favoring his right uninjured leg. Therefore, he was mostly using his right posterior chain to propel himself forward, explaining the increase in temperature of the right posterior leg. Moreover, the type of injury that the participant suffered include structures located in the knee joint. Finally, as seen in the participant's baseline pictures (6/1/2023), the avatars for the posterior view of the lower extremity and the close-up view of the knees have been replaced by the thermal images taken with the camera. The thermal images are presented because the images were not taken with the proper framing, so the Thermohuman ® Software was unable to process them. For instance, the thermal image for the anterior close-up view of the knees was taken from too far away, so it included more than the mid thigh to mid tibia framing required by the software. The improper framing of the thermal images only occurred for a few of the participants when taking the baseline photos only. The views with improper framing were not used in the data anaylsis. For the example of the participant with the PCL tear, tibial bone bruise and baker's cyst rupture, the lack of a proper close-up view of the knee at baseline also contributed to choosing the anterior knee region of interest from the anterior lower extremity view for our data analysis.

The baseline, time of injury, and return to play avatars (1st row), thermal images (2nd row) and thermograms (3rd row) for the participant with the PCL tear, bone bruise and baker's cyst rupture are shown on page 26. While there is a noticeable difference in temperatures between the injured and uninjured limbs at the different time points, the exact location and extent of the temperature changes is hard to determine, which makes them difficult to analyze. Thus, the complexity of the thermal images is why we decided to use the avatars when selecting the region(s) of interest for the data analysis.

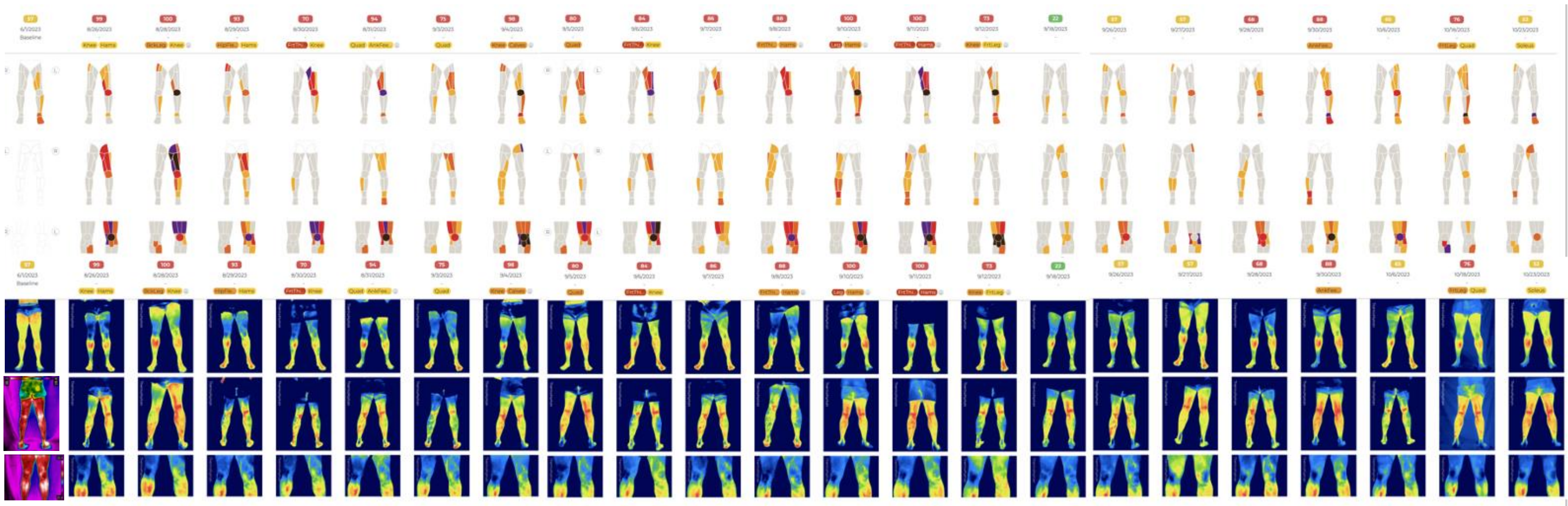

Figure 10. Here we present all the images from one participant who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee. Each colum of the figure represents an individual time point. At each time point, three images were taken: an anterior view of the lower extremity, a posterior view of the lower extremity and a close-up anterior view of the knees. The bottom three rows are the thermograms displaying the thermal images. The thermal images are uploaded to the Thermohuman ® Software to generate the avatars and regions of interest in the top three rows.

Figure 11. A zoomed-in view of the avatars from figure 10. The avatars display the thermal images taken at the first 6 time points of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee. The first column of pictures (numbered 57 in yellow on top) were taken on June 1st, 2023, prior to the athlete's injury (identified as "baseline"). The second column of images (numbered 99 in red on top) were taken on August 26, 2023, less than 48 hours follow the athlete's injury (identified as "time of injury"). The last 4 columns of pictures represent the avatars for the thermal images taken from August 28th to August 31st, 2023, but wre not use for the data analysis. In the first column, the posterior view of the legs and the close-up of the knees were replaced by the thermal images as the photos were not taken from the right distance, so the Thermohuman ® Software was unable to process the images to generate avatars.

Figure 12. Above there are 7 series of avatars that display the thermal images taken at 7 timepoints between September 3rd, 2023, and September 10th, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

Figure 13. Above there are 7 series of avatars that display the thermal images taken at 7 timepoints between September 11th, 2023, and September 30th, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

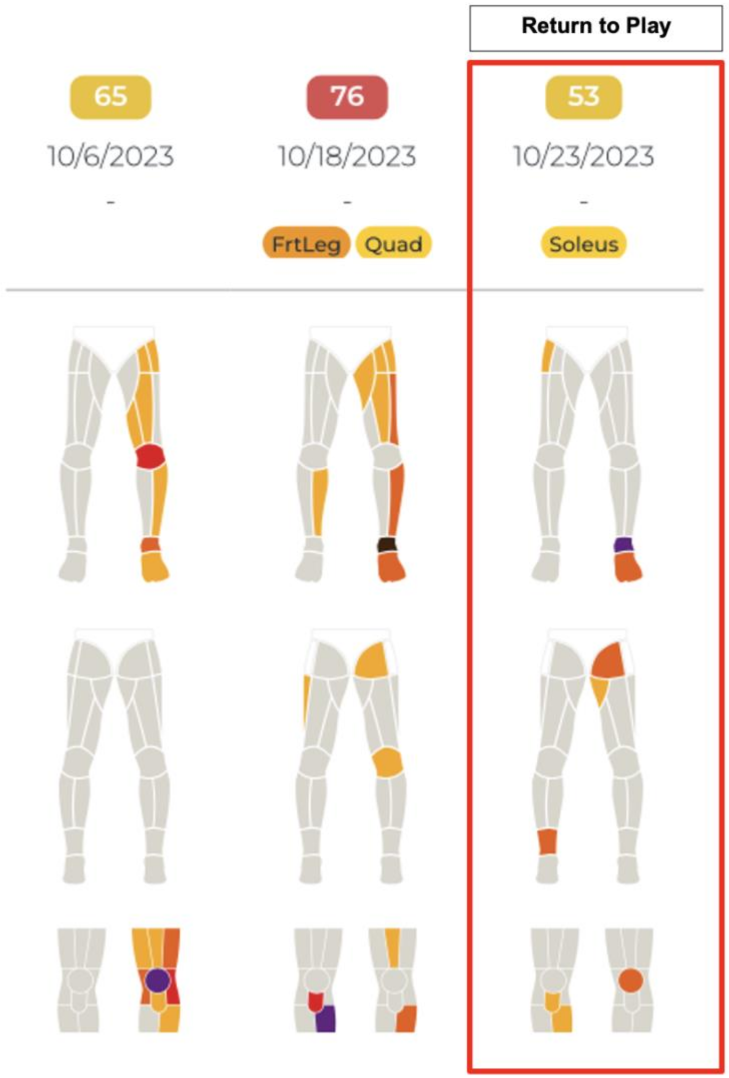

Figure 14. Above there are 3 series of avatars that display the thermal images taken at 3 timepoints between October 6th, 2023, and October 23rd, 2023. The images were taken during the rehabilitation of a professional football athlete who suffered a PCL tear, a tibial bone bruise and a Baker's cyst rupture in his left knee.

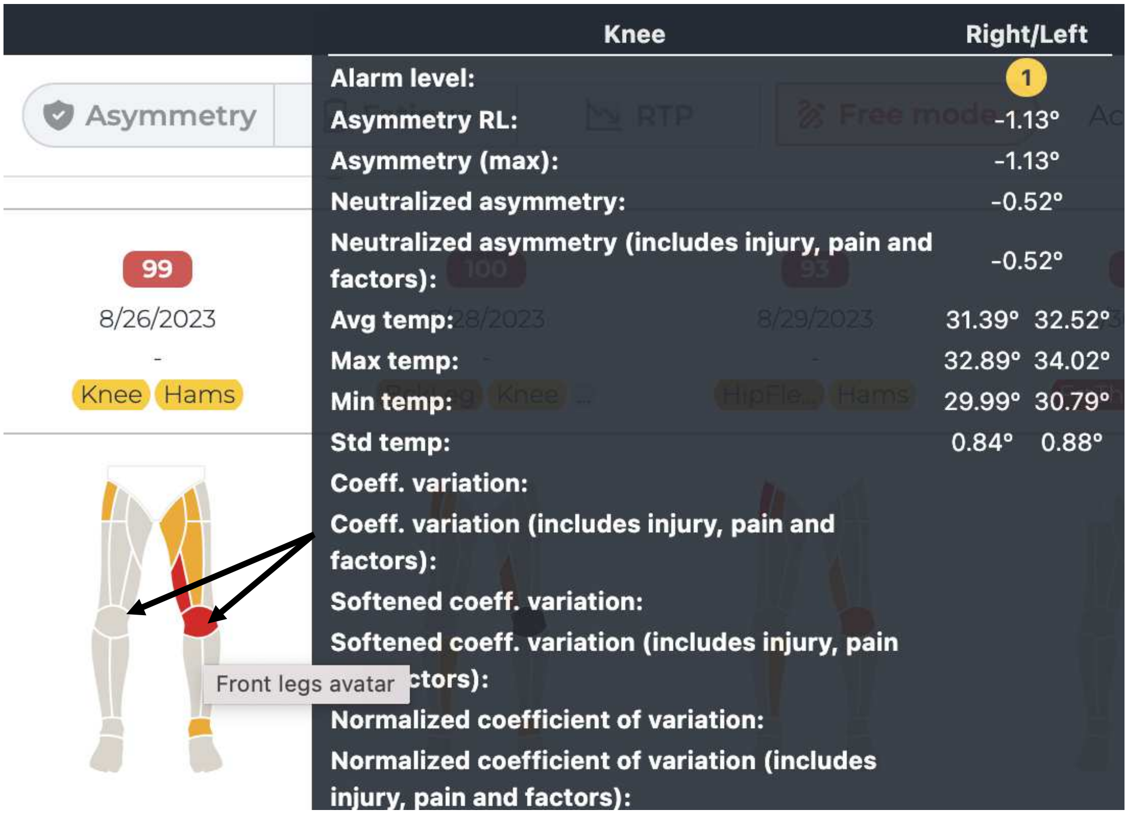

Figure 15. The region of interest selected for the participant with the PCL tear, tibial bone bruise and Baker's cyst rupture was the "knee" of the anterior view of the legs. The "knee" region of interested is indicated by the two black arrows. The box on the right is the example of all the temperature readings obtained for the "knee" region of interest for the participant at the time of injury.

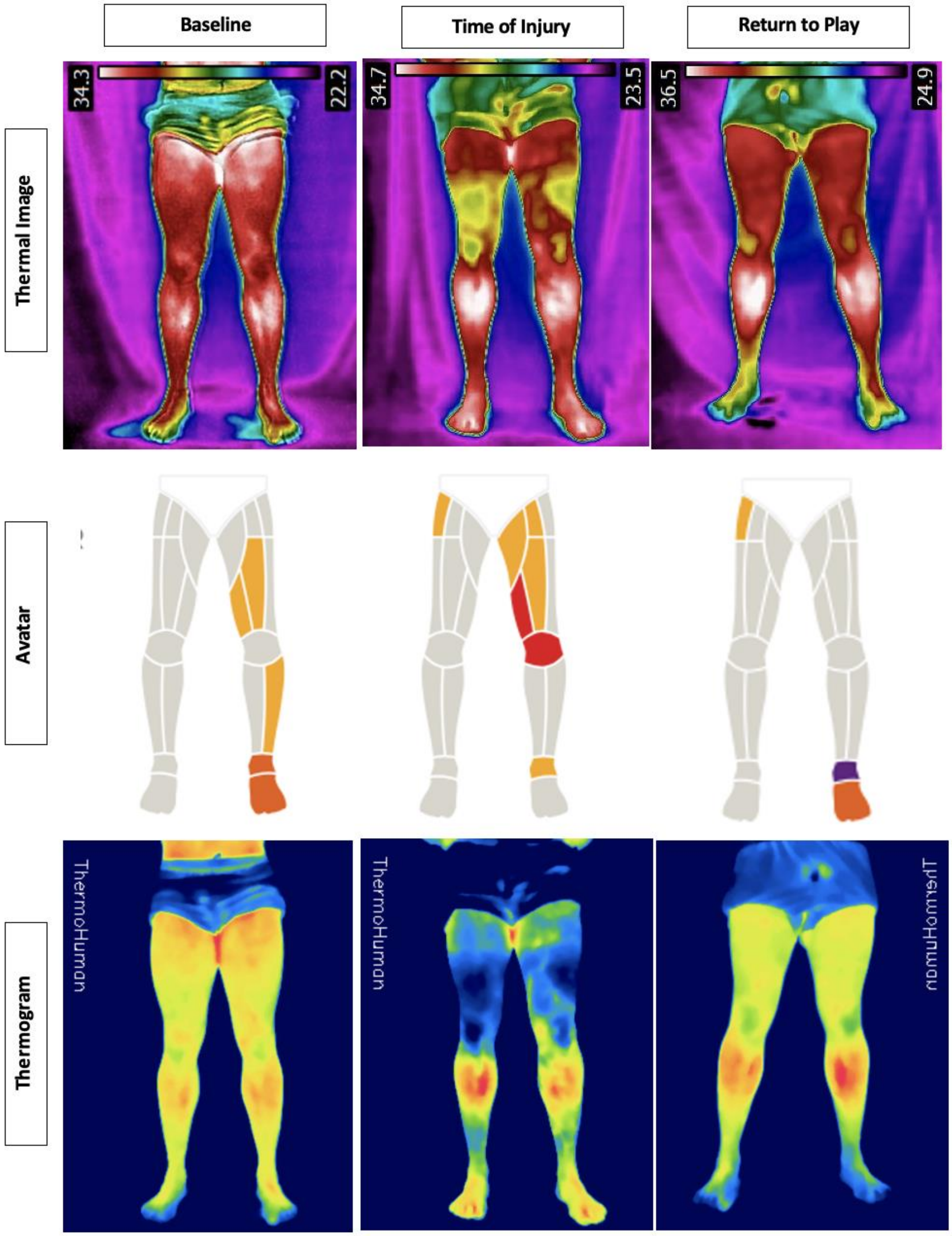

Figure 16. The first row of pictures represents the raw thermal images taken of an athlete that suffered a PCL tear, tibial bone bruise and Baker's cyst rupture at baseline (1st column), time of injury (2nd column) and return to play (3rd column). The second row shows the corresponding avatars produced by the Thermohuman ® Software. The avatars are seprated into regions of interest to display the athlete's thermal distribution. The last row shows the thermograms that represent each thermal ima

Maximum Temperature Analysis

Once the region or regions of interest was/were determined for each participant, then the maximum tempature was determined for each time period at baseline, time of injury and return to competition. If a participant had more than one region of interest selected for the data analysis, the average maximum temperature of the selected regions of interest was calculated and used for the repeated measures ANOVA.

The Mauchly's test of sphericity shows that the assumptions for a repeated ANOVA for the average of the maximum temperatures of the injured side at three time points were met, with a p-value of 0.056. Therefore, we used the results of the tests of within-subjects effects with sphericity assumed, which gave a p-value of 0.011. The results of the repeated measured ANOVA show that there was a significant difference between at least two of the means ($p = 0.011$). While a post-hoc test cannot be completed using SPSS, the results indicate that there was a significant increase in the average of the maximum temperatures of all regions of interest of the injured side from baseline (mean = 32.043) to time of injury (mean = 34.419), as these are the two means that have the greatest difference. From the results, we can also conclude that there was most likely a significant increase in the average of the maximum temperatures of all regions of interest of the injured side from baseline (mean = 32.043) to return to play (mean = 34.297). However, we cannot conclude that there was a significant decrease in average maximum temperature of the regions of interests between time of injury (mean = 34.419) and return to play (mean = 34.297).

Time point	**Mean maximum temperature of injured side (°C)**	**Standard deviation**
Baseline	32.043	2.772
Time of injury	34.419	1.210
Return to play	34.297	1.046

Table 2. The table shows the mean maximum temperature values at baseline, time of injury and return to play for our group of injured profession football athletes. The mean maximum temperature is the average of the maximum temperatures of the selected ROIs of the injured side. A repeated measures ANOVA indicated that there was a significant increase in mean maximum temperature of the injured side from baseline to time of injury ($p = 0.011$).

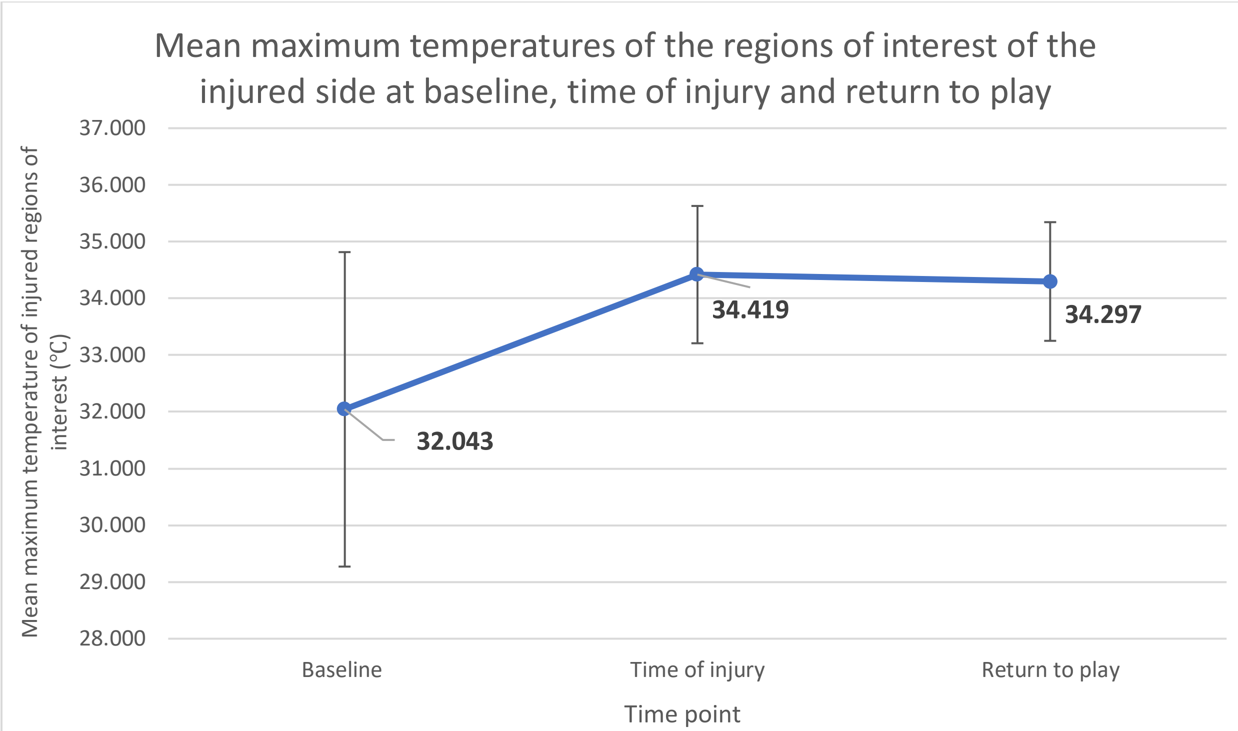

Figure 17. We took thermal images of professional football players that suffered a lower extremity injury (n = 9). A repeated measures ANOVA was used to compare the mean maximum temperature of the injured side at baseline (32.043), time of injury (34.419), and return to play. (34.297). There was a significant increase in mean maximum temperature of the injured side from baseline to time of injury (p = 0.011).

Temperature Asymmetry Analysis

To calculate the average temperature asymmetry, we started by manually calculating the temperature asymmetry between the maximum temperature of each region of interest of the injured and uninjured side. We recorded the maximum temperature of the region of interest of the injured side and subtracted the maximum temperature of the regions of interest of the uninjured side. We compared the value obtained manually to the asymmetry calculated by the ThermoHuman ® Software [“asymmetry (max)”]. There was one data point where the value calculated manually and the one calculated by the software were not identical. For the analysis, we used the value calculated manually. If participants had more than one selected region of interest, the asymmetries of each region of interest were used to calculate the average asymmetry of all regions of interest for each participant.

Participant	Mean Max. Temp. Injured @ Baseline (°C)	Mean Max. Temp. Injured @ TOI (°C)	Mean Max. Temp. Injured @ RTP (°C)	Avg. Temp. Asymmetry @ Baseline (°C)	Avg. Temp. Asymmetry @ TOI (°C)	Avg. Temp. Asymmetry @ RTP (°C)
1	26.915	34.460	35.275	1.065	0.525	0.745
2	30.220	34.207	34.010	-0.213	-0.523	-0.080
3	30.486	34.410	33.649	1.071	0.736	1.108
4	35.395	36.520	34.675	0.340	0.125	0.335
5	34.760	35.170	32.695	0.085	0.120	-0.240
6	33.898	34.882	35.074	0.724	1.376	0.646
7	32.857	34.233	35.223	-0.120	0.117	0.247
8	30.100	31.920	32.815	0.130	0.985	0.985
9	33.76	33.970	35.260	0.200	0.160	0.330

Table 3: We took thermal images of professional football players that suffered a lower extremity injury (n = 9). We used the mean maximum temperature and average temperature asymmetry of each of the participants at baseline, time of injury and return to play for our data analysis.

The Mauchly's test of sphericity shows that the assumptions for a repeated measures ANOVA for the average asymmetry of the regions of interest at three different time points were met, with a p-value of 0.643. Therefore, we used the results of the tests of within-subjects effects with sphericity assumed, which gave a p-value of 0.808. Thus, there is no significant difference in the average temperature asymmetry of the various regions of interest at the three different time points (baseline, time of injury, return to play).

Time point	Mean temperature asymmetry between the injured and uninjured side (°C)	Standard deviation
Baseline	0.367	0.481
Time of injury	0.402	0.567
Return to play	0.453	0.457

Table 4. The table shows the temperature asymmetry values at baseline, time of injury, and return to play for our group of injured professional football athletes. The asymmetry number is the temeprature difference between the injured side and the uninjured side. A repeated measures ANOVA indicated that there was no significant difference found between the means at the three time points (p = 0.808).

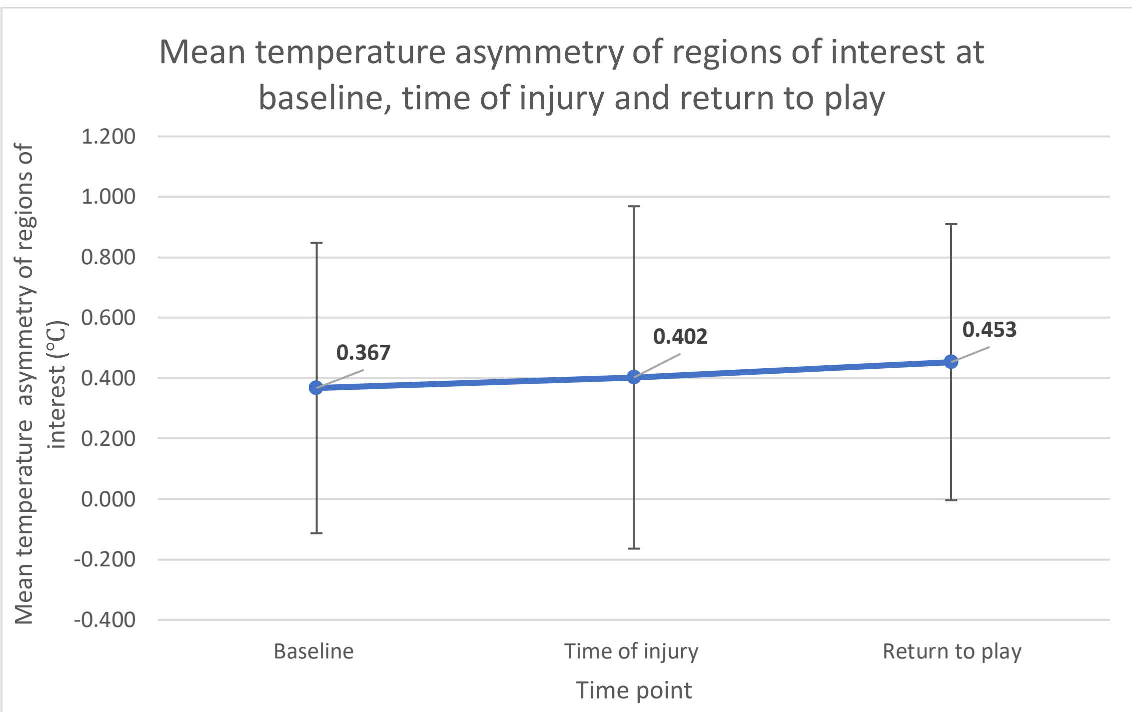

Figure 18. We took thermal images of professional football players that suffered a lower extremity injury (n = 9). A repeated measures ANOVA was used to compare the mean temperature asymmetry between the injured and uninjured side at baseline, time of injury, and return to play. There was no significant difference found between the means at the three time points (p = 0.808).

Correlation
Despite the small sample size and varied data, correlations were still generated to get a general idea of the results since one of our hypotheses was to determine if there was a relationship between temperatures and lower extremity function. We generated multiple correlations and found three correlations with higher correlation coefficients (Table 5). First, a higher average asymmetry between the injured side and the uninjured side at baseline was correlated with a higher average asymmetry at return to play following an injury ($p = 0.034$, $R = 0.704$) (Figure 19). Moreover, a higher average temperature asymmetry at time of injury was correlated with a higher average temperature asymmetry at return to play ($p = 0.019$, $R = 0.755$) (Figure 20). Finally, the LEFS score at return to play was negatively correlated with the average temperature asymmetry at time of injury ($p = 0.037$, $R = -0.698$) (Figure 21)[52,53]. In other words, A higher average temperature asymmetry at time of injury was correlated with a lower LEFS score at return to play.

When calculating correlation, there are a few assumptions that must be taken into consideration. The assumptions for correlation include a representative sample, independence of observations, normal distribution of both variables, a linear relationship of both variables, and there must be no outliers[53]. While the variables used for the correlations are continuous, the small sample size ($n = 9$) and the varied data are a limitation and need to be considered. With a small sample size, there is a higher chance that our data is not representative of our population and that the data is not normally distributed. There may also be a few outliers in our data, as seen when observing the scatterplots (Figures 19 & 20). Therefore, the assumptions for correlation were not met, and we interpret the results of our correlations with caution.

	Average Maximum Temperature @ Baseline	Average Maximum Temperature @ TOI	Average Maximum Temperature @ RTP	Average Temperature Asymmetry @ Baseline	Average Temperature Asymmetry @ TOI	Average Temperature Asymmetry @ RTP	LEFS @ TOI	LEFS @ RTP
Average Maximum Temperature @ Baseline	1	0.524	0.007	-0.378	-0.090	-0.481	0.158	-0.207
Average Maximum Temperature @ TOI	0.524	1	0.312	0.172	-0.262	-0.406	0.630	0.407
Average Maximum Temperature @ RTP	0.007	0.312	1	0.212	-0.019	0.034	-0.169	0.333
Average Temperature Asymmetry @ Baseline	-0.378	0.172	0.212	1	.612	.704	.243	.039
Average Temperature Asymmetry @ TOI	-0.090	-0.262	-0.019	0.612	1	0.755	-.216	-.698
Average Temperature Asymmetry @ RTP	-0.481	-0.406	0.034	.704	.755	1	-.163	-.241
LEFS @ TOI	0.158	0.630	-0.169	0.243	-0.216	-0.163	1	0.478
LEFS @ RTP	-0.207	0.407	0.333	0.039	-0.698	-0.241	0.478	1

Table 5. We generated the Pearson Correlation (R) values between maximum temperature, temperature asymmetry and LEFS score at baseline, time of injury and return to play are presented in the table for 9 professional football athletes that suffered an acute lower extremity musculoskeletal injury.

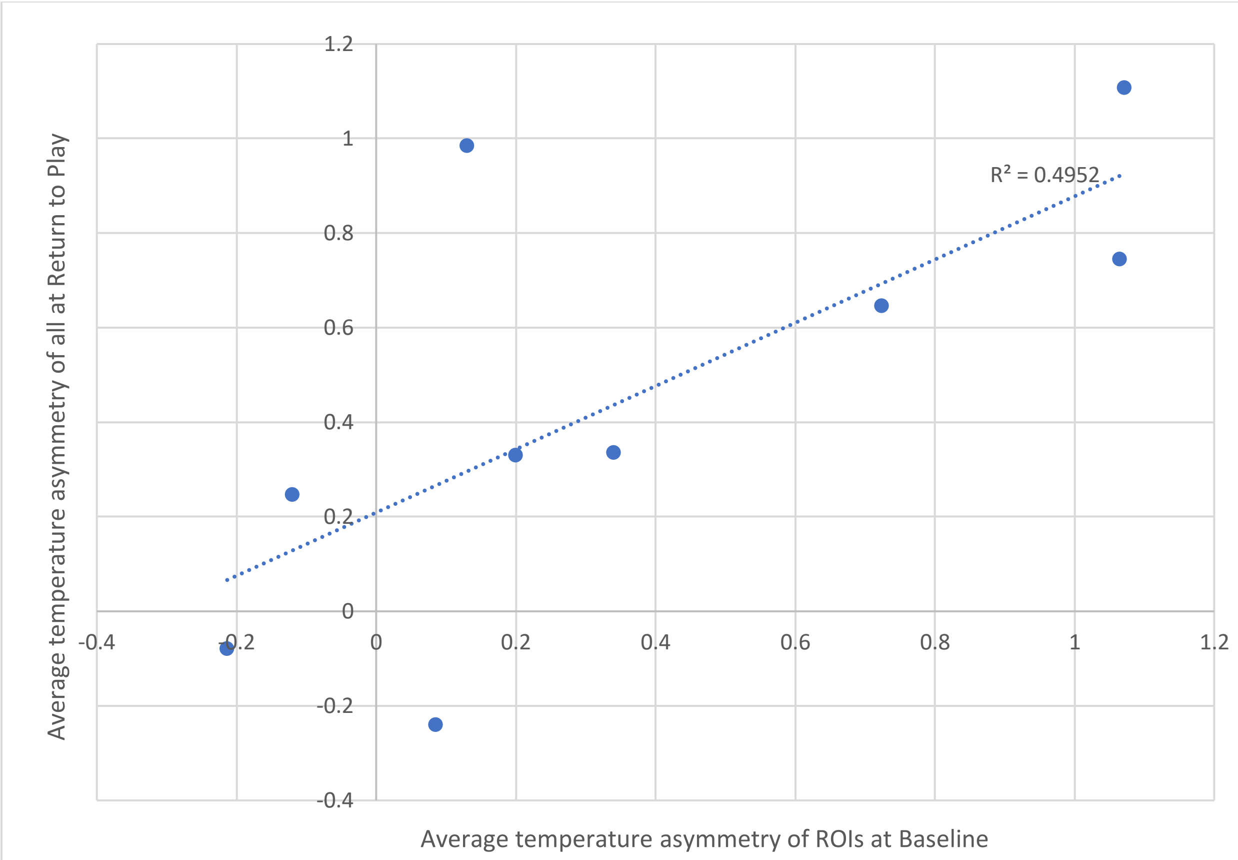

Figure 19. Figure illustrating the relationship between the temperature asymmetry at baseline compared to return play in 9 injured professional football players. Asymmetry is the ratio between the temperature on the injured side compared to the uninjured side. A higher average asymmetry between the injured side and the uninjured side at baseline was correlated with a higher average asymmetry at return to play following an injury ($p = 0.034$, $R = 0.704$).

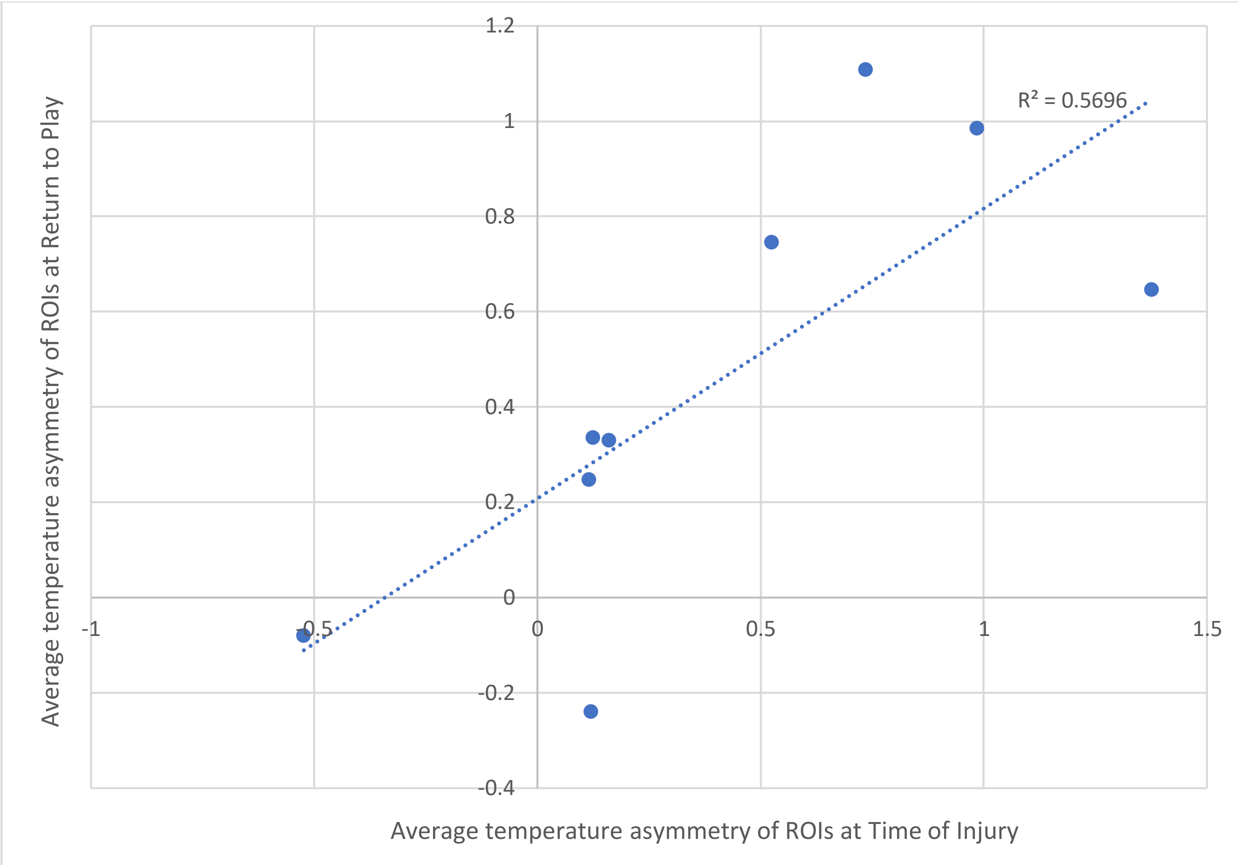

Figure 20. Figure illustrating the relationship between the temperature asymmetry at time of injury compared to return play in 9 injured professional football players. Asymmetry is the ratio between the temperature on the injured side compared to the uninjured side. A higher average temperature asymmetry at time of injury was correlated with a higher average temperature asymmetry at return to play ($p = 0.019$, $R = 0.755$).

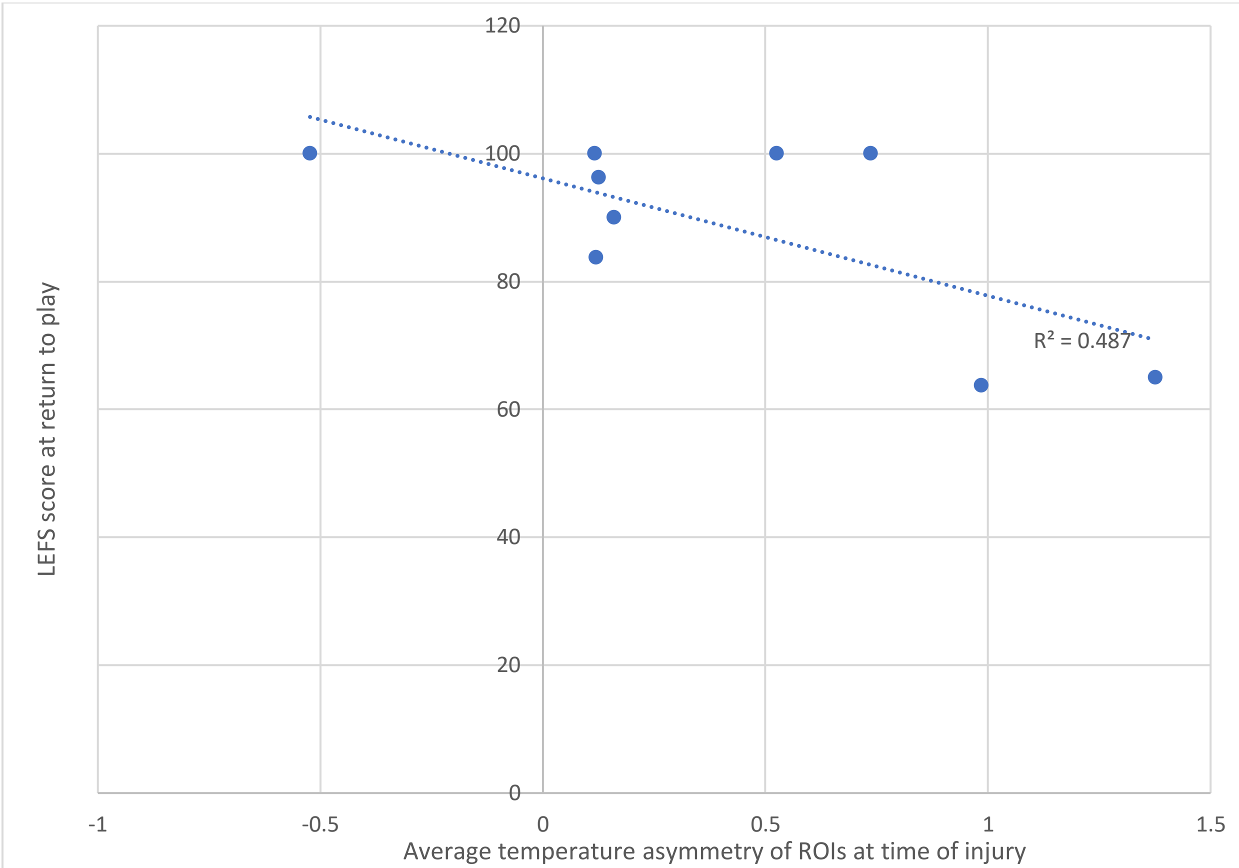

Figure 21. Figure illustrating the relationship between the temperature asymmetry at time of injury and the LEFS score in 9 injured professional football players. The LEFS is a self-reported questionnaire to measure lower extremity function. A higher average temperature asymmetry at time of injury was correlated with a lower LEFS score at return to play ($p = 0.037$, $R = -0.698$).

Participant	LEFS score at Time of injury (%)	LEFS score at Return to play (%)
1	56.25	100
2	18.75	100
3	57.5	100
4	71.25	96.25
5	73.75	83.75
6	15	65
7	46.25	100
8	17.5	63.75
9	16.25	90
Average	41.39	88.75
SD	24.63	14.06

Table 6. The LEFS is a self-reported questionnaire that measure lower extremity function. The table presents the self-reported lower extremity function values using the LEFS scale for 9 professional football athletes at the time of injury compared to when they returned to play.

DISCUSSION

Our study examined the use of infrared thermography for tracking acute musculoskeletal injuries to the lower extremity in professional football players. We concluded that infrared thermography could be used to track the temperature change during the rehabilitation of acute musculoskeletal lower extremity injuries, but more studies with larger sample size are required to determine the importance of temperature asymmetry with regards to injury recovery.

Maximum Temperature

The results of the repeated measures ANOVA indicated that there was a significant increase in maximum temperature of the injured limb at the time of injury compared to baseline. The increase in maximum temperature agrees with our initial hypothesis because when a player gets injured, there is an inflammatory process that occurs which would result in an increase in temperature. Tissue inflammation following a musculoskeletal injury leads to swelling, redness, and heat.[54] The temperature increase after inflammation has been directly measured in a previous study using the tissue chamber model in farm animal species.[55] The authors noted an increase in skin temperature accompanying the acute inflammatory process induced by the injection of carrageenan. The increase in skin temperature was different between the four different animal species included in the study, but ranged from approximately 1.85°C to 5°C and occurred between 6h and 48h following the injection of the inflammatory agent. The skin temperature returned to baseline by the 72 hour time point.[55] There is a good example of the inflammation temperature change in humans, but it is a case series.[56] The authors used infrared thermography to measure temperature changes in a patient with an ankle sprain, a male who completed allergen testing, and a research team member with a minor crush injury. In the case of the ankle sprain, a thermal image was taken 1 hour following injury and indicated that the foot was 5°C hotter than the ankle. Another image was taken 3 hours following injury and the use of ice and NSAIDs, and the increase in temperature had significantly reduced. When the thermal images were repeated at

5 days and 3 weeks following the injury, the temperature readings were normal.[56] Apart from mentioning that the foot was 5°C warmer than the proximal ankle, the study did not report any other temperature averages. In the present study, the heat caused by inflammation following a musculoskeletal injury lead to a higher superficial body temperature, which was detected by the thermal camera at the time of injury.

The significant increase in maximum temperature from baseline to time of injury was still present at return to play and did not return to baseline values. Considering that the later stages of tissue healing and injury rehabilitation such as tissue remodelling and regeneration as well as regaining normal function are paired with the resolution of inflammation, we would have expected the maximum temperature of the injured limb to return to close to baseline by the time of return to play.[54] Our results are different from some previous studies.

The lack of significant decrease in superficial temperature between time of injury and return to play found in our study differ is different from previous studies measuring ligament injuries . For instance, a previous study analyzed the changes in maximum temperatures of the lower extremity during the rehabilitation process following ACL surgery.[30] The only significant difference in maximum temperatures found in the ACL study was in the posterior view of the thigh, which the authors attributed to compensation patterns. In the study on ACL rehabilitation following surgery, there was no significant difference found for the maximum temperature of the anterior view of the legs between the beginning and the end of the rehabilitation program. However, the rehabilitation program only lasted 6 weeks, while ACL rehabilitation usually takes 9 to 12 months.[30,57] Accordingly, the study on ACL patients differs from the present study since the participants would not have been considered fully rehabilitated when the last maximum temperature reading was recorded. Moreover, the results of our study differ from the results of a case study on an ankle sprain, where the initial increase in maximum temperature decreased by the seventh day following the injury.[8]

A potential explanation for the discrepancy with the temperature in our paticipants not returing to baseline as noted in previous studies coud be that in professional sports, due to expectations and timelines, athletes may return to play sooner than recreational athletes, athletes at a non-professional level, and non-athletes.[40] For instance, the 3 participants of the present study that suffered an ankle sprain returned to play after 4, 6 and 8 days (Table 1). During the tissue healing process, the inflammatory stage lasts from 1 to 5 days, with the proliferative phase starting around day 5 and lasting until about 21 days. Furthermore, the literature states that mild to moderate ankle sprains take between 7 and 18 days to return to sport.[58,59] Therefore, while the athletes may have been able to return to play and fulfill their roles on the team, their injury may not have been fully healed at the time of return to play. The faster return to play could potentially explain why the superficial temperature had not significantly decreased from time of injury. Also, when nearing time to return to play, the athlete's rehabilitation exercises have reached a higher level of difficulty as the athlete is being tested functionally to determine readiness to return to play. The increased stress and load imposed at the later phase of rehabilitation may have caused an increase in temperature in the injured area. This may be another reason why there was not a significant decrease in maximum temperature between time of injury and return to play.

Temperature Asymmetry

The results of the present study showed that there was no significant change in temperature asymmetry at the three different time points (baseline, time of injury, and return to play). There are a few reasons that can explain why there was no significant change found in the average temperature asymmetry between the injured and uninjured limb at baseline, time of injury and return to play. The lack of statistical significant difference between the three means at baseline, time of injury and return to play can partially be attributed to the standard deviations and the low sample size. The standard deviations (SD = 0.481, 0.567, and 0.457) were larger than the means themselves. Moreover, the sample size of this study consisted of only 9 participants.

A possible reason explaining the lack of significant change in average temperature asymmetry is the body's compensatory mechanism that accompanies musculoskeletal injuries. As the temperature of the injured limb increased at the time of injury due to inflammatory processes, the temperature of the uninjured limb may also increase in certain regions of interest due to compensation patterns. In some cases, we were able to exclude the areas that showed temperature asymmetries as a result of compensation. A compensation is an adaptation made by the body following an injury to make up for weaknesses or deficiencies caused by the injury.[60] For instance, if a person injures one leg, they may shift their body weight to the other leg during gait and develop a limp as a compensatory mechanism. As an example, Figure 22 below displays the thermal images and avatars for the participant that suffered a PCL tear, tibial bone bruise and Baker's cyst rupture to the left knee. When looking at the thermal image and the avatar, we notice areas of increased temperature in the right posterior chain (notably the hamstrings). The increased temperature is most likely a result of compensations, as the athlete was limping and mostly using his right leg to propel himself forward. We decided not to include these regions of interest when doing our data analysis so that the compensations would not affect the temperature asymmetry readings. In other cases, we were not able to exclude areas of compensations during the selection of our regions of interest for our data analysis. For instance, an athlete who sprained his right ankle and was limping may have increased the stress on his left ankle, which would also cause a temperature increase in the uninjured left ankle (Figure 23). When observing the figure below, we see the thermal image and the corresponding avatar of a professional football athlete that suffered a right ankle sprain. The thermal image was taken less than 24 hours following the athlete's injury. While the injury sustained was to the right ankle, we notice that the thermal image shows more white areas (hotter areas) in the left uninjured leg. When looking at the avatar, we also observe red, yellow and purples colours on the left (uninjured) side, displaying higher superficial temperatures. An explanation for the higher temperatures on the uninjured side compared to the injured side is that the athlete was limping. Therefore, if both limbs increased in temperature, there would not have been a significant change in average temperature asymmetry of the regions of interest. As the injured limb heals and inflammation (and temperature) decreases, there are less compensations of uninjured areas, which would also entail a decrease in temperature.

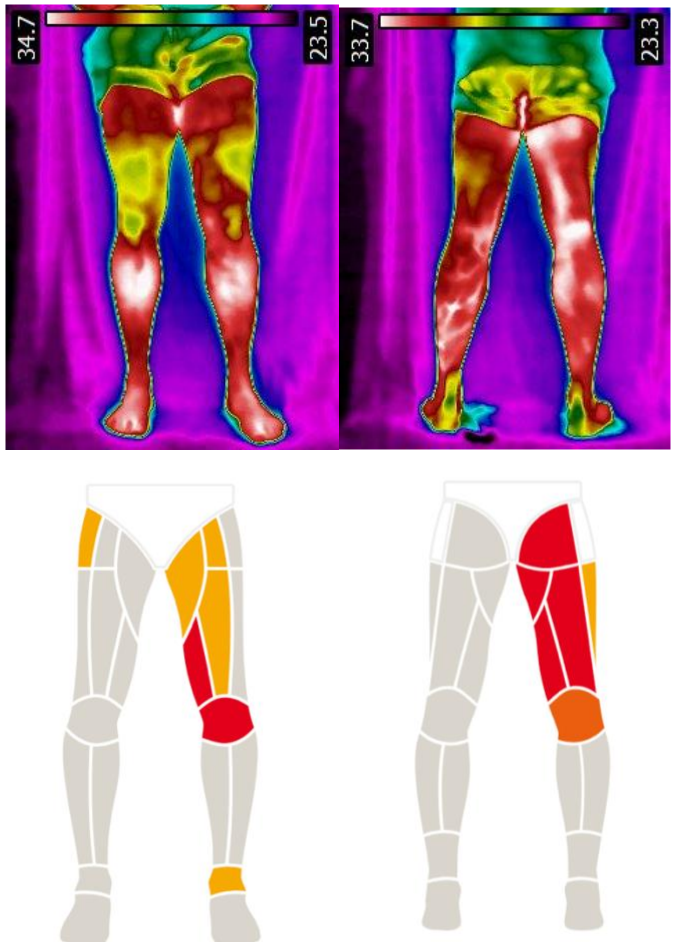

Figure 22. The first row of pictures represents the raw thermal images of the anterior lower extremity (left) and the posterior lower extremity (right) of the participant that suffered a PCL tear, tibial bone bruise and Baker's cyst rupture at time of injury. Red and white show areas of hotter temperatures. The second row shows the corresponding avatars produced by the Thermohuman ® Software. The coloured regions show areas of higher temepratures. When looking at the posterior lower extremity images in the right column, we notice that there are areas of increased temperatures in the right (uninjured) leg, notably in the hamstring and posterior knee areas.

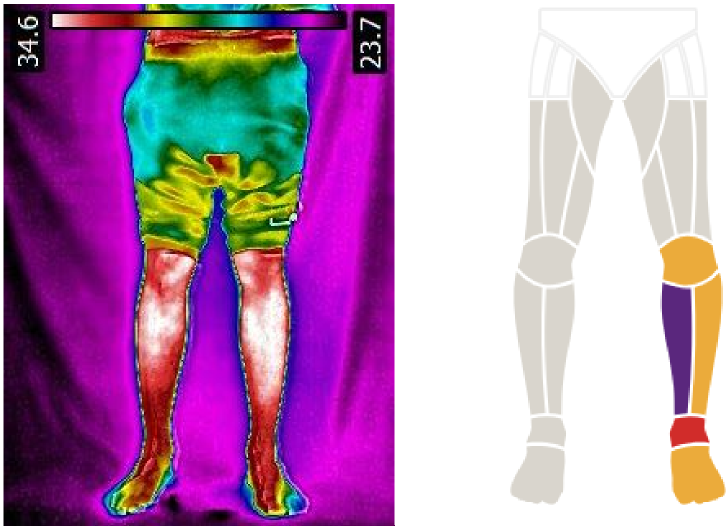

Figure 23. We took a thermal image of a professional football athlete that suffered a right ankle sprain. The thermal image was taken less than 24 hours following the injury. On the day that the image was taken, the athlete had been limping and putting most of his weight on his uninjured left side. The image displays a higher temperature in the uninjured left ankle and nearby regions of interest compared to the injured right ankle.

Another variable than can affect the asymmetry comparison is what region of interest is used in the analysis. We selected regions of interest based on the injured area/tissue that would best represent the injured area and therefore the temperature change of interest for our study. However we acknowledge that if we used different areas of interest, it could change the average temperature in the area and therefore the asymmetry value. For example, figure 24 shows the thermal image and corresponding avatar for the knees of a participant that sustained a left knee contusion. When observing the thermal image and the avatar, we see that selecting the exact area of injury is challenging. On the thermal image, we notice a white area on the left knee which shows the inflammation and increased blood flow occuring at the area of injury. When observing the avatar, we can see that It is difficut to perfectly match the area of injury of the thermal image to a certain region or regions of interest. So we picked the area that best represented the injured area which would still include the maximum temperature reading. Unless the maximum temperature area changed location over time, the correct maximum temperature would have still been captured in our analysis.

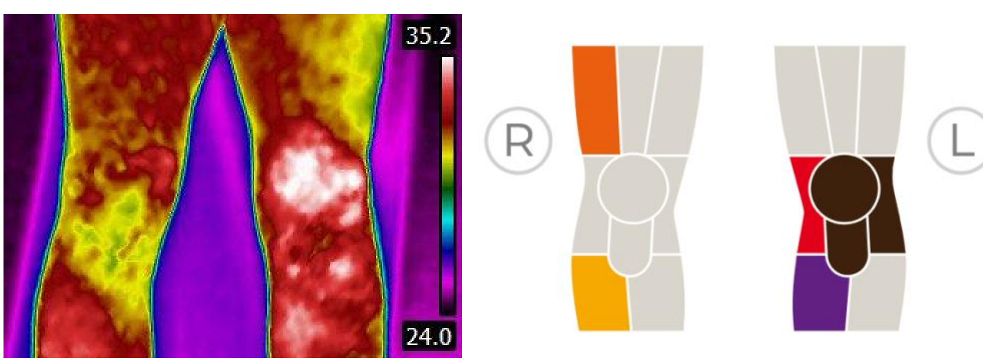

Figure 24. The thermal image (left) and avatar of the knees (right) for a participant who suffered a right knee contusion.

Correlation

There was a strong positive correlation between the average temperature asymmetry at baseline and the average temperature asymmetry at return to play following an injury ($p = 0.034$, $R = 0.704$).[53] There was also a strong positive correlation between average temperature asymmetry at time of injury average temperature asymmetry at return to play ($p = 0.019$, $R = 0.755$).[53] Finally, there was a strong negative correlation between the average temperature asymmetry at time of injury and the LEFS score at return to play ($p = 0.037$, $R = -0.698$) [53]. In other words, a higher average temperature asymmetry at time of injury was correlated with a lower LEFS score at return to play. However, our results must be interpreted with caution since the assumptions for running a Pearson correlation were not met. For instance, the small sample size would most likely have affected the correlation. With a small sample size, chance may have impacted the results of the correlation. In other words, there is a chance that the results do not properly represent the population of interest.[53] The high R-values do show that there may be a relationship between temperature asymmetry and function, so future studies with larger sample sizes should further explore the relationships between temperature asymmetries and lower extremity function throughout an injured athlete's rehabilitation process.

Additional Challenges with Temperature Asymetery

Intially, we were going to use a temperature asymmetry of > 0.3ºC at baseline as an exclusion criteria, but we opted not to. Previous studies report that a temperature asymmetry > 0.3ºC means that a tissue is "at risk of injury", or "unhealthy". When performing the literature review, there were not many studies regarding the use of infrared thermography for musculoskeletal injuries. The cut-off temperature asymmetry values for what was considered "heathy", "at risk of injury", and "injured" also varied amongst the limited studies, and were not always found in the references. Based on the data that we obtained, using a cut-off of 0.3 ºC as an exclusion criteria was troublesome, as most of the present study's participants had a "healthy" baseline despite having temperature asymmetries of > 0.3ºC. Therefore, we decided not to use a temperature asymmetry of > 0.3ºC as an exclusion criteria for multiple reasons.

The baseline temperature asymmetries of > 0.3ºC could be due to various reasons, so an asymmetry > 0.3ºC was not used as an exlusion criteria. First, the temperature asymmetries recorded at baseline may have had higher asymmetries than expected since the thermal images were taken following football training camp. The football training camp took place in May, following the players' off-season. Training camp consists of 1 to 2 practices per day, with some recovery days throughout. The training camp is a duration of approximately 3 weeks. During training camp, the players are suddenly exposed to a higher duration and frequency of football practice compared to the type of training the players have been doing for the previous 4-5 months of the off-season. There are also a limited amount of rest days. The increased load on the players' body, including joints and muscles, could lead to increased stress and inflammation in certain tissues. For instance, tissues that have either been injured previously or tissues that may be weaker on one side compared to the other may show an increase in temperature from being overloaded. Thus, the temperature asymmetry present at baseline may also be due to compensatory mechanisms that were heightened due to training camp. Although the players were not necessarily injured, the thermal asymmetry can represent the different stresses that were placed on the players' bodies during training camp. Indeed, intensification in acute training load is linked to higher injury risk.[61] Following the first phase of the pre-season, semi-elite and elite athletes were found to have not only increases in creatine kinase level indicative of muscle damage, but also greater concentrations of inflammatory factors. A greater concentration of inflammatory factors could have affected the blood flow and heat in certain areas, which would alter the temperature readings recorded when taking the thermal images. Second, another reason that coud explain why the cut-off of 0.3ºC should be reviewed and why we did not use it as an exclusion criteria is the variability of the temperature asymmetries on a daily basis. Throughout the present study, we took pictures of the participants on a frequent basis (almost every day). When observing the data, we can see that there is a fluctuation in the temperature asymmetries from one day to another. Therefore, we did not exclude participants with an asymmetry > 0.3 ºC due to the variability in the temperature asymmetry readings from day to day. Finally, we also must keep in mind that the participants of the present study all suffered a lower extremity musculoskeletal injury throughtout the season. The presence of a temperature asymmetry of greater than 0.3 ºC found in the majority of the participants could have been an indication that the participant was indeed at risk of injury. In future studies, it could be interesting to compare the baseline temperature asymmetries of the players that ended up getting injured to the baseline temperature asymmetries of the players that did not get injured throughout the season. Thus, a temperature asymmetry of > 0.3ºC at baseline was not used as an exclusion criteria due to the potential effect of the images being taken following training camp, and the idea that the temperature asymmetry may have been a predictor of injury.

The average temperature asymmetries at time of injury obtained in the present study were lower compared to the temperature asymmetries found in previous studies. For instance, in a case study on a participant that suffered an ankle sprain, there was a temperature asymmetry of 2.5ºC between the injured and uninjured side.[8] While the average temperature asymmetry values obtained in our study at time of injury (0.402ºC) and the case study on the ankle sprain (2.5 ºC) are different, the results from the case study were strictly descriptive due to the sample size of one. Also, the participant in the case study was a 60 year old male who injured himself playing basketball, and the thermal images were taken from a medial and lateral view of the ankle.[8] More studies regarding the use of infrared thermography for musculoskeletal injuries are required to determine what numbers to expect when looking at temperature asymmetries.

Other Factors that can Affect Temperature Measurement with IRT

The change in maximum temperature after injury was the main finding from this study, however it is important to acknowledge extrinsic factors that can influence temperature changes including food/drink intake and medication use.[18] It has been suggested that food intake is related to higher body temperatures, but the overall effects on superficial body temperature are inconclusive.[18] A study examining food intake and superficial skin temperature recorded a thermal image of 5 men at baseline, following an overnight fast. The men then ingested a test meal, and the researchers captured 10 additional thermal images. The study concluded that there were 2 peaks in skin temperature elevation after a meal, one at 30 minutes and one at 90 minutes, followed by a gradual return to baseline.[62] In terms of hydration, a review article on the factors affecting superifical temperature refers to an article stating that the intake of sparkling water causes a decrease in superficial body temperature reaching -0.89 ºC. However, I was unable to find the article cited upon searching multiple research platforms.[18] In terms of medication, more research needs to be done to determine the effects of different types of medication on skin temperature. An early study on anti-inflammatory medication and thermography looked at how the temperature of arthritic joints (in the knees, hand, and foot) changed following the oral ingestion of NSAIDs (aspirin, benorylate, and indomethacin) versus a steroid injection.[63] In both cases, there was a decrease in the thermographic index, but the decrease was slower with the oral ingestion compared to the steroid injection.[63] The study also showed a difference in temperature changes with the use of an analgesic drug (paracetamol) and an anti-inflammatory drug (aspirin). One of the patient's with rheumatoid arthritis of the hand was given paracetamol for a few days. During the paracetamol treatment period, the patient's thermographic index was rising. Around day 7, they were given aspirin, and their thermographic index started to decrease.[63]

In the present study, we controlled for many variables that could affect the temperature change but as stated above there are several that could still influence the temperature of a participant. The technical factors such as the camera, the software, the protocol, the temperature and lighting of the room used were kept constant. Moreover, the pictures were not taken after the participant had received athletic therapy or physiotherapy treatment since manual therapy and modalities such as massage, ultrasound and electrical stimulation affect superficial temperature. We also asked the athletes if any type of physical activity had been performed prior to taking the pictures, such as working out or biking to the stadium. Therefore, the extrinsic factors that have affected maximum temperature must be kept in mind but are not expected to have had a great effect on the results of the present study since we did see a significant change in maximum temperature as stated above. Future studies should control for the extrinsic factors as much as possible that may affect the maximum temperature readings.

Study Complications and Limitations

During the present study, we encountered more complications than expected. One of the biggest challenges was our data reduction. Moreover, as discussed previously, we had a small sample size, which affects the significance of our results. Future studies would need to include a larger sample size to obtain significant results. The participants of this study had a variety of lower extremity injuries and different return to play timelines. One of the strengths of infrared thermography is that we believe it could be used for various types of musculoskeletal injuries such as ligaments sprains, muscle strains, and contusions. However, one of the challenges regarding research with infrared thermography and injuries is the difference in the length of the rehabilitation process. For instance, the time to return to play varied greatly between the participants according to the type and severity of their injury, with the quickest time to return to play being 3 days, and the longest time to return to play being 67 days. Therefore, although we took pictures of each participant nearly daily, we had to choose common time points to be able to compare the participants' data. In future studies, using more time points would be interesting to see how the temperature distribution varies on a daily basis and throughout the different stages of recovery. When planning the study, comparing the temperature of the injured limb to the uninjured limb seemed simple. However, the selection of the regions of interest was more of a challenge than we had anticipated. We had to decide which areas we would and would not be including when comparing temperatures. We had to differentiate between what was directly related to the injury from what was the result of compensations. Therefore, the data analysis was complex, and there are still ways to go until the use of infrared thermography becomes clinically simple.

CONCLUSION

Infrared thermography was able to detect changes in tissue temperature that accompany musculoskeletal injuries and can be used to track injury. However, data reduction poses a significant challenge when using infrared thermography in studies on musculoskeletal injury rehabilitation. Careful attention must be focused on capturing the pictures to ensure that the areas to be photographed are properly exposed, that the person being photographed is well positioned, and that the framing of the pictures includes all required areas. More studies with larger sample sizes must be performed to obtain more significant results. Studies examining the normal temperature variability in professional football players would also be necessary to determine what constitues "normal" or "healthy" temperature asymmetries.

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APPENDIX

Activities		Extreme Difficulty or Unable to Perform Activity	Quite a Bit of Difficulty	Moderate Difficulty	A Little Bit of Difficulty	No Difficulty
a.	Any of your usual work, housework, or school activities.	0	1	2	3	4
b.	Your usual hobbies, recreational or sporting activities.	0	1	2	3	4
c.	Getting into or out of the bath.	0	1	2	3	4
d.	Walking between rooms.	0	1	2	3	4
e.	Putting on your shoes or socks.	0	1	2	3	4
f.	Squatting.	0	1	2	3	4
g.	Lifting an object, like a bag of groceries from the floor.	0	1	2	3	4
h.	Performing light activities around your home.	0	1	2	3	4
i.	Performing heavy activities around your home.	0	1	2	3	4
j.	Getting into or out of a car.	0	1	2	3	4
k.	Walking 2 blocks.	0	1	2	3	4
l.	Walking a mile.	0	1	2	3	4
m.	Going up or down 10 stairs (about 1 flight of stairs).	0	1	2	3	4
n.	Standing for 1 hour.	0	1	2	3	4
o.	Sitting for 1 hour.	0	1	2	3	4
p.	Running on even ground.	0	1	2	3	4
q.	Running on uneven ground.	0	1	2	3	4
r.	Making sharp turns while running fast.	0	1	2	3	4
s.	Hopping.	0	1	2	3	4
t.	Rolling over in bed.	0	1	2	3	4
Column Totals:						

Figure 25: The Lower Extremity Functional Scale.[46]