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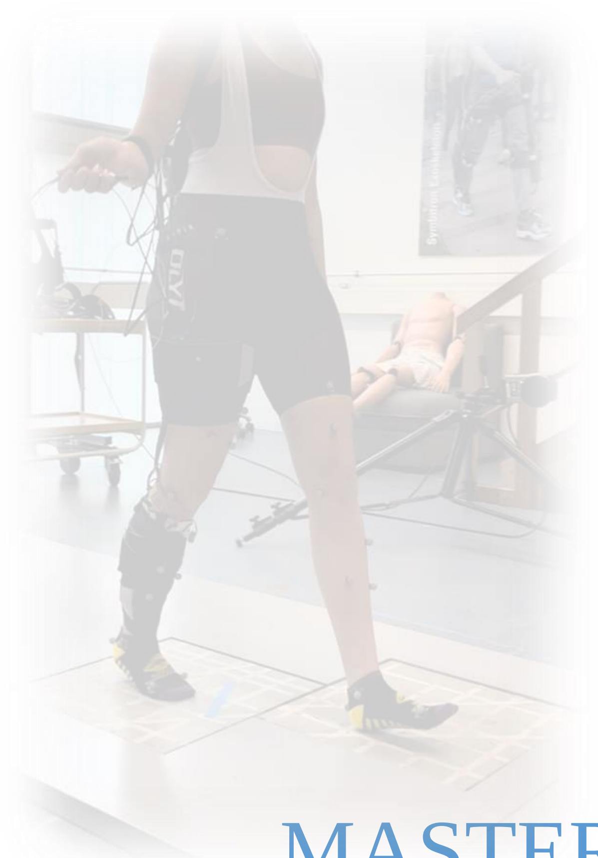

MASTER THESIS

The Potential of Musculoskeletal Modeling and Surface Electromyography in Assessing Return-To-Play in Patients with Lateral Ankle Sprain

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The Potential of Musculoskeletal Modeling and Surface Electromyography in Assessing Return-To-Play in Patients with Lateral Ankle Sprain

I. J. Waaijer[1]

***Abstract*— Lateral ankle injuries, including ankle sprains, are common among athletes, leading to significant economic burdens and high recurrence rates. Current rehabilitation methods often overlook crucial neuro-muscular parameters, potentially hindering effective treatment and increasing the risk of relapse. This thesis aims to explore a comprehensive approach to assess and enhance rehabilitation outcomes for lateral ankle injury patients.**
Objective: This thesis evaluates the potential of musculoskeletal models and surface electromyography (sEMG) in aiding physiotherapists to determine an injured patient's readiness for Return-to-Play (RTP). Additionally, it aims to determine the potential utility of musculoskeletal modeling and sEMG measurements in identifying differences between patient groups, informing rehabilitation strategies, and enhancing patient outcomes in lateral ankle injury rehabilitation.
Methods: The study involved eight healthy subjects and three individuals with a lateral ankle sprain. The subjects were equipped with a garment for EMG measurements. Movement data, recorded using retroreflective markers and optical motion capture cameras, were synchronized with force plate data to analyze joint angles, muscle activity, and muscle tendon lengths in muscles around the ankle.
Results: For the joint angles and the muscle tendon length, differences were observed between dominant and non-dominant legs in healthy subjects. Variation analysis for the wobble exercise indicated significant differences between healthy and injured groups.
Conclusion: Results indicate the potential of musculoskeletal modeling and sEMG muscle information as valuable tools in assessing patient functional recovery. Further exploration of their integration into clinical practice is recommended to enhance RTP decision-making. Continued research could establish standardized protocols, fostering their seamless integration into physiotherapy practice and ultimately optimizing patient outcomes in musculoskeletal injury rehabilitation.

***Keywords*— Lateral ankle sprain, musculoskeletal model, electromyography (EMG)**

I. Introduction

The most common injury experienced by athletes is an ankle sprain in which the lateral ligamentous apparatus is affected the most with up to 85% of all documented ankle sprain cases [1]. Almost half of the lateral ankle injuries, 47%, need medical treatment which results in 80 million euros of medical bills each year [2]. In addition, multiple studies show that almost 80 % of the athletes are likely to get injured a second time on the same ankle [3].
At present, treatment options for a lateral ankle sprain range from conservative approaches, such as immobilization, to functional methods, including mobilization exercises, and even surgical intervention [2].
The high relapse rate of patients with a lateral ankle sprain is often attributed to the current methods used by physiotherapists to assess Return-To-Play (RTP). RTP refers to the process of an injured person or athlete returning to full participation in their sport or physical activity following injury rehabilitation. The current RTP evaluation of a patient is based on visual assessment and questionnaires. These visual assessments include for example assessing the amount of pain of the patient, the quality of movement , functionality of movement, redness or swelling of the ankle [3]. Following physiotherapy treatment, patients are given questionnaires to help reduce the likelihood of a relapse. However, the number of relapses is still very high, and it is found in several studies that there is a relapse rate of about 22,6% within a year and about 54% after six years [3][4][5].

Quantitative analysis techniques, such as motion tracking systems and surface electromyography (sEMG), offer valuable insights into neuro-muscular parameters affected by injury. sEMG, a non-invasive method for recording muscle electrical signals, provides crucial information on muscle activation patterns [6]. By measuring muscle contractions or elongations triggered by brain stimuli, sEMG reveals differences in muscle properties between injured and healthy muscles, such as delays in muscle onset and altered activation patterns [7]. Despite the recognized potential of surface sEMG in rehabilitation, its widespread integration remains limited [6].
Similarly, motion tracking systems, often integrated with kinetic sensors like force plates, track body positions and orientations, enabling the measurement of external forces [7]. Combining motion tracking technologies with sEMG allows for comprehensive data collection on muscle activity and joint kinematics during prescribed exercises, facilitating a deeper understanding of neuromuscular responses to injury.
For instance, studies have demonstrated significant differences

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in knee and ankle joint movements during activities like drop landing, highlighting key injury mechanisms and potential deficits in absorbing ground reaction forces [8]. Additionally, changes in tendon length post-rupture of the Achilles tendon can impact muscle-tendon function, affecting the ability to generate force and hindering rehabilitation progress [9]. Current assessment methods often overlook crucial neuro-muscular parameters, such as muscle strength in the ankle, leading to a lack of comprehensive understanding of the patient's true condition. Consequently, rehabilitation efforts may be hindered in effectively addressing the needs of individuals with lateral ankle injuries. This highlights a gap in the effective utilization of advanced assessment techniques for comprehensive evaluation and treatment of these neuromuscular impairments.

To bridge this gap, this study aims to address the limitations of current assessment methods by integrating advanced techniques, such as sEMG and motion tracking, into rehabilitation protocols for lateral ankle injuries. By doing so, clinicians can more accurately evaluate patient readiness for RTP and tailor treatment plans to target specific neuromuscular impairments associated with lateral ankle injuries [10].

For this thesis, the specific injury that will be researched is a lateral ankle injury (lateral ankle sprain). Studies have demonstrated significant delays in muscle onset and differences in activation ratios between injured and healthy muscles or differences in joint angles, particularly in the ankle [11] [12] [13]. Given these measurable differences in sEMG, it is hypothesized that this information can be leveraged to quantify the functional recovery rate for individual patients. To explore this hypothesis, the muscle activity and kinematics of patients undergoing treatment for lateral ankle injuries will be evaluated. Investigating the potential of musculoskeletal modeling to enhance RTP determination in physiotherapy is crucial. Unlike previous studies focusing solely on muscle activity or joint kinematics, our research adopts a holistic approach by concurrently examining both aspects across various motor tasks [14]. By bridging this gap, our study aims to optimize rehabilitation outcomes and reduce relapse rates in individuals with lateral ankle injuries. Specifically, we examine

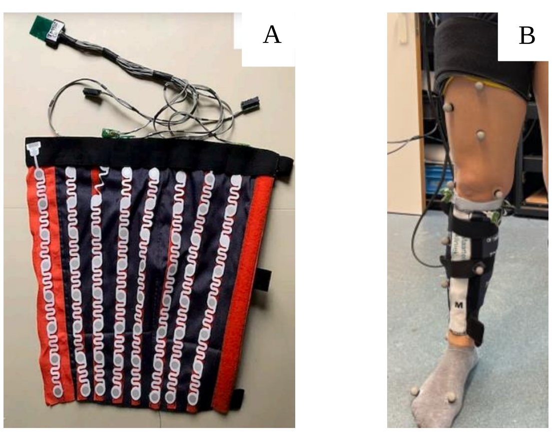


Fig. 1. *EMG leg garment. (A) Inside-view [15]; (B) Garment worn by healthy subject.*

the muscle activity of key ankle muscles - Tibialis anterior, Gastrocnemius medialis, Gastrocnemius lateralis, Peroneus longus, Peroneus brevis and the Soleus - alongside kinetic performance metrics.

In this study, we aim to investigate the effects of lateral ankle injuries on neural and kinetic parameters and their implications for rehabilitation. Firstly, we will compare muscle activity, joint angles, and muscle-tendon length between healthy individuals and those with lateral ankle injuries during various motor tasks.

Secondly, we will analyze longitudinal changes in these parameters in injured individuals throughout rehabilitation to assess progress towards return-to-play.

Finally, we will determine the potential utility of musculoskeletal modeling and surface electromyography (sEMG) measurements in identifying differences between patient groups and informing rehabilitation strategies. By integrating these advanced techniques, we aim to provide physiotherapists with valuable insights into functional deficits and recovery trajectories, enhancing patient outcomes. Through this comprehensive investigation, we hope to contribute to a deeper understanding of lateral ankle injuries and pave the way for more effective rehabilitation strategies tailored to individual patient needs.

II. Methods

A. Experimental set-up

The regional medical ethics committee of Eastern Netherlands (METC Oost-Nederland) approved the study procedures (reference number 2022–13658). Data were recorded from eight healthy subjects, and 3 subjects with a lateral ankle sprain (age = 31.8 ± 13.3 years, height = 176.6 ± 10.0 cm, weight = 71.6 ± 10.8 kg) that volunteered after signing an informed consent. The experiments were performed in the lab on the University of Twente. Each of the participants was equipped with a wearable garment (Fig. 1) [15]. Before the garment was applied, the leg was thoroughly cleaned and, if necessary, shaved. Hereafter, the leg was sprayed with a water-salt solution to enhance contact and the functionality of the sEMG sensors. A ground electrode was attached to a bony area on the right lateral epicondyle. The garment was placed on the dominant lower leg for healthy subjects, and on the injured lower leg for the patients suffering from a lateral ankle sprain. The electromyographic signals (EMGs) were then sampled at 2048 Hz from 64 dry floating electrodes utilizing a multi-channel amplifier (REFA, TMSi, The Netherlands). In the lower leg the muscle activation of the muscles Gastrocnemius lateralis and medialis, Peroneus longus and brevis, Tibialis anterior and Soleus were measured.

Movement data of healthy subjects were captured at a rate of 128 Hz and at 100 Hz for the injured subjects, utilizing retroreflective markers positioned on the subject's bony landmarks and anatomical segments (Sartori et al., 2014), as tracked by twelve optical motion capture cameras (Qualisys Oqus, Sweden). This system recorded the positions of 33 retro-reflective markers to provide comprehensive movement analysis, while the tasks were performed atop two floor-

embedded force plates (Kistler 9286BA, Kistler, Winterthur, Switzerland). The combined data from the optical motion system and force plates provide information on parameters such as joint angles, torque, and muscle forces around the ankle.
To ensure the proper functioning of both the motion capture system and the calculation of inverse kinematics, it is essential to obtain the weight and height measurements of each subject. Detailed subject information can be found in Appendix A.

B. Requirements

Inclusion criteria are needed to determine if an individual is eligible to participate in this study. The inclusion criteria for the healthy participants of this study were:

- The subject is aged between 18 and 60 years old
- The subject is not injured elsewhere on the body
- The subject has signed an informed consent

For the patients that were tested, extra inclusion criteria were applied:

- The subject had a lateral ankle sprain
- The subject received physiotherapy on the above-mentioned injury at Topvorm Twente

Also, some exclusion criteria were included to determine when a subject was excluded from participation in this study:

- The subject did not agree and/or signed an informed consent
- The subject has or had an (other) injury in the lower extremities in the past year on the healthy leg or the now injured leg.

C. Experimental procedure

When a patient with a lateral ankle sprain arrives at the physiotherapist's office, the initial procedure involves assessing whether they meet the pre-established requirements (see II. B. Requirements). If eligible, the patient is then invited to participate in the study. Upon consenting, they are requested to sign an informed consent form.
During the rehabilitation process overseen by the physiotherapist, patients engage in various exercises aimed at strengthening the muscles and ligaments surrounding the injured ankle. These exercises, including side hops, box drops, and basic walking.
At specific intervals during their rehabilitation journey, patients undergo sEMG and musculoskeletal modeling assessments at the university. These assessments are scheduled around the fifth and tenth week of treatment to track their progress. During these assessments, patients perform exercises identical to those conducted during their physiotherapy sessions, to ensure they feel natural and mirror a typical physiotherapy session. In contrast, healthy subjects, serving as the control group, only undergo measurement procedures once and do not participate in physiotherapy sessions.
The flowchart detailing the activities and measurement times for both the healthy and injured groups can be found in Appendix B, while the specific execution details of the performed exercises are provided in Table I. Additionally, images of the exercises performed can be found in Figure 2, providing visual examples of each exercise. In Appendix C, you will find the patient information folder, which includes the complete experimental protocol.

TABLE I. LIST OF PERFORMED TASKS.

Task	***Trials***	***Repetition***	***Leg***
Static standing pose	2	5 sec.	Both
Walking (comfortable speed)	2	6 gait cycles	Both
Drop jump from box	2	6 jumps	Dominant Injured
Drop jump from box	2	6 jumps	Non-dominant Non-injured
Lateral jump (side hop)	2	6 jumps	Dominant Injured
Lateral jump (side hop)	2	6 jumps	Non-dominant Non-injured
Balancing on wobble board	2	5 sec.	Dominant Injured
Balancing on wobble board	2	5 sec.	Non-dominant Non-injured

D. Data processing

Signal processing of all the data was done in Matlab (Matlab R2019b, MathWorks, Natick (MA), USA).
The EMG garment utilized in our study comprised a network of 64 EMG electrodes, despite our focus being on only six specific muscles. Therefore, we had to accurately identify and isolate the electrodes that matched these muscles.
After the initial measurement session, the garment was gently removed from the subject's leg. Due to its snug fit, the electrodes left visible marks on the skin of the lower leg. To identify the electrodes associated with the targeted muscles, the

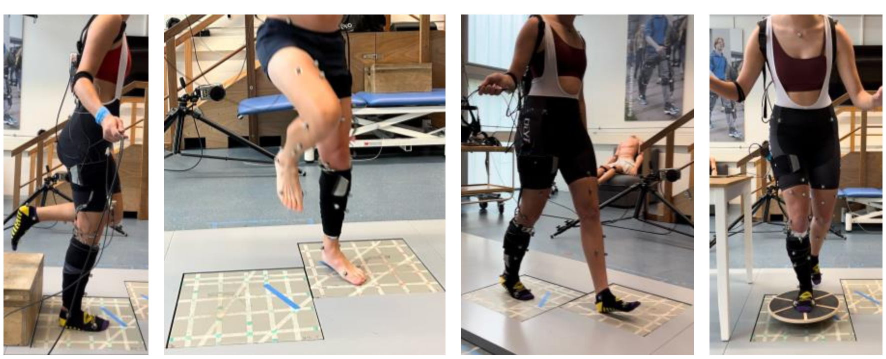


Fig. 2. *The performed exercises during the experiments: dropjump, side hop, walking and balancing on the wobble board.*

subject was instructed to contract those specific muscles. By observing the positioning of the electrodes relative to the muscle contractions, we identified the two electrodes situated above each muscle of interest. The EMG signals captured by these two electrodes were processed. This is a bipolar approximation derived from two monopolar channels, with the electrodes approximately aligned to the fiber orientation. We achieved this by subtracting the signals recorded by one electrode from the signals recorded by the other. This resulting signal, unique to each muscle, was then processed to derive linear envelopes. Initially, the re-referenced signals underwent high pass filtering at 20 Hz using a zero-lag 4th order Butterworth filter followed by full wave rectification. Subsequently, the rectified signals were subjected to a moving median filter, simulating the behavior of a low-pass filter with a 6 Hz cut-off frequency as described by Conforto et al. (1999). This filtering step effectively eliminated residual spikes attributed to movement artifacts. Normalization was then applied, wherein the resulting linear envelopes were normalized against the maximum observed linear envelope value across all tasks performed for each corresponding channel. The force plate data was subjected to moving average filtering and used for cutting the data into events, since each exercise had multiple repetitions. We processed filtered kinetic and kinematic data to derive joint kinematics and analyze muscle dynamics, including muscle activity and muscle tendon length. Utilizing the open-source software OpenSim 4.1 (Delp et al., 2007) and marker trajectories captured during a static task, we customized a generic musculoskeletal model (gait 2392) to fit the subject-specific musculoskeletal geometry. Subject-specific scaling was performed for each participant utilizing static recordings to tailor the musculoskeletal model. Subsequently, the data underwent automated processing in MATLAB BioMechPro software [16], where scaling, inverse kinematics (IK), and dynamics (ID) analyses were conducted for each exercise seamlessly. The program facilitates the generation of data such as joint angles and muscle-tendon lengths.

Before analyzing the data for muscle activity, joint angles, and muscle tendon length, it is segmented into repetitions for each subject. Table I indicates that each exercise comprises six repetitions, with the exception of the wobble exercise, which consisted of a single five-second repetition.
In the drop jump exercise, data segmentation relies on force plate data. The peak of the force plate data signifies the moment of landing, followed by a stabilizing phase and a subsequent smaller peak indicating the push-off. Segmentation begins one second before the peak to capture pre-jump muscle activation, as corroborated by existing literature [17]. The endpoint of each segmented repetition aligns with the stabilizing phase.
In the side hop exercise, force plate data is integrated with pelvis marker data to outline distinct phases: loading, jumping, and stabilizing. Segmentation occurs immediately preceding the loading phase and immediately following the landing phase.
In the walking exercise, the positioning of the calcaneus marker is synchronized with the force plate data analysis. Each leg is analyzed separately. The subject traverses the walkway six times, crossing over the force plates from one side to the other, without returning. This ensures that the subject initiates contact with the right force plate using their right leg first, followed by the left force plate with their left leg. Segmentation begins when the calcaneus marker aligns with the force plate data and concludes when the calcaneus marker reaches its lowest point.
In the wobble exercise, segmentation relies on force plate data. A peak is observed in the force plate data when the subject steps onto it, followed by a decrease when they step off. The endpoint is identified by a decrease in force below a unique threshold for each subject. The starting point is set five seconds before this endpoint to encompass the balance maintenance period during the exercise.

E. *Assessment metrics*

Following the processing of the EMG data, the average EMG envelope per repetition per exercise is computed for each of the six muscles. Subsequently, the area under the curve (AUC) of these mean EMG envelopes signals is calculated, serving as an indicator of muscle activity. However, the AUC is not computed for the wobble exercise due to the inherently fluctuating nature of the EMG envelope signal caused by the balancing task. Instead, for this exercise, the focus shifts to analyzing signal variability. Consequently, the coefficient of variation (CoV) is determined for each subject and muscle, providing insights into the signal fluctuation. The CoV is computed using the following formula (1):

$$CoV = \frac{Standard\ Deviation}{Mean} * 100\% \tag{1}$$

With the mean value of the EMG envelope and the corresponding standard deviation.

Following the generation of inverse kinematics (IK) files by the BioMechPro program, these files are utilized to compute joint angles. Specifically, the focus is on ankle and knee angles, which are analyzed per exercise repetition, subject, and exercise. For healthy participants, the angles are categorized into dominant and non-dominant ankle and knee angles, whereas for injured subjects, the distinction is made between injured and non-injured ankle and knee angles. Subsequently, the mean angle across events is calculated, providing an average knee and ankle angle over time for each exercise and subject. Comparisons are then made between knee angles (dominant vs. non-dominant, injured vs. non-injured, dominant vs. injured and non-dominant vs. non-injured) and ankle angles accordingly. However, for the wobble exercise, due to the considerable variation in angles between subjects caused by the free nature of the task, a different approach is adopted. Here, the focus shifts back to analyzing the coefficient of variation (CoV) to assess signal variability.

The final parameter analyzed is the muscle tendon length, employing a similar methodology as with the joint angles. The Muscle tendon length is derived using OpenSim. By integrating muscle-tendon actuators and applying inverse kinematics (IK) to ascertain joint angles, OpenSim calculates the length changes of individual muscles during movement tasks on force plates. The mean muscle tendon length is computed per muscle and per leg (dominant, non-dominant, injured, and non-injured) for the drop jump, side hop, and walking exercises. For the wobble exercise, the focus again shifts to assessing the coefficient of variation (CoV) due to the dynamic and fluctuating nature of the task.

Comparisons between healthy and injured subjects were done using Mann-Whitney U test for muscle activation, joint angles, and muscle tendon length during motor tasks. This comparison aims to identify differences in these parameters between healthy individuals and those with lateral ankle injuries, providing insights into the impact of injury on neuromuscular and musculoskeletal function.
Additionally, we employ the Kruskal-Wallis test to compare measurements taken at two time points for injured subjects. This test aims to assess whether there is a statistically significant improvement in muscle activity, joint angles, and muscle tendon length over the course of rehabilitation. Understanding these longitudinal changes is essential for evaluating progress towards RTP and informing rehabilitation strategies.
Lastly, we perform within-group comparisons using the Wilcoxon signed-rank test to analyze muscle activation and cross correlations for joint angles, and muscle tendon length in both healthy and injured subjects. This comparison aims to evaluate the reliability and consistency of musculoskeletal modeling and sEMG measurements within each group. Additionally, between-group comparisons using the Mann-Whitney U test can further assess differences between healthy and injured subjects. These statistical analyses help determine the potential utility of these techniques in identifying differences between patient groups and guiding rehabilitation strategies.

III. RESULTS

In this study, we investigate the potential of musculoskeletal modeling and sEMG data in assessing RTP in patients with lateral ankle sprain. We analyze joint angles, muscle activation, and muscle-tendon lengths to identify key factors influencing functional recovery and RTP readiness.

A. Joint angles

Utilizing force plates, OpenSim, and musculoskeletal modeling, we computed the joint angles of each subject. Since we are analyzing ankle injuries, we examine ankle angles. However, since knee angles can also influence ankle angles, we include them in our analysis. In the healthy subject cohort, we compared knee and ankle angles between the dominant and non-dominant legs across various exercises. Similarly, in the injured subject group, we compared knee and ankle angles between the injured and non-injured legs. Additionally, cross-correlation analysis was performed to assess differences in knee and ankle angles during drop jump, side hop, and walking exercises.
Significant differences were observed in ankle angles between healthy and injured subject groups during side hop exercises, and in knee angles during drop jump and walking exercises. Notably, no significant disparities were found in ankle angles between dominant and non-dominant legs among healthy subjects, while significant differences were evident within the injured subject cohort during the walking exercise ($p < 0.05$). Furthermore, comparison between healthy and injured subject groups revealed notable differences in ankle and knee angles, particularly evident during the drop jump exercise. These differences are visually represented in Figure 3.
The wobble exercise prompted an examination of CoV values, revealing a significant difference in ankle angles between the injured and non-injured legs within the injured subject group ($p < 0.05$). Furthermore, when comparing the injured ankle angles to those of the dominant and non-dominant legs in the healthy subject group, significant differences were also observed. These findings are illustrated in Figure 4. Additionally, there were no significant differences detected in any of the exercises between the initial and subsequent measurements within the injured subject group.

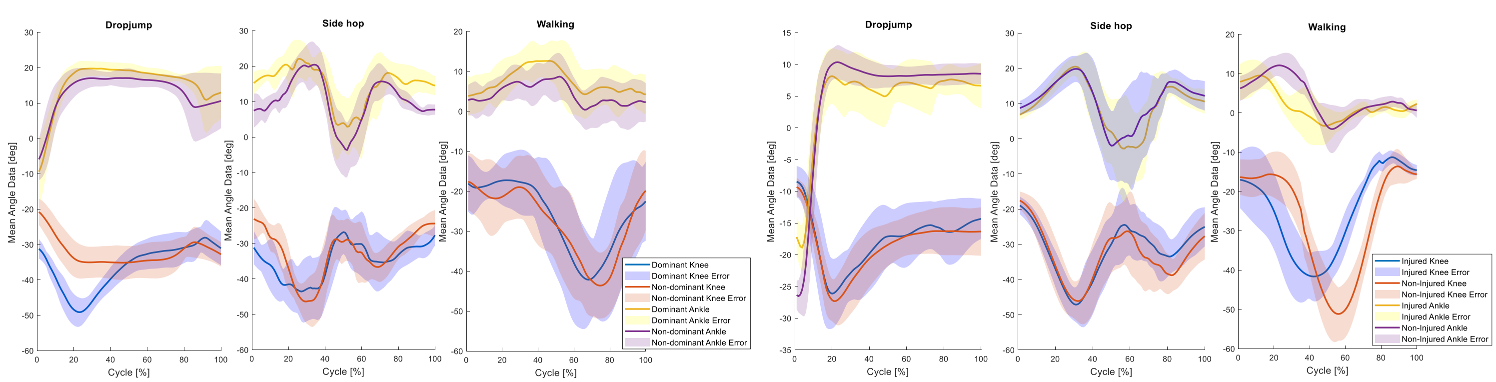


Fig. 3. Mean joint angles over time of the dominant/injured knee (blue), non-dominant/non-injured knee (orange), dominant/injured ankle (yellow) and non-dominant/non-injured ankle (purple), including the standard deviation as corresponding shaded error bar, for the exercises; dropjump, side hop and walking.

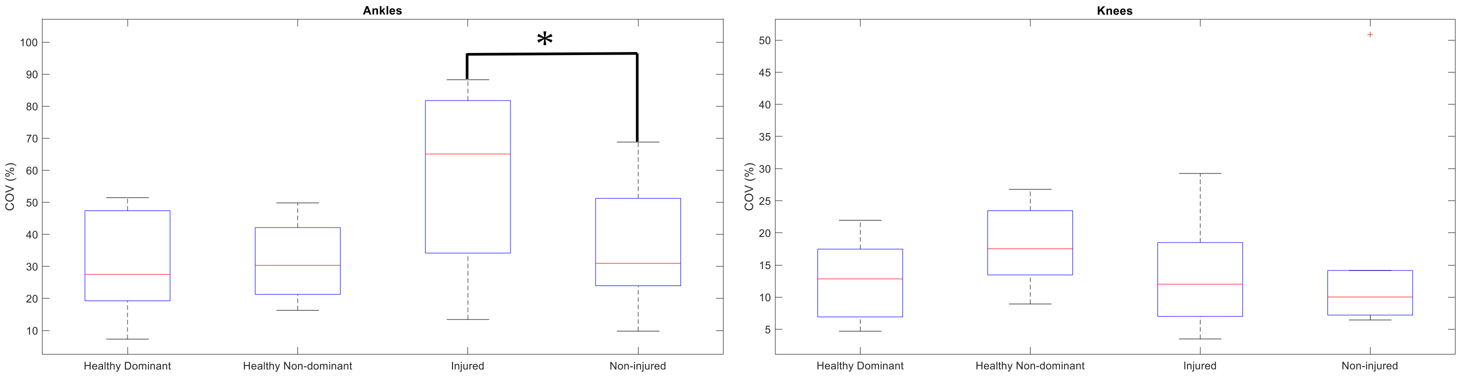


Fig. 4. *Boxplots of the CoV values of the ankle angles (left) and knee angles (right) during the wobble exercise. For the dominant and non-dominant leg of the healthy subjects and the injured and non-injured leg of the injured subjects. With * significant difference with $p < 0.05$.*

B. Muscle activity

In line with our objectives, we evaluated muscle activity using sEMG measurements on the dominant leg for healthy subjects and the injured leg for patients with a lateral ankle injury. The sEMG garment was employed to measure the electrical activity in the muscles Tibialis anterior, Peroneus brevis, Peroneus longus, Gastrocnemius medialis, Gastrocnemius lateralis, and Soleus. Muscle activation was assessed by analyzing the AUC for each EMG recording. The AUC values per muscle and per exercise are illustrated in the boxplots in Fig. 5.
Statistical analysis revealed significant differences between the healthy and injured subject groups for each muscle ($p < 0.05$). Additionally, significant differences were observed in the AUC values of the exercises between the injured and healthy groups, indicating variations in muscle activation patterns during specific tasks.
For the wobble exercise, no significant differences were found between the CoV of the healthy and injured muscles, indicating similar variability in muscle activation between the two groups. However, within the injured group, significant differences ($p < 0.05$) were detected between the first and second measurement moments for all exercises, suggesting changes in muscle activation over the course of rehabilitation. Further details and graphical representations of these findings are provided in Fig. 6.

C. Muscle tendon length

Following the scaling and inverse kinematics procedures applied to the generic model for each subject, muscle tendon lengths were calculated for both legs. Cross-correlation analysis was conducted between the dominant and non-dominant legs in healthy subjects, and between the injured and non-injured legs in the injured subject group, across six muscles: Tibialis anterior, Peroneus brevis, Peroneus longus, Gastrocnemius medialis, Gastrocnemius lateralis, and Soleus. Additionally, comparisons were made between the healthy and injured subject groups.
Significant differences ($p < 0.05$) were observed between the dominant and non-dominant legs in healthy subjects for Tibialis anterior. Similarly, within the injured subject group, significant differences ($p < 0.05$) were noted between the injured and non-injured legs for both Tibialis anterior and Gastrocnemius medialis. In Fig.7. the mean muscle tendon length across all subjects, per muscle and per exercise is given.
Furthermore, for the wobble exercise, we examined CoV values. Our results revealed a significant difference between the two subject groups for Tibialis anterior ($p < 0.05$), as well as for Peroneus brevis between the dominant and injured legs. These findings are visually represented in Fig. 8. Notably, there were no significant differences observed between the initial and subsequent measurements within the injured subject group across the jumping and wobble exercises. However, a notable difference emerged during the walking exercise.

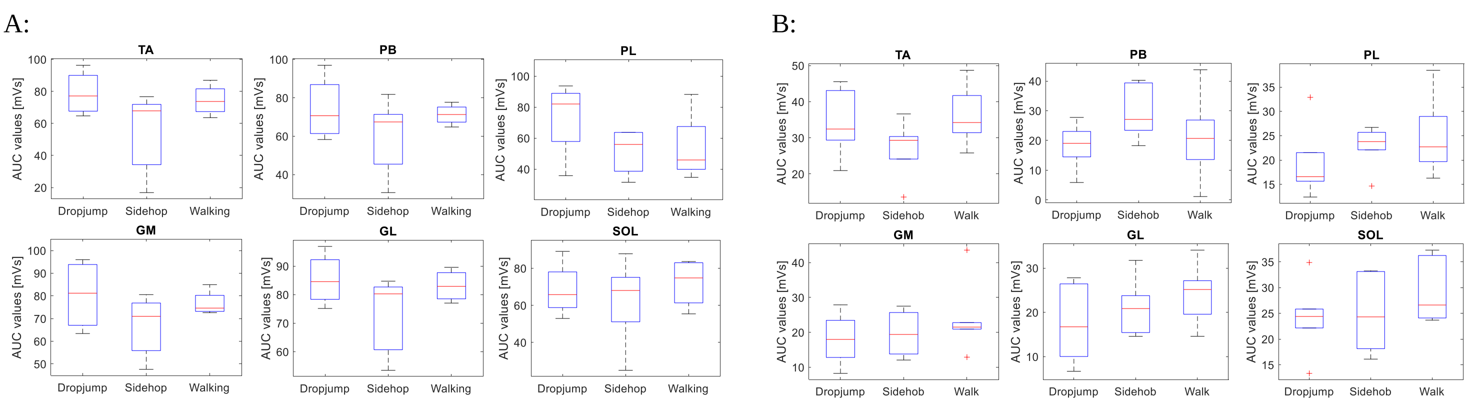


Fig. 5. *Boxplots of the muscle activity of the healthy subjects (A) and the injured subjects (B) of the exercises; dropjump, side hop and walking. Categorized by muscle; Tibialis anterior (TA), Peroneus brevis (PB), Peroneus longus (PL), Gastrocnemius medialis (GM), Gastrocnemius lateralis (GL) and Soleus (SOL).*

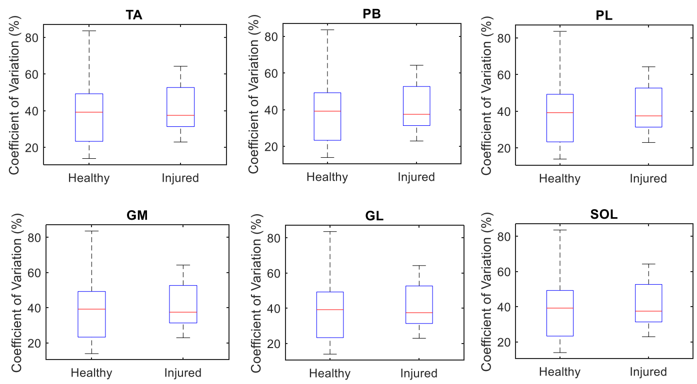
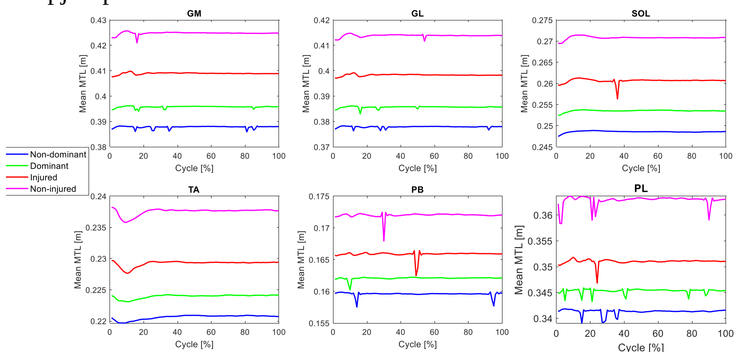
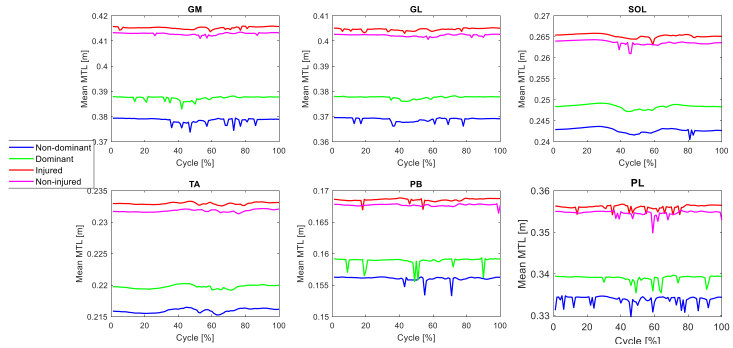


Fig. 6. *Boxplot of CoV values for the muscles activity during the wobble exercise for the muscles: Tibialis anterior (TA), Peroneus brevis (PB), Peroneus longus (PL), Gastrocnemius medialis (GM), Gastrocnemius lateralis (GL) and Soleus (SOL). Comparing healthy and injured subjects.*

Dropjump:



Side hop:



Walking:

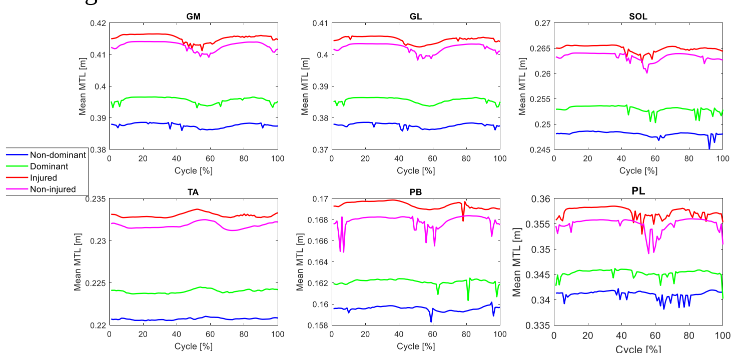


Fig. 7. *Mean muscle tendon lengths [m] during the exercises dropjump, side hop and walking per muscle: Tibialis anterior (TA), Peroneus brevis (PB), Peroneus longus (PL), Gastrocnemius medialis (GM), Gastrocnemius lateralis (GL) and Soleus (SOL). Comparing dominant and non-dominant leg from healthy subjects, injured and non-injured leg from injured subjects.*

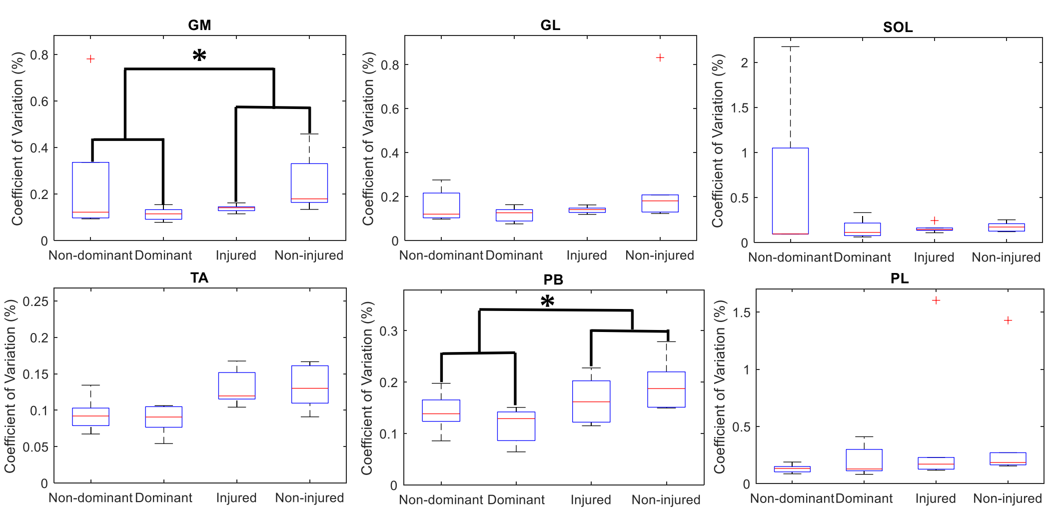


Fig. 8. *Boxplot of CoV values for the muscle tendon length during wobble exercise per muscle: Tibialis anterior (TA), Peroneus brevis (PB), Peroneus longus (PL), Gastrocnemius medialis (GM), Gastrocnemius lateralis (GL) and Soleus (SOL).. Comparing the dominant and non-dominant leg of the healthy subjects with the injured and non-injured leg from the injured subjects. With * significant difference with $p < 0.05$.*

IV. Discussion

In this study, we evaluated the effectiveness of musculoskeletal modeling and sEMG data in assessing lateral ankle injuries and guiding rehabilitation. Our primary objective was to compare muscle activity, joint angles, and muscle-tendon length between healthy individuals and those with lateral ankle injuries during various motor tasks. Additionally, we analyzed longitudinal changes in these parameters throughout the rehabilitation process to track progress towards RTP.

Throughout the experiments and joint angle visualization, it became evident that the injured leg displayed greater stiffness, leading to reduced knee flexion compared to the non-injured leg, consistent with findings in literature [18]. The observation of greater stiffness in the injured ankle was particularly evident during activities such as the drop jump exercise. Limited ankle dorsiflexion compelled the patient to readjust their leg before being able to step up onto the box again for the drop jump exercise. The differences in ankle and knee joint angles can be seen in Fig.3. Conversely, healthy participants exhibited increased flexibility and stability in both knee and ankle joints during post-jump balancing tasks, such as the drop jump and side hop exercises. However, individuals with injured legs faced challenges in maintaining balance during the wobble exercise. Future research could explore this stiffness through calibrated EMG-driven models.

Comparison between healthy and injured subject groups revealed significant differences in ankle angles during side hop exercises and in knee angles during drop jump and walking exercises. Within the injured subject group, differences were also observed between the injured and non-injured legs for joint angles and muscle tendon length. Additionally, variations in muscle activity were noted between the healthy and injured subject groups across all exercises and muscles. These results are clarified by the feedback provided by injured patients about their experience during the experiment. Patients indicated that they relied more on their non-injured leg during specific movements. For instance, during the drop jump exercise, patients tended to exert force primarily through their non-injured leg when stepping back onto the box. Conversely, when landing on their non-injured leg, patients predominantly utilized this leg to propel themselves back onto the box. Analysis of muscle activity during the drop jump, side hop, and wobble exercises revealed lower CoV values and AUC values for injured patients compared to healthy subjects. This suggests reduced muscle activity in the injured group across these exercises. However, for the walking exercise, significant variations were observed between healthy and injured subjects, potentially due to individual differences in walking mechanics and gait patterns.

The wobble exercise, performed on a wobble board, challenges balance and stability. In analyzing this exercise, attention is directed towards variations in angles, EMG activity, and muscle tendon length, quantified by the CoV. The inherent balancing aspect of the task was apparent from the observed fluctuations in joint angles and muscle tendon lengths, reflecting the dynamic nature of the task. The notable disparities observed between the injured and non-injured ankles, as well as between healthy and injured groups, are logically explicable. Individuals with lateral ankle injuries encountered difficulties maintaining balance on the wobble board, while healthy participants generally found the exercise less challenging. Comparing our findings with existing literature, our observations align with previous research indicating that balance exercises performed on unstable surfaces significantly increase ankle kinematics and muscle activity compared to stable surfaces [19]. Specifically, our study reveals greater average muscle activation levels during the wobble exercise, consistent with higher angular excursions and stability demands on unstable surfaces. This correlation underscores the importance of incorporating balance exercises, particularly those utilizing unstable surfaces like the wobble board, in rehabilitation programs for individuals with lateral ankle injuries.

Injured patients underwent measurements approximately six and ten weeks into their rehabilitation under the supervision of a physiotherapist. However, no significant differences were observed between the joint angles and muscle tendon lengths measured at the two time points for the jumping and wobble exercises. This absence of noticeable difference may be attributed to the short interval between measurements, which may not allow sufficient time for noticeable improvements in ankle and knee function. Literature suggests that it typically takes around six weeks post-injury to see improvements in joint proprioception, mobilization, and motor control [20]. Conversely, significant differences were observed in the CoV values of the EMG signals between the first and second measurement moments. This discrepancy may be attributed to the potential improvement in muscular strength and endurance, facilitated by physiotherapy, during the two to six weeks post-injury period [21]. This aligns with literature, indicating that exercise-induced changes are faster at the neural/muscular level than at the joint level [21]. Highlighting this aspect further emphasizes the dynamic nature of muscular adaptation and its rapid response to rehabilitation interventions.

Additionally, significant differences were observed between the first and second measurements for the injured subject group specifically during the walking exercise, particularly in muscle tendon length. This finding suggests a dynamic response to rehabilitation interventions during weight-bearing activities like walking, which may contribute to improved recovery and stimulate stronger healing of the injured ligaments and tendons [22].

The original plan was to conduct three measurements on the injured subjects, approximately in the second, fifth, and tenth weeks post-injury. However, due to time constraints, only two measurements were carried out during the 6th and 10th weeks of rehabilitation. Additionally, it was initially intended for the physiotherapist to be present during the first measurement session to assess the patients' ability to jump, as outlined in the information folder provided in Appendix C. However, since there was no first measurement in the second week, this assessment was deemed unnecessary. Instead, the physiotherapist was contacted for the initial measurement session (after approximately six weeks of physiotherapy) and instructed to monitor the patients during the experiment.

Healthy subjects 2 and 3 did not have force data due to technical issues with the force plates, which were discovered after the experiment had concluded. Consequently, these subjects were only considered for EMG measurements and subsequent tests. Furthermore, there was no EMG recorded for the wobble board exercise for healthy subject 4. This was due to depleted batteries in the garment, and the time required to recharge them and repeat the exercise within the allotted timeframe.

While our study utilized a single garment for data collection, future investigations could enhance the fidelity of the analysis by incorporating two garments. This would facilitate a more comprehensive comparison between the dominant and non-dominant legs, as well as the injured and non-injured limbs. Furthermore, The reliance on lab-based camera systems and force plates restricts the mobility of participants and limits data collection to controlled laboratory environments. To address these limitations, future research endeavors will prioritize the integration of fully wearable sensors into the experimental setup. Using fully wearable sensors can help us monitor muscle activity and joint movements more conveniently and continuously, even in everyday settings. This shift holds potential for making our research more relevant to real-life situations and applying it directly in physiotherapy practices.
Additionally, given more time, a larger sample size could be tested. Furthermore, patients could undergo follow-up assessments at later time points to capture potential improvements over time, as the current four-week interval between measurements may be insufficient to observe significant changes.
Lastly, future studies will explore the application of EMG-driven musculoskeletal modeling for determining return-to-play (RTP) in patients with lateral ankle sprains. Following calibration, personalized EMG-driven musculoskeletal models can estimate joint torques (ankle and knee) using input joint angles and normalized EMG signals during novel trials.

V. Conclusion

Joint angles offer a straightforward and easily computable metric, providing valuable insights into movement patterns. However, our findings indicate that they may not be sensitive enough to capture subtle changes over time, as evidenced by the lack of significant differences between the first and second measurements. This limitation undermines their utility in reliably tracking progress towards return to play (RTP). Conversely, muscle activity profiles exhibited discernible differences between initial and subsequent measurements, suggesting their potential as informative parameters for RTP assessment. Yet, it's important to acknowledge that factors such as noise and individual variability, including training status, can confound the interpretation of muscle activity data. Moreover, while muscle tendon lengths also displayed differences between the first and second measurements, their noisy signal and more complex computational requirements pose challenges for drawing conclusive interpretations. Despite these challenges, integrating both joint angles and muscle activity profiles in RTP decision-making may provide a more comprehensive assessment of functional recovery and readiness for return to play. Moving forward, it is recommended to further explore the implementation of musculoskeletal modeling in clinical practice to enhance RTP decision-making processes. Continued research in this area may lead to the development of standardized protocols and guidelines for integrating musculoskeletal models into physiotherapy practice. Ultimately, the integration of musculoskeletal modeling into clinical workflows has the potential to optimize patient outcomes and facilitate the rehabilitation process for individuals recovering from musculoskeletal injuries.

Declaration of Competing interest

The authors declare that there are no competing interests associated with this publication. No significant financial support was received for this work that could have influenced its outcome.

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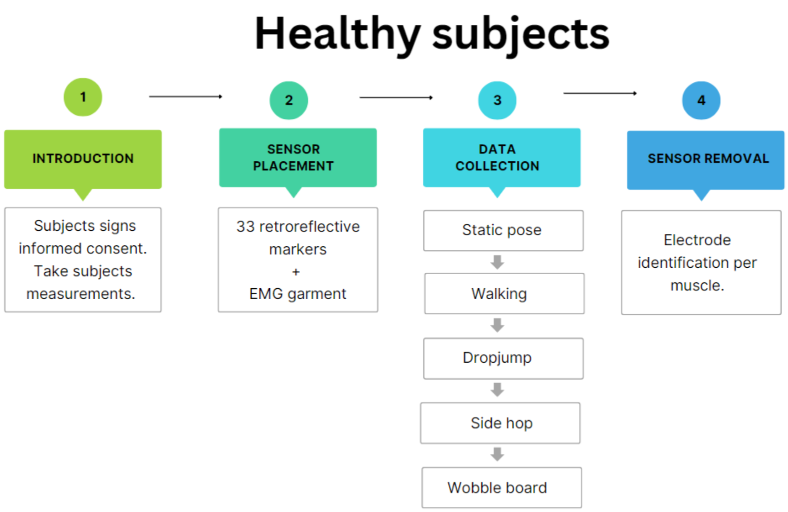
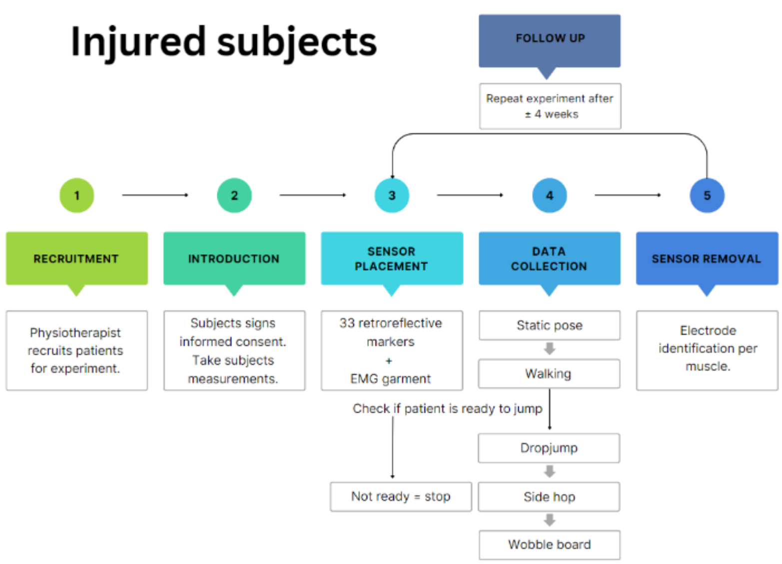
VI. Appendix

A. Table with subject information

Subject	*Gender*	*Height [cm]*	*Weight [kg]*	*Injured/ Dominant leg*	*Non-injured/ Non-dominant leg*	*Time of injury till measurement 1*	*Time of injury till measurement 2*
Sub01	Female	161	58	Right	Left	N/A	N/A
Sub02	Female	164	51	Right	Left	N/A	N/A
Sub03	Female	164	65	Right	Left	N/A	N/A
Sub04	Male	184	88	Right	Left	N/A	N/A
Sub05	Female	178	73	Right	Left	N/A	N/A
Sub06	Male	182	76	Left	Right	N/A	N/A
Sub07	Female	177	66	Right	Left	N/A	N/A
Sub08	Male	180	77	Right	Left	N/A	N/A
Injured sub09	Male	175	74	Left	Right	5 weeks	9 weeks
Injured sub10	Male	193	78	Left	Right	6 weeks	11 weeks
Injured sub11	Male	185	82	Right	Left	5 weeks	9 weeks

B. Flowchart of activeties and measurement times for healthy and injured subject groups





C. Information folder for participants including complete experimental protocol

Subject information for participation in medical research EMG as a support for physiotherapy

"Investigating the role of an EMG- driven musculoskeletal model in determining Return-To-Play in patients with lateral ankle sprain by physiotherapists"

Introduction

Dear Sir/Madam,

With this letter, we would like to ask you to take part in a medical study. Participation is voluntary. You have received this letter because the physiotherapist has found you have a lateral ankle sprain or because you are a healthy individual that will participate as control subject. You can read about the medical study in this information sheet, what it means for you, and what the pros and cons are. It is a lot of information. Please take your time to read this information and ask the investigator if you have any questions. You can also ask the independent expert mentioned at the end of this letter for additional information. You can also discuss it with your partner, friends, or family. If you want to take part in this study, please complete the form in Appendix D.

1. General information

This study is conducted by the University of Twente and the physiotherapists of Topvorm Twente. A total of about fifteen subjects (5 with a lateral ankle sprain, 10 healthy subjects) are expected to participate.

2. Background of the study

Ankle injuries are a common injury seen in physiotherapy. The current way a physiotherapist determines if a patient is ready to play, is by assessing different factors like a gait analysis (an analysis of the walking pattern of the patient), functional test such as jumping and running, the level of swelling of the ankle or the pain a patient feels. Despite this assessment, there is still a large amount of patients who reinjure the same ankle within a year. To see if this assessment can be objectified, the experiments will collect electromyography (EMG) and inertial measurement unit (IMU) data of the patients during the normal assessment of the physiotherapist. This data will be used to create a computer model that can calculate different forces on the joints and muscles, which can be used by the physiotherapist as an objective measurement value.

3. Purpose of this study

In this study we will look at the signals from EMG sensors, i.e. sensors that can measure muscle activation. Together with IMUs we are able to record motion. The recorded motion with EMG and IMUs can be combined and displayed with the help of musculoskeletal modelling and this model is used to calculate for example muscle forces. Muscle forces is a direct estimate of the muscles' strength, which is an important assessment measure for the physiotherapist. The recorded and computed information can be used to get metric parameters that can be used to assess if the patient is ready to go back to the sport they are practicing. This is also called "Return-To-Play".

4. What happens during the study?

How long will the study take?

For the study, you will have to visit the biomechanics lab at the University of Twente three times. One time at the beginning of your treatment, once in the middle of your physiotherapy treatment and once during the last physiotherapy session. The first experiment will take about 40 minutes and the other two experiments will take about 50 minutes. This includes the setting up of the measurement systems. Three months after the last session we will also send you a questionnaire with questions about the injury.

For healthy participants, who will be participating as a control subject, you only have to come to the biomechanics lab at the University of Twente once.

Step 1: are you eligible to take part?

The physiotherapist will assess your injury. If you are suited for the research, the physiotherapist will ask if you are interested to participate in this research.

Please note, it is possible that you are not eligible for this study, even if you are healthy. The investigator will tell you more about this.

Before the second measurement moment, the physiotherapist will evaluate if you are eligible to continue. This is because there are jumps involved in the second and third measurement moment. If you are not able to perform jumps, the experiment will be postponed until the physiotherapist decides it is safe enough to continue.

Step 2: the experiment

In appendix B you can find the experimental protocol. As mentioned before, there will be three measurement moments. This will be approximately in week 2, 5 and 8 of the treatment with the physiotherapist.

Step 3: the treatment

Your physiotherapy treatment will stay exactly the same. The only difference is that you will be wearing the EMG sensors and some IMU's during three of your treatments. These will not interfere in the way your treatment will go.

What is the difference with standard care?

This study is not different from standard care.

5. Agreements

We want the study to go well. That is why we want to make the following agreements with you:

- You go to every physiotherapy appointment
- You should contact the investigator in these situations:
  1. You no longer want to take part in the study
  2. Your telephone number, address, or email address changes

6. What side effects, adverse effects or discomforts could you experience?

There will be no impactful side effects besides some light skin rashes from the EMG and IMU sensors. If your skin is hairy we will need to shave (parts of) your lower leg. This will always be done in consultation with you and only done if strictly necessarily.

7. Pros and cons of taking part in this study

You will not directly benefit from participating in this study. You will contribute to the research that could possibly help to objectify parts of physiotherapy. This way, we hope to improve the assessment methods of physiotherapist in the future.

In the unlikely case that we find irregularities in your measured data, your physiotherapist, and an independent physician will be consulted. If they consider that the findings need more attention, your general practitioner will be informed of the findings. Logically, you will also be informed and your general practitioner will then discuss your best options with you. However, please note that the purpose of the data recordings in this study is not to find irregularities

8. When does the study end?

The investigator will let you know if there is any new information about the study that could be important to you. The investigator will then ask you if you want to continue to take part.

In the following situations, the study will stop for you:

- All checks according to the schedule are finished
- The end of the whole study has been reached
- You want to stop participating in the study yourself. You can stop at any time. Report this to the investigator immediately. You do not have to explain why you want to stop. Your standard treatment will continue with the physiotherapist as normal but now without the EMG and IMU sensors. The investigator will still invite you to fill in a follow-up questionnaire
- The investigator or the physiotherapist thinks it is better for you to stop. The investigator will still invite you to fill in a follow-up questionnaire
- One of the following authorities decides that the study should stop:
  - A supervisor of the BME faculty of the University of Twente
  - the government, or
  - the Medical Ethics Review Committee assessing the study.

What happens if you stop participating in the study?

The investigators will still use the data that have been collected up to the moment that you decide to stop participating in the study.

9. What happens after the study has ended?

About six months after you took part in the study, the investigator will inform you about the most important results of the study if you are interested. Please let the investigator know if you are interested in this information.

10. What will be done whit your data?

Are you taking part in the study? Then you also give your consent to collect, use and store your data.

We will store the following data:

- Your patient number
- Gender
- Weight
- Date of birth
- Information about your health
- EMG and IMU data we collect the study
- Distances between body landmarks

Why do we collect, use and store your data?

We collect, use, and store your data to answer the questions of this study. With the help of your data we will be able to publish results and inform physiotherapists. To properly scale the computer model, we need your weight, gender and distance between body landmarks.

How do we protect your privacy?
To protect your privacy, we give a code to you. We only put this code on your data. We keep the key to the code in a safe place in the University of Twente. When we process your data and body material, we will only use that specific code. Even in reports and publications about the study, nobody will be able to see that it was about you.

Who can see your data?
Some people can see your name and other personal information without a code. These are people checking whether the investigators are carrying out the study properly and reliably. The following persons can access your data:

- Members of the committee that keeps an eye on the safety of the study
- Supervisors of the investigator from the BME faculty

These people will keep your information confidential. We ask you to give permission for this access.

For how long do we store your data and body material?
We store your data in the University of Twente for 1 year.

Can you take back your consent for the use of your data?
You can take back your consent for the use of your data at any time. But please note: if you take back your consent, and the investigators have already collected data for research, they are still allowed to use this information.

Do you want to know more about your privacy?
For general information about your rights concerning the processing of your personal data, please consult the website of the Dutch Data Protection Authority: https://autoriteitpersoonsgegevens.nl/en. If you have any questions or complaints regarding the processing of your personal information, we recommend that you contact the study site. You can also contact the Data Protection Officer for the institution (M. Davids, see contact details in Appendix A) or the Dutch Data Protection Authority.

11. Are you insured during the study?
The University of Twente has a liability insurance. Because this study imposes no additional risks, the Medical Ethics Review Committee of the region Arnhem-Nijmegen (who approved this study) has decided that it is not necessary for the University of Twente to take out a supplementary insurance for the study.

12. Do you have any further questions?
You can ask the physiotherapist who is treating you questions about the study. Also the investigator and/or the supervisor can be asked questions at any time.
If you would like to get advice from someone who is independent from the study, you can contact Jaap Buurke. He knows a lot about the study, but is not a part of this study.
If you have any complaints regarding this study, you can discuss it with the investigator or the physiotherapist who is treating you. If you prefer not to do so, please visit the "Complaints, Clinical Research Coordinator". Appendix A tells you where to find this.

13. How do you give consent for the study?
The first step is to carefully think and evaluate this study yourself. Hereafter, you can inform the investigator if you understand the information and if you want to take part or not. If you want to take part in this study, fill in the consent form that you can find with this information sheet. You and the investigator will both get a signed version of this consent form.

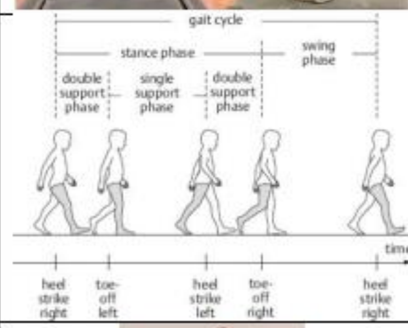
Should you need any further information, please do not hesitate to contact me.
Thank you for your attention.

Isabella Waaijer
i.j.waaijer@student.utwente.nl

Appendix B: experimental protocol

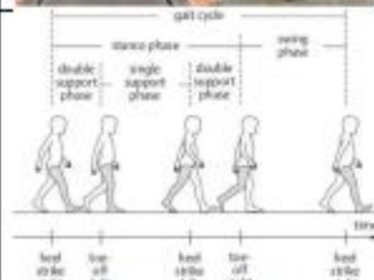
Week 2

In approximately week 2 of the treatment with the physiotherapist the first experiment will take place. In the following scheme the exercises and duration of this experiment can be found.
This scheme is not applicable for the healthy subjects.

Movement	**Repetitions**	**Duration**	**Example**	**Set up/rest**
Static pose	1 x 10 sec.	10 sec.		30 minutes
Walking	2 x 6 gait cycles (normal speed) 2 x 6 gait cycles (faster speed)	± 2 min.		5 minutes
Wobble board	2 x 5 sec. (injured leg) 2 x 5 sec. (healthy leg)	20 sec.		5 minutes
Total		*2 min. 30 sec.*		*40 minutes.*

Week 5 and week 8

In approximately week 5 and week 8 of the treatment with the physiotherapist, the second and third experiment will take place. As mentioned before, the physiotherapist will evaluate if the patient is ready to perform jumping movements before continuing with these experiments. In the following scheme the exercises and duration of this experiment can be found.
The exercises in the scheme below are also applicable for the healthy subjects.

Movement	**Repetitions**	**Duration**	**Example**	**Set up/rest**
Static pose	1 x 10 sec.	10 sec.		30 minutes
Walking	2 x 6 gait cycles (normal speed)	± 60 sec.		5 minutes
Wobble board	2 x 5 sec. (injured leg) 2 x 5 sec. (healthy leg)	20 sec.		5 minutes
Drop jump	2 x 6 jumps (injured leg) 2 x 6 jumps (healthy leg)	2 min.	 Dropping and landing on 1 leg from a 30 cm height box	5 minutes
Side hob	2 x 6 hobs (injured leg) 2 x 6 hobs (healthy leg)	2 min.	 Jumping 30 cm side ways	5 minutes
Total		*5 min. 30 sec.*		*50 minutes.*

Appendix C: information about the insurance

The university of Twente has taken out insurance for everyone who takes part in the study. The insurance pays for the damage you have suffered because you participated in the study. This concerns damage you suffer during the study or within 4 years after the study has ended. You must report damage to the insurer within 4 years.

Have you suffered damage as a result of the study? Please report this to this insurer:

The insurer of the study is:
Name: …
Address: …
Telephone number: …
Email: …
(Policy number: …)
(Contact person: …)

< include only if there is a claims representative – this is compulsory if the insurer is established outside the Netherlands>
The claims representative of the study is:
Name: …
Address: …
Email:
Telephone number: …

The insurance pays a maximum of *<amount to be copied from policy, this must be at least €650,000 >* per person and *<amount to be copied from policy, this must be at least €5,000,000>* for the entire study (and *<amount to be copied from policy, this must be at least € 7,500,000>* per year for all studies by the same sponsor).

Please note that the insurance does not cover the following damage:

- Damage due to a risk about which we have given you information in this sheet. But this does not apply if the risk turned out to be greater than we previously thought. Or if the risk was very unlikely.
- Damage to your health that would also have happened if you had not taken part in the study.
- Damage that happens because you did not follow directions or instructions or did not follow them properly.
- Damage caused by a treatment method that already exists. Or by research into a treatment method that already exists.

These provisions can be found in the 'Besluit verplichte verzekering bij medischwetenschappelijk onderzoek met mensen 2015' ('Medical Research (Human Subjects) Compulsory Insurance Decree 2015'). This decision can be found in the Government Law Gazette (https://wetten.overheid.nl).

Appendix D: informed consent form – subject

Belonging to
EMG as a support for physiotherapy

- I have read the information sheet. I was able to ask questions. My questions have been answered well enough. I had enough time to decide if I wanted to take part
- I know that taking part is voluntary. I also know that at any time I can decide not to take part in the study. Or to stop taking part. I do not have to explain why
- I give the investigator consent to inform my physiotherapist that I am taking part in this study
- I give consent to give my doctor or specialist information about accidental discoveries made during the study that are important for my health
- I give consent to collect and use my data. The investigators only do this to answer the question of this study
- I know that some people will be able to see all of my data to review the study. These people are mentioned in this information sheet. I give consent to let them see my data for this review
- I want to take part in this study
- Please tick yes or no in the table below

I give consent to ask me after this study if I want to participate in a follow-up study.	Yes ☐	No☐

My name is (subject): ………………………………….
Signature: ……………………… Date : __/__/__

I declare that I have fully informed this subject about the study mentioned.

If any information becomes known during the study that could influence the subject's consent, I will let this subject know in good time.

Investigator name (or their representative): ……………………
Signature:……………………… Date: __/__/__

The study subject will receive a complete information sheet, together with a signed version of the consent form.