EMG as a support tool for physiotherapy

Investigating the role of EMG in determining Return-To-Sports in patients with lateral ankle sprain by physiotherapists

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Abstract

Electromyography (EMG), particularly surface electromyography (sEMG), has the potential to revolutionize modern physiotherapy by providing a non-invasive means to measure muscle activation. This study focuses on using sEMG's potential to enhance the objectivity and effectiveness of return-to-sports assessments in the context of lateral ankle sprains. It also explores baseline left-right differences in muscular activation among healthy individuals to establish a normative range.

Observing three patients during their rehabilitation for lateral ankle sprains, this research combined sEMG measurements and kinematic assessments to monitor muscle activation. A control group of six healthy subjects was included for baseline comparisons. Measurements were taken during the middle and final stages of treatment, with follow-up assessments four weeks later.

Among the key findings, Root Mean Square Error (RMSE) emerged as a promising metric for injury detection and recovery assessment. The Consistency of muscle activation patterns between injured and non-injured limbs seems to be a noteworthy marker, indicating the potential for sEMG to evaluate a patient's readiness to return to sports. However, the Coefficient of Determination (CoD) exhibited variability, reducing its reliability as an injury indicator. The analysis of muscle onset timing suggested potential changes, indicating the need for more sophisticated threshold approaches in future research.

While the study provides preliminary insights into sEMG's application in assessing muscle activation patterns related to lateral ankle injuries, further research with a larger and more diverse subject pool is imperative. This research lays the foundation for future investigations in sports medicine and rehabilitation, aiming to enhance diagnostic and evaluative tools.

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Chapter 1

Introduction

Electromyography (EMG), and more specifically surface electromyography (sEMG), is a non-invasive technique used to measure muscle activation [3]. With almost 100 years of research on humans and the commercial availability of EMG systems since 1950, several novel techniques and devices have been developed [4]. However, despite its extensive history and diverse applications, EMG remains an underutilized tool in rehabilitation [5][3]. This observation is particularly striking when compared to other electrophysiological signals such as electrocardiography and electroencephalography, which are widely employed in healthcare practices. According to L. McManus in 2020, the primary barrier to the more widespread use of sEMG is the lack of technical knowledge among physiotherapists [3]. Overcoming this obstacle could enable sEMG to play a vital role in contemporary physiotherapy.

sEMG has the potential to contribute significantly to modern physiotherapy, particularly in cases of lateral ankle sprains. Ankle sprains, as the chosen subject of this research, are a particularly apt focus for several key reasons. First, they present a substantial pool of potential subjects, given the high annual incidence of ankle sprains resulting from sports activities in the Netherlands, which stands at approximately 234,000 cases [6, 7]. Notably, 47 % of these injuries necessitate medical treatment, generating over 80 million euros in medical costs annually. Importantly, these figures exclude non-sports-related ankle sprains, suggesting that the actual costs may be even higher.

Lateral ankle sprains make a compelling choice for investigation, primarily due to their noteworthy recurrence rates, as will be addressed in a subsequent section of this introduction [8, 9, 10]. This recurring nature of ankle sprains highlights the potential for enhancing the treatment and rehabilitation process, a critical aspect in which sEMG may offer significant contributions.

Currently, physiotherapists rely on a combination of subjective and objective factors to assess a patient's readiness to return to sports, also known as their return-to-sports level. Subjective assessment methods often involve the physiotherapist visually observing and asking the patient about their pain levels, the quality of their movements, their mobility, the functionality of their movements, and the presence of joint swelling. On the other hand, the Koningklijke Nederlands Genootschap voor Fysioterapie (KNGF) provides more objective assessment methods including the use of tools such as the Ganganalyselijst Nijmegen (GALN) [11]. The GALN provides a comprehensive list of assessments that a physiotherapist can use to objectively evaluate a patient's movement in the gait. These assessments help in quantifying the patient's progress and readiness to return to sports. Despite the utilization of these assessment methods, the relapse rate within one year ranges from 20.7% to 22.6%, with the highest relapse rate occurring within the first three months. Some studies have even reported a relapse rate of 54% within 6.5 years [8, 9, 10].

Utilizing sEMG to non-invasively assess muscle activation in terms of amplitude, envelope form, and the timing of onset provides physiotherapists with valuable insights into a patient's preparedness for sports reintegration. However, the underutilization of sEMG in rehabilitation, mainly due to a lack of technical knowledge among physiotherapists [3], is a significant obstacle that needs to be addressed to fully realize the potential benefits of this method.

By capturing signals closer to the source, sEMG offers potential advantages over other experimental devices/prototypes in improving objective assessment methods used by physiotherapists to gauge a patient's readiness for a return to sports [12, 13]. Several studies have investigated the combination of injuries with sEMG and have demonstrated that injured muscles or joints, such as the ankle, exhibit a significant delay in muscle onset compared to healthy muscles (Beckman 1995, Bullock-Saxton 1994, Van Deun 2007, Morrissey 2012, Newcomer 2002, Osborne 2001). Studies by Rivera et al. (2013), Bullock-Saxton et al. (1994), Beckman et al. (1995), Osborne et al. (2001), Newcomer et al. (2002), Van Deun et al. (2007), and Morrissey et al. (2012) collectively reveal methodologies focusing on muscle onset timing, activation patterns, and muscle activity ratios. Studies investigating onset patterns in lateral ankle injuries typically focus on muscles such as the peroneus, plantar flexors like the gastrocnemius, and the tibialis anterior. Some research even extends to examining changes in the onset of the gluteus during lateral ankle injuries. A common methodology shared among these studies is the utilization of surface sEMG to assess muscle activation patterns between injured and non-injured muscles or joints during various movements. The researchers employed controlled studies and diverse experimental setups to investigate different aspects of muscle function related to specific injuries or conditions. Specific metrics include the time between muscle onset and activation, reflex response latency, baseline activity, peak EMG, onset latency, and peak EMG latency. The investigations use these metrics to explore conditions such as severe unilateral ankle sprains, ankle inversion perturbations, ankle disk training effects, footplate perturbations in low back pain patients, chronic ankle instability, and chronic abductor injury. A common outcome observed across these studies is the identification of altered muscle activation patterns associated with various conditions and injuries. The research collectively reveals insights into the impact of severe unilateral ankle sprains, chronic ankle instability, and chronic adductor injury on muscle function.

In a study conducted by Edgerton et al. in 1996, the relationship between muscle dysfunction and EMG patterns was explored [14]. The researchers investigated nine motor tasks, including bilateral anterior arm flexion, trunk rotation, and shoulder shrug. The analysis focused on ratios of EMG amplitudes between pairs of different muscle combinations that performed similar functions. The findings proposed that identifying altered neural strategies was possible through the analysis of these EMG amplitude ratios. Moreover, the study suggested the clinical applicability of muscle amplitude ratios to detect dysfunction in individuals with sprain/strain injuries.

In recent years, there has been a surge in research focusing on the intersection of EMG and return to sport, particularly following injuries such as anterior cruciate ligament (ACL) reconstruction. Noteworthy studies by Kotsifaki et al. (2022), Piroth et al. (2023), and Blasimann et al. (2021) have made substantial contributions to this field [15, 16, 17].

Kotsifaki et al. (2021) delved into the appropriateness of utilizing a vertical jump as an evaluative movement to assess knee function in athletes who underwent ACL reconstruction, aiming to determine their preparedness for a return to sports. The researchers employed measurements of joint kinematics and EMG from various muscles, utilizing this data with muscular-skeletal modelling to calculate muscle forces and joint torque. Notably, the study revealed that the soleus force contribution was consistently lower bilaterally in the ACL reconstruction group compared to the control group indicating a subject not ready to return to sports.

Piroth et al. (2023) propose the utilization of EMG assessments as a valuable tool for evaluating a patient's readiness to return to sports. The study emphasizes a qualitative approach to muscle analysis through EMG, emphasizing key questions such as whether the corresponding muscle is active or inactive, the level of muscle activity, and the timing of muscle activation. While the paper does not specify particular metrics, it underscores the significance of a nuanced qualitative assessment using EMG to gauge readiness for a return to sports.

Blasimann et al.'s (2021) investigation focused on evaluating neuromuscular control after an ACL injury, with a focus on facilitating a safe return to sports. The study compared the neuromuscular control of ACL-injured adults with the contralateral limb or healthy controls during dynamic activities. Parameters, including time, amplitude, and EMG-related activity, were considered as outcome measures. Despite the diverse array of EMG outcome measures for neuromuscular control, none were employed to determine a safe return to sports. The research emphasizes the need for further studies to establish comprehensive assessments of neuromuscular control in adult ACL patients in combination with readiness to return to sports.

The current body of research has predominantly investigated differences in muscle onset or EMG amplitude between healthy and injured muscles or joints [18, 19, 20, 21, 22, 23]. More recently, studies have looked into applying EMG to gauge readiness for a safe return to sports, particularly following ACL reconstruction, using kinematics or muscle amplitude analysis [15, 16, 17]. However, a gap exists in the literature concerning the integration of muscle onset assessments with considerations for return to sports. Moreover, limited attention has been given to evaluating the practicality of EMG in determining readiness for sports resumption after a lateral ankle injury. This research aims to contribute clarity to the viability of employing EMG for a comprehensive assessment of a patient's readiness to return to sports.

In physiotherapy, establishing a margin of approximately 10% (6% in athletes) difference in muscular strength between legs has been conventionally accepted. This allowance acknowledges the inherent variability in left-right balance, which is seldom perfectly equal in individuals. However, it is essential to note that this margin is largely informed by clinical experience rather than robust scientific evidence. Consequently, this study will encompass a control group of uninjured subjects to estimate the normal range of left-right differences in muscular strength among healthy individuals. Understanding what constitutes an acceptable healthy difference between the legs becomes crucial in the context of this research, which aims to analyze and compare EMG measurements between healthy and injured legs of patients.

With a clear understanding of the accepted standards in place, this research sets forth two primary objectives. First and foremost, it aims to assess the feasibility of sEMG as a diagnostic tool for determining a patient's readiness to return to sports following lateral ankle sprains. This will be achieved through a comprehensive analysis of muscle activation disparities between the injured and unaffected legs during the rehabilitation process.

In parallel, the secondary objective of this study is to investigate the baseline left-right differences in muscular activation among a population of healthy individuals. By establishing this normative range, it becomes possible to determine a scientifically sound and practical threshold for evaluating a patient's readiness for going back to sports.

Collectively, these objectives serve as a foundational framework for this investigation, combining clinical experience with scientific rigor to advance our understanding of lateral ankle sprains and the role of sEMG in the rehabilitation process. Through this research, we aim to provide valuable insights into the enhancement of clinical practices and the optimization of patient care.

Chapter 2

Methodology

2.0.1 Research Design

The research design for this study is structured as an observational study that involves three patients diagnosed with lateral ankle sprains, who underwent physiotherapy treatment. sEMG measurements and kinematic assessments were conducted during the middle and final stages of their treatment, as defined by the physiotherapist, to determine their readiness for return-to-sports level. Additionally, a control group comprising six healthy subjects was recruited to assess the disparities between two healthy legs. The initial measurement coincided with the point when the physiotherapist considered the patients fit to perform complex and explosive movements such as the drop jump and side hop. The follow-up measurements were performed four weeks after the initial measurements.

2.0.2 Study Population

The population for this study consists of patients with a lateral ankle sprain recruited from Topvorm Twente, while healthy subjects were recruited from the University of Twente. To ensure the validity of the study, the following inclusion and exclusion criteria will be applied.

Inclusion criteria for the study participants are as follows:

- Signed informed consent by the subject.
- Age between 18 and 50 years.
- The injured subject: diagnosed with a lateral ankle sprain.
- The injured subject will receive treatment from a physiotherapist of Topvorm Twente.
- The injured subject will have at least three treatment sessions with the physiotherapist.

A potential subject will be excluded from participation in this study if:

- The subject is unwilling to participate.
- The subject has suffered an ankle, knee, or hip injury in the past year, either on the healthy or now injured leg.
- The subject currently competes at the national or international level in a sport.

2.0.3 Ethical Considerations

For ethical considerations, the researcher sought guidance from the Medical Ethical Committee (METC) regarding whether the study was subject to the Dutch Law on Medical Research Involving Human Subjects (WMO) and required approval from an accredited medical ethical review committee. The METC determined that the research did not involve WMO-regulated actions or behaviors that would require approval. Therefore, a positive assessment from the METC or any other accredited medical ethical review committee was not necessary for the study's implementation. However, the METC only assessed the study's WMO-priority and did not provide an opinion on its content.

2.0.4 Data Collection

In this study, several systems were used for data collection and analysis. A multi-channel stationary system (SAGA 64+, TMSi, The Netherlands) for physiological research, was used to amplify and record EMG signals from the muscles of interest. The AMTI, ACG model, force plates were used to record the ground reaction forces during the movements. The Qualisys Motion Capture System, a CE-certified optical tracking technology, was used to capture motion data of the participants using thirty-three markers on the body. The system mainly consisted of 12 motion capture cameras and software for medical and industrial standards. In addition, a sensorized garment was used around either the injured or the non-dominant leg to collect data on muscle activity.

2.0.5 Measuring protocol

The measuring protocol for this study consisted of several steps to collect data on muscle activity and motion patterns of the participants. To obtain EMG signals, six bi-polar sensors were attached to the dominant or non-injured leg, specifically on the tibialis anterior, peroneus longus, gastrocnemius medial, gastrocnemius lateral, soleus, and peroneus brevis muscles. The sensor placement followed the recommendations outlined in the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines [24]. The same sensorized garment with 64 channels, as utilized in Simonetti et al., 2023 [25], was employed for EMG data collection on the injured or non-dominant leg. The selection of channels for specific leg muscles was carried out based on the method outlined in the paper of Simonetti et al., 2023 [25]. The utilization of two different set-ups stemmed from practical considerations, including limitations in the lab set-up that prompted the exploration of an alternative garment-based approach. Additionally, the garment set-up provided an opportunity to assess clustering methodologies relevant to a concurrent PhD study, extending the applicability of the research to broader patient populations. For the cluster selection procedure, manual channel pairs were selected for the six leg muscles. The EMG envelopes derived from these manually selected channels were obtained through subtraction of the raw monopolar EMG signal from the muscle-specific electrode pairs, following the processing procedures detailed in Section 2.3 of the paper. Additionally, a 3D motion tracking system (Qualisys) with 12 cameras was employed, using 33 retro-reflective markers placed on bony landmarks, following the methodology outlined in Sartori et al., 2012 [26]. The inclusion of kinematic measurements in this study serves as an extra tool for cycle detection in the various movements assessed. While not directly tied to the immediate research questions, this additional kinematic data also offers the flexibility for potential future applications, such as muscular-skeletal modeling, expanding the scope and possibilities of the research. To begin the data collection, participants were instructed to perform a static measurement by standing still on the force plates. This was followed by a gait analysis, during which participants were asked to walk back and forth on a runway with force plates for a total of eight gait cycles. To further assess lower limb function, participants were then asked to perform a Drop Jump exercise, in which they stood on a 25cm high box, dropped onto a force plate, and stabilized on one leg. This exercise was performed six times per leg as shown in 2.1.

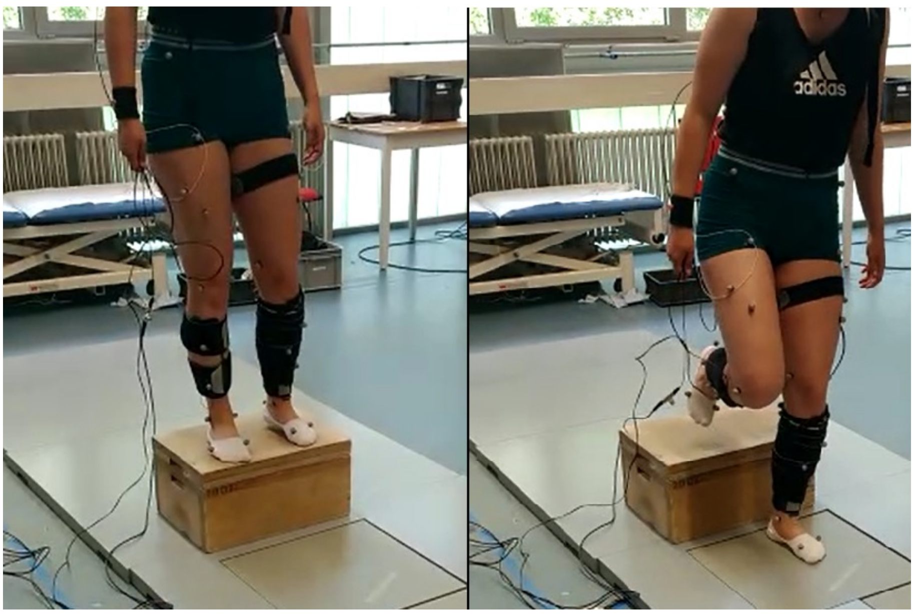

Figure 2.1: Start and end positions of the drop jump movement

Lastly, participants performed a Side Hop exercise. This involved placing tape 30cm apart on the force plates and instructing participants to hop from one side of the tape to the other side on one leg without touching the tape. This jump was performed three times laterally and three times medially 2.2.

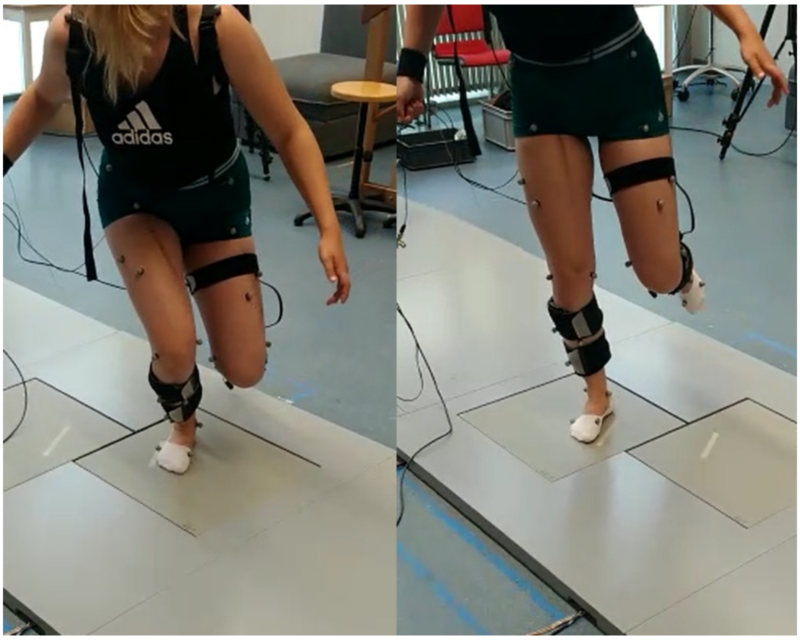

Figure 2.2: Start and end position of the side hop movement

All exercises were performed twice, and the injured or non-dominant leg was tested first in both repetitions.

2.0.6 Data processing

The trials were performed as continuous measurements, necessitating subsequent segmentation into individual repetitions for meaningful comparison. Proper segmentation is critical to ensure meaningful comparisons between repetitions.

Gait cycle detection

The gait cycle identification process in this study is a procedure that relies on the analysis of vertical positional data from markers attached to the calcaneus of both the right and left feet during gait. The markers' vertical positions are combined into a single dataset that encompasses all local minima points from both the right and left calcaneus markers.

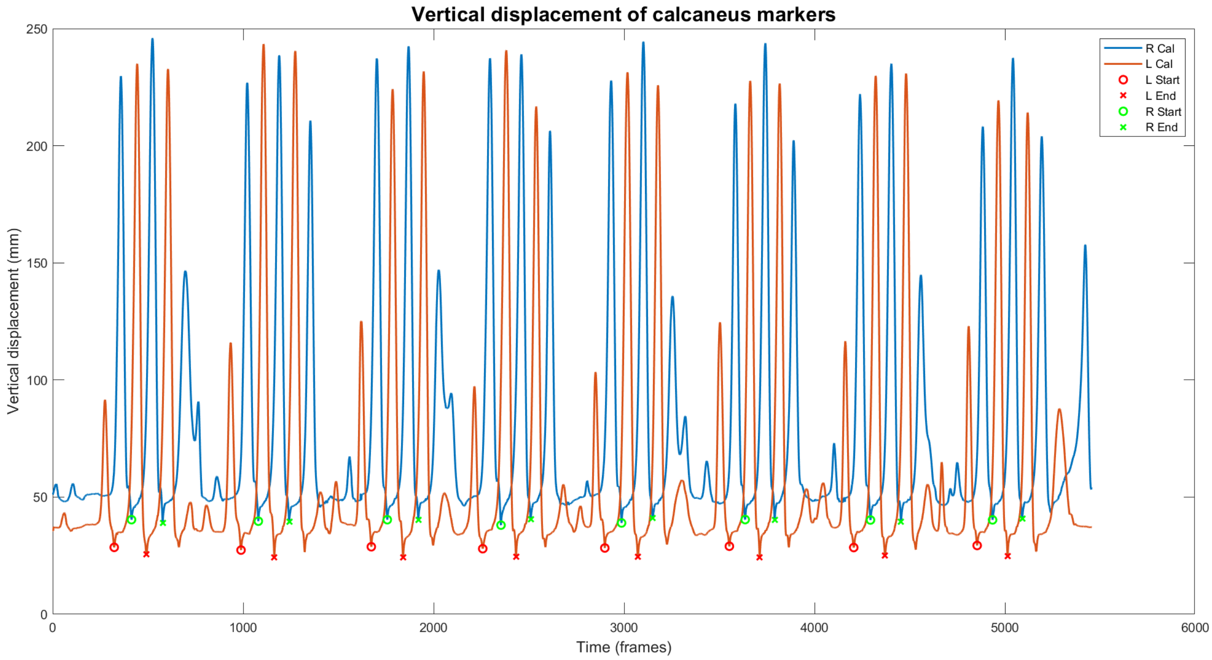

Figure 2.3: Vertical displacement of the right calcaneus (R - blue line) and left calcaneus (L - red line) with the corresponding begin (vertical blue line) and end points of the gait cycle.

The dataset is synchronized with the activation trigger of the right force plate. When the force plate exceeds ten newtons, the system identifies the nearest local minima in the dataset using the MATLAB function 'localminima,' corresponding to the initial heel strike of the right gait cycle. To establish the endpoint of the right gait cycle, the system searches for a local minimum point occurring two instances later in time.

Subsequently, the detection of the left gait cycle is obtained by identifying a local minima immediately before the initiation of the right gait cycle. The left gait cycle's end is determined by detecting a local minima that follows the start of the right gait cycle. Figure 2.3 shows the vertical displacement of the calcaneus markers during the whole gait measurements with the detected begin and endpoints.

Drop jump cycle detection

To pinpoint the beginning and end of each drop jump repetition, the differential of the force plate data is used, as illustrated in Figure 2.4. The onset of the drop jump is recognized by identifying the first noticeable positive surge in differential force, indicative of the moment when the subject lands on the force plate. A subject-specific threshold is employed, manually determined based on the peak height of the initial peaks, ensuring that only the initial peaks surpass this threshold. Once the force data differential surpasses this limit, the MATLAB function "localmaxima" is used to pinpoint the location of this peak.

The initial downturn in the force plate data's differential signifies that the subject has finished deceleration on the force plate, with only their body weight now resting on it. Subsequently, the second negative peak in the differential drop jump value denotes that the subject has stepped off the force plate, signaling the completion of the drop jump cycle. Detecting this endpoint involves the manual selection of a subject-specific threshold, designed to encompass only the first and last negative peaks falling below this value. Once this criterion is met, a local minimum is detected using the MATLAB function "localminima" to serve as the endpoint for the drop jump cycle.

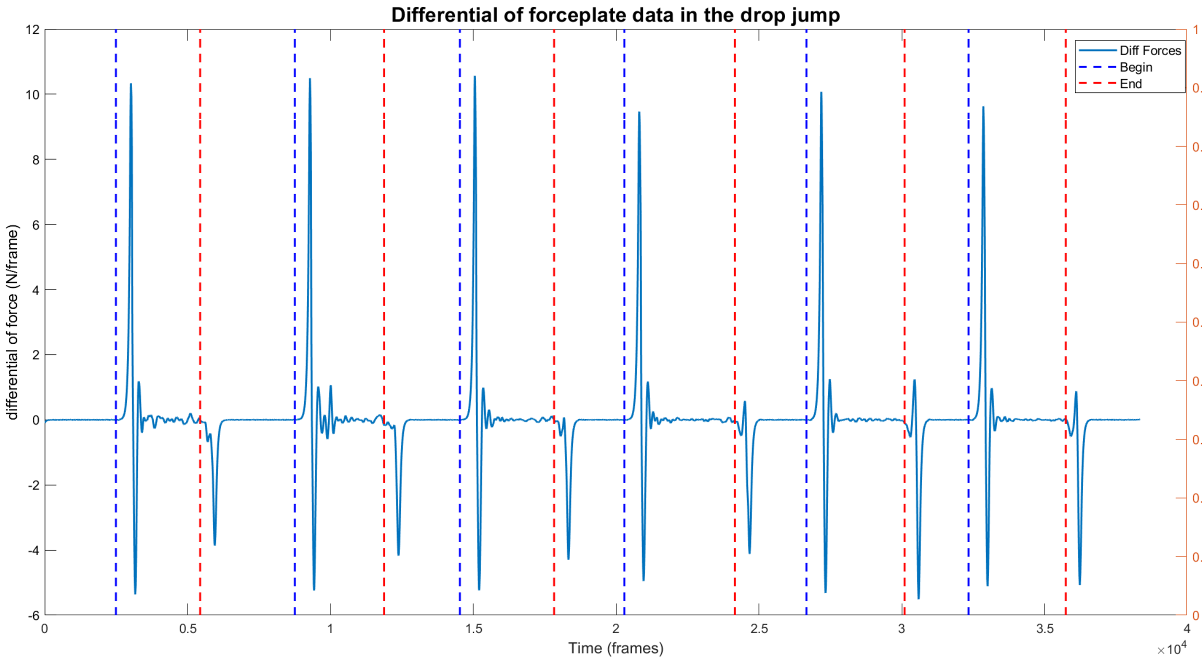

Figure 2.4: Differential of the force plate data during the drop jump with the begin and end points of each cycle.

Furthermore, to account for any early muscle activation that may occur due to anticipation of impact, the system establishes the beginning of a repetition half a second before impact. This approach guarantees that the complete muscle activation profile is recorded and analyzed. The determination of the endpoint is set at half a second before the subject steps off the force plate, ensuring that any potential influence from stepping on the box is excluded from the EMG signal.

Side hop cycle detection

In the detection of side hop repetitions within this study, the vertical displacement data from the marker positioned on the sacrum was utilized. This marker was favored for its reduced noise and increased consistency in comparison to the calcaneus marker. Figure 2.5 shows the vertical displacement of the sacrum over time with the indicated beginning and end points.

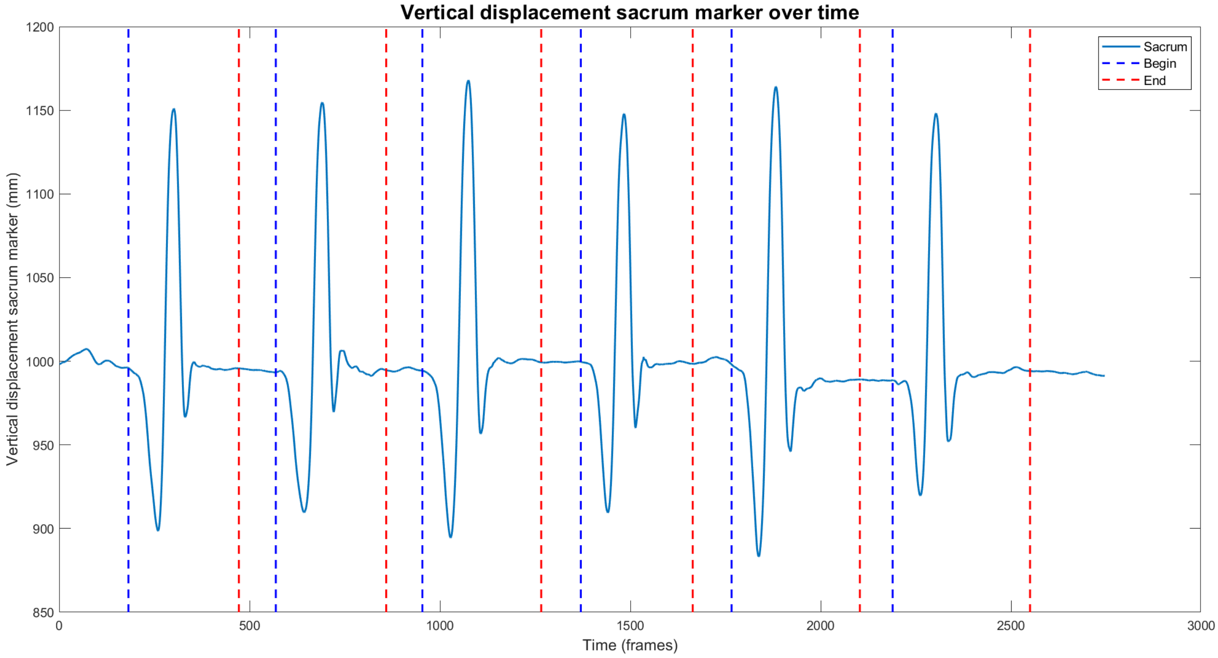

Figure 2.5: Vertical displacement of the sacrum during the side hop movement, with the beginning and end points of each cycle.

The figure illustrates distinct phases within the vertical displacement of the sacrum, reflecting the subject's movements during the side hop cycle. Initially, there is a noticeable dip, signifying the moment when the subject loads their leg in preparation for the jump. Following this loading phase, a peak emerges, marking the flight phase where the subject is momentarily airborne. Subsequently, another dip is observed, indicating the subject's landing and a slight bending motion to absorb the impact.

For the detection of the side hop cycle, a subject-specific threshold is manually established, ensuring that only the initial negative peaks go below this value. The MATLAB function "localminima" is then applied to identify the precise locations of these minima, serving as the starting point for the sidehop movement. To identify the endpoint, a local maximum, occurring approximately 2 seconds after the loading phase, is detected within the vertical displacement of the sacrum. This peak indicates that the subject has successfully landed and returned to a stable position.

To ensure that the muscle activation during the loading phase is accurately captured, the starting point is defined as 0.5 seconds before the onset of the loading phase.

2.0.7 Metrics for Determining return-to-sports level

To determine the return-to-sports level, three metrics are employed in this research for the comparison of healthy and injured legs. The Root Mean Square (RMSE) assesses amplitude differences, the Coefficient of Determination (CoD) Quantifies the shape overlap, and muscle onset timing evaluates the duration of muscle activation. These meatrics will be discussed in the sections below. These metrics will be discussed more extensively in the sections below.

Signal Processing

Signal processing of the raw EMG, kinetic and kinematic data was done on Matlab (Matlab2018a, MathWorks, Natick (MA), USA).

The EMG signals in this study underwent a series preprocessing steps to ensure that the data was suitable for further in-depth analysis. This analysis is based on Simonetti et. al. 2023 [25]. The choice of this filter is aligned with the setup used in the study by Simonetti et al. (2023). To maintain comparability with their results, the signal processing, including the filtering methods, was adapted from their research methodology.

To start, a 4th-order Butterworth bandpass filter with a frequency range of 20 to 450 Hz was applied. Following the bandpass filtering, a signal rectification was performed by taking the absolute value of the data.

To further refine the signals and facilitate a more comprehensive analysis, an envelope using a moving median filter was generated. This filter was designed with a window size of approximately one-sixth of the signal's sampling frequency.

To ensure that the EMG data could be effectively compared across different subjects and movements, the signals were normalized. The normalization process involved dividing each muscle-specific envelope by the maximum value of the muscle-specific envelope within one system across all movements.

For the final assessment, mean values were computed across all repetitions, specifically for gait, drop jump, medial side hop, and lateral side hop, providing a consolidated representation for more profound and insightful analysis, aligning with scientific standards.

Root Mean Square Error

The RMSE is a widely used metric for quantifying the dissimilarity between two sets of data points. Mathematically, it is calculated as the square root of the mean of the squared differences between corresponding data points from two datasets [27]. In the context of this study, the RMSE is computed by comparing the data obtained from the sensorized garment-based (injured/non-dominant leg) sensors (represented as $leg\_data\_garment$) with data from Bi-polar sensors (healthy dominant leg) (represented as $leg\_data\_Bi - Polar$). The formula for RMSE can be expressed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(leg\_data\_garment_i - leg\_data\_Bi - Polar_i)^2}$$

This formula iteratively squares the differences between data points, averages these squared differences, and then takes the square root of the result to provide an overall measure of the agreement between the two datasets.

The RMSE value is a vital indicator of the level of agreement or disparity between the two datasets. A lower RMSE signifies a closer match and implies that the data acquired from the two sources are in better concordance. Conversely, a higher RMSE indicates a larger discrepancy, suggesting significant differences between the datasets.

Coefficient of Determination

CoD is a widely utilized statistical measure across various scientific disciplines to assess how well a model fits observed data [27]. In the context of this research, CoD is harnessed to compare the shapes of enveloped signals acquired from the healthy (or dominant) leg with those from the injured (or non-dominant) leg.

The formula for calculating CoD in this research involves first computing the correlation coefficient (R) between the data from the healthy leg and the injured leg. The correlation is calculated by taking the correlation coefficient between the two data sets, which quantifies the strength and direction of their linear relationship. In this context, it helps assess how closely the shapes of the enveloped signals from the healthy and injured legs are related. The resulting coefficient ranges from -1 to 1, with 1 indicating a perfect positive correlation, -1 indicating a perfect negative correlation, and 0 indicating no correlation between the two datasets. Subsequently, the square of the correlation coefficient, R squared (R^2), is calculated to obtain the CoD value.

Muscle Onset

As described in the introduction multiple researchers have detected some differences between healthy and injured legs when comparing the muscle onset [18, 19, 20, 21, 22, 23]. Some of these researches use an elaborate way to calculate this onset with a variable threshold.

In this research, a simplified method is employed, inspired by Abbink et. al. (1998) and Beckman et al. (1995)[28, 18] This method offers a more straightforward means of evaluating muscle onset.

The process encompasses the following steps:

Initially, a threshold is computed by utilizing the mean and standard deviation of the signal recorded between repetitions of a movement. The threshold is derived using the formula:

$$Threshold = mean + 3 \times standard\ deviation.$$

In the study of Abbink, it was observed that inter-repetition rest intervals play a crucial role. This observation stems from the understanding that muscles do not return to a state of complete rest activation during these intervals, potentially resulting in an erroneously low threshold calculation.

After establishing the movement and muscle-specific threshold, the cycle EMG signal is employed to identify the onset point when the muscle activates. This moment is quantified as a percentage of the movement cycle. Subsequently, the onset from the healthy or dominant leg is subtracted from the injured or non-dominant leg, yielding a percentage that signifies the difference in onset between both legs within the movement cycle. A negative value indicates a delayed onset in the non-injured or dominant leg, while a positive value suggests a delayed onset in the injured or non-dominant leg.

This simplified approach streamlines the assessment of muscle onset, offering a practical means of comparing onset times between legs and potentially revealing significant insights into muscle activation patterns.

Chapter 3

Results

3.1 results

This section presents an analysis of the study's results. Initially, the collective outcomes of all healthy subjects will be explored, and observations will be made based on the collected data. Following this, attention will be directed toward the injured subjects, where their results will be discussed individually. The need for an individual approach in this case arises from the limited number of participants in the study and the considerable diversity in the types of lateral ankle injuries observed. This approach allows for detailed observations of unique characteristics and implications within each case, providing a more nuanced understanding of the experiences within the study cohort. A detailed overview of the subject characteristics is available in Appendix .1, which offers additional context for the study's findings. It is noteworthy to mention that the study initially included 6 healthy and 3 injured subjects. However, due to insufficient signal quality, two healthy subjects had to be excluded from further examination.

3.1.1 Healthy subjects

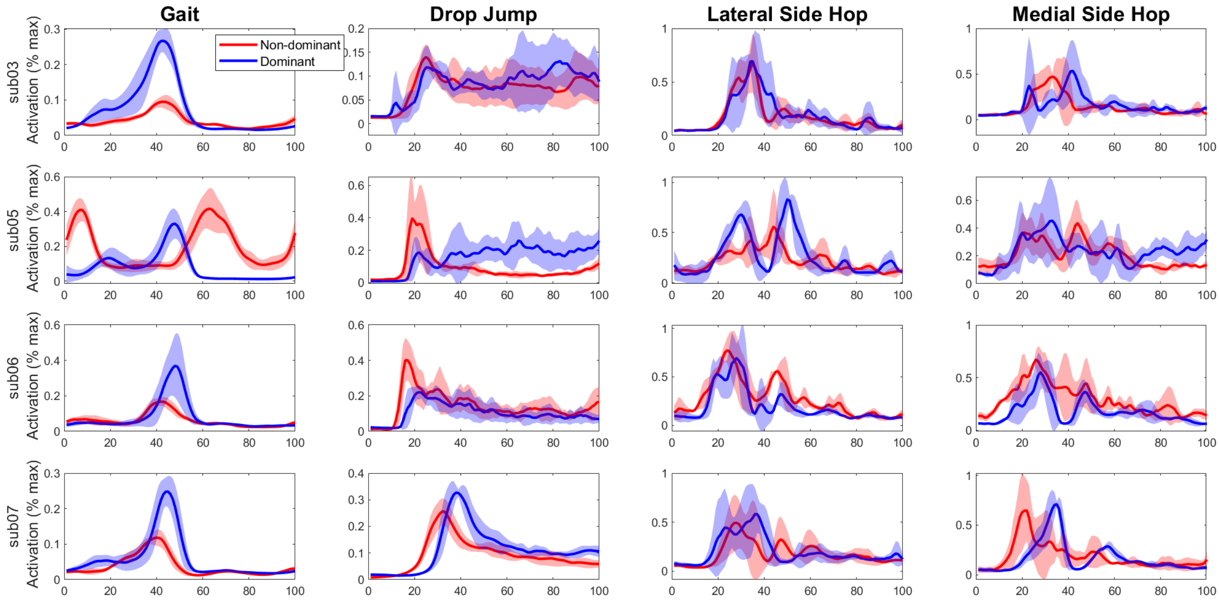

Figure 3.1: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the gastrocnemius lateralis. The continuous line indicates the mean value while the shaded line is the standard deviation

Figure 3.1 illustrates the muscle activation of the gastrocnemius lateralis across various movements. The activation pattern for the gastrocnemius lateralis exhibits a consistent trend for subject 03, 06, and 07 characterized by a single prominent peak in the middle of the gait movement. This pattern is also observed in other muscles, such as the peroneus brevis, gastrocnemius medialis, and gastrocnemius lateralis, as demonstrated in figures 2, 4, and 5 in Appendix .2.

In contrast, the tibialis anterior demonstrates a distinctive activation pattern. It exhibits an initial activation at the beginning of the gait cycle and a subsequent activation toward the end, as depicted in figure 1 in Appendix .2. This pattern remains consistent across subjects and between both legs.

The peroneus longus, presented in figure 3 in Appendix .2, deviates from other muscles. Its activation pattern is not consistent across legs or subjects. It displays a combination of a single activation peak and a pattern reminiscent of the tibialis anterior, featuring two activation peaks during the gait.

When examining muscle activation during the drop jump, a common pattern emerges among all muscles. This pattern entails a single activation peak followed by a gradual decline in activation levels. This consistent pattern is depicted in Figure 3.1 and is evident in the figures 4 to 5 in Appendix .2. This pattern remains consistent across legs and subjects, with subjects 7, exhibiting shorter activation peaks than the other subjects across all muscles.

Similarly, both side hop movements exhibit a shared pattern characterized by a single activation peak in the muscles, as displayed in Figure 3.1 and the figures 4 to 3 in Appendix .2. The tibialis anterior, however, diverges from consistency in this instance, showing no uniform pattern across subjects or legs, as illustrated in figure 1. The pattern in the side hop movements is less consistent across legs and subjects compared to the drop jump.

Muscle Group	Gait	DJ	SH lateral	SH medial
Tib	0.10 (0.07)	0.08 (0.06)	0.14 (0.07)	0.18 (0.07)
PerL	0.08 (0.07)	0.08 (0.05)	0.17 (0.05)	0.15 (0.05)
PerB	0.07 (0.03)	0.13 (0.08)	0.19 (0.07)	0.20 (0.08)
GasM	0.09 (0.03)	0.09 (0.03)	0.18 (0.05)	0.13 (0.03)
GasL	0.08 (0.07)	0.07 (0.05)	0.15 (0.04)	0.13 (0.05)
Sol	0.06 (0.02)	0.07 (0.04)	0.14 (0.06)	0.12 (0.05)

Table 3.1: Mean (± std) RMSE of the mean over all subjects per muscle overall movements. (DJ: Drop Jump, SH: Side Hop).

Table 3.1 displays the RMSE values and their respective standard deviations across all movements for the six muscle groups. The highest RMSE values are consistently observed in the medial and lateral side hop movements for each muscle, for example in the peroneus longus that has a mean (± std) RMSE value of 0.19 (0.07) in the lateral side hop and 0.20 (0.08) in the medial side hop. In contrast to this, the gait movement consistently yields the lowest overall mean (± std) RMSE values, For example in the peroneus brevis that has an RMSE value of 0.07 (0.03). These RMSE values will be used as a benchmark for evaluating the results of the injured subjects.

Muscle Group	Gait	DJ	SH lateral	SH medial
Tib	0.71 (0.07)	0.48 (0.12)	0.26 (0.20)	0.16 (0.16)
PerL	0.23 (0.26)	0.30 (0.22)	0.13 (0.15)	0.07 (0.14)
PerB	0.19 (0.21)	0.25 (0.24)	0.13 (0.16)	0.04 (0.12)
GasM	0.50 (0.13)	0.12 (0.22)	0.08 (0.13)	0.15 (0.18)
GasL	0.73 (0.16)	0.39 (0.25)	0.47 (0.28)	0.40 (0.22)
Sol	0.67 (0.23)	0.23 (0.35)	0.25 (0.26)	0.40 (0.31)

Table 3.2: Mean (± std) CoD over all subjects per muscle overall movements. (DJ: Drop Jump, SH: Side Hop).

Table 3.2 offers an overview of the mean (± std) CoD values across all healthy subjects and movements for the six muscle groups. The highest CoD values are consistently observed in the soleus and tibialis anterior muscles, particularly during the gait movement, where the tibialis anterior has a mean (± std) CoD value of 0.71 (0.07) and the soleus has a mean (± std) value of 0.67 (0.23), while the lowest values are consistently found in the peroneus longus and brevis muscles, especially during the medial side hop where the peroneus longus has a mean (± std) CoD value of 0.07 (0.14) and the peroneus brevis, has a mean (± std) CoD value of 0.04 (0.12). These CoD values will serve as the reference or baseline for evaluating the results of the injured subjects.

Muscle Group	Gait	DJ	SH lateral	SH medial
Tib	-36.1 (37.9)	-6.6 (26.7)	-0.10 (9.5)	-7.6 (23.6)
PerL	-22.9 (31.7)	-4.3 (13.3)	3.0 (16.1)	-6.5 (18.0)
PerB	-12.1 (36.0)	-4.3 (12.2)	-0.1 (27.5)	8.3 (29.4)
GasM	0.2 (12.0)	-0.7 (15.4)	12.0 (28.3)	-11.4 (31.0)
GasL	-0.4 (8.6)	0.8 (17.2)	-1.6 (15.0)	-2.8 (24.4)
Sol	-7.3 (15.6)	-15.9 (13.8)	-3.1 (11.5)	-6.4 (14.6)

Table 3.3: Mean (± std) onset Differences Between Legs Across Muscle Groups and Movements in Percentage of the Movement Cycle (DJ: Drop Jump, SH: Side Hop).

Table 3.3 presents the mean (± std) difference in onset values between both legs across all subjects for the six muscle groups during various movements, expressed as a percentage of the movement cycle.

In the observed data, the tibialis anterior exhibits the most notable mean (± std) difference in onset times, showing a delay of -36.1 (37.9). On the other hand, the peroneus longus during the lateral side hop demonstrates the smallest mean (± std) difference in onset values, with a difference in onset times of -0.1 (27.5) percent of the movement.

It is noteworthy that across all measurements, the standard deviation tends to surpass the mean value. The only exception to this trend is observed in the soleus during the drop jump, where the mean (± std) is 15.9 (13.8).

3.1.2 Injured Subject 1

Injured subject 1 is a male of 23 years old and experienced an ankle injury on his right leg, that did not significantly disrupt his daily activities. Although the subject reported no major hindrances in most daily tasks, there was a slight awareness of the injury during certain more explosive movements. This awareness, however, had disappeared by the follow-up measurement as the subject was near the completion of their physiotherapy regimen, indicating significant progress toward a full recovery, as confirmed by the physiotherapist.

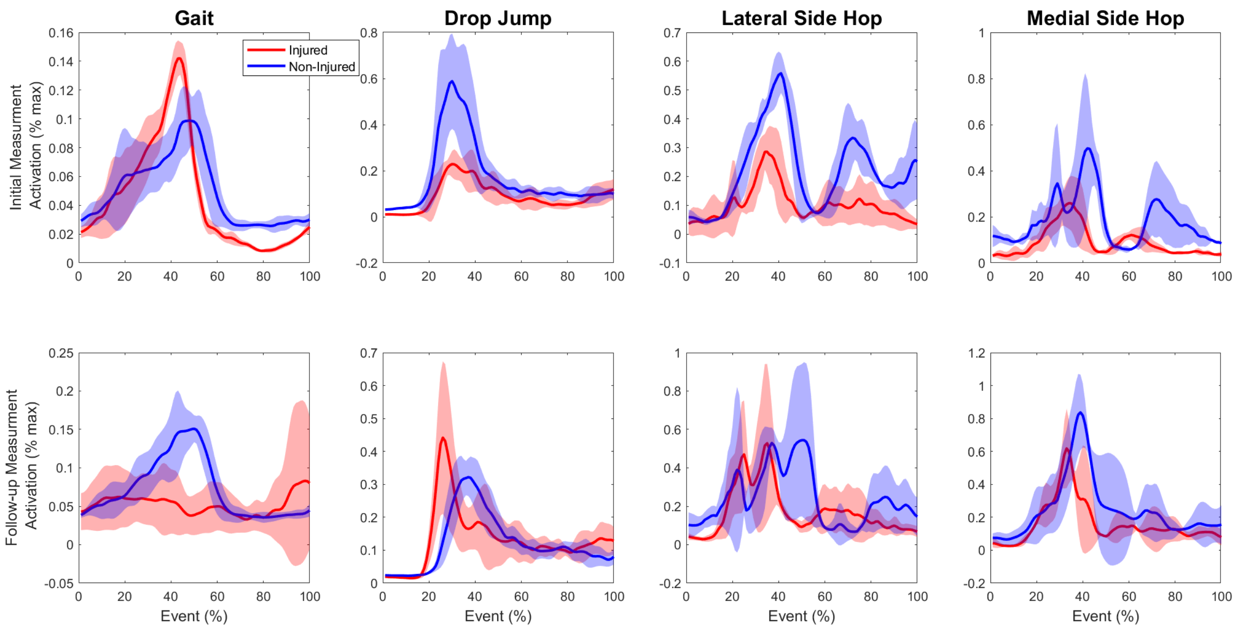

Figure 3.2: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the gastrocnemius lateralis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Upon close examination of the activation of the gastrocnemius laterals in figure 3.2 and activation of the other muscles shown in the figures 3 to 6 to in Appendix .2, a distinct pattern emerges in the muscle activation of injured subject 1 during the follow-up gait measurement. This pattern is characterized by consistently low muscle activation levels across all muscles and an inconsistent activation pattern. In contrast to the non-injured leg muscles, the injured leg muscles exhibit reduced activation, and this discrepancy is evident across all muscle groups. Importantly, this pattern remains consistent throughout the follow-up measurement for all the gait trials.

An additional common trend observed in all muscles pertains to the drop jump movement, which closely mirrors the patterns seen in healthy subjects. The peak activation in the injured leg muscles is consistently wider than that in the non-injured leg muscles in the initial measurement. However, this pattern changes in the follow-up measurement, with the peak in the injured leg muscles becoming shorter across all muscle groups.

The figures in Appendix .2 and figure 3.2 also reveal a recurring trend during the side hop movement, characterized by a substantially higher initial activation followed by a smaller activation peak. Nevertheless, this pattern lacks uniformity across both legs and both measurements and no consistent disparities are apparent between the initial and follow-up assessments.

Muscle	m#	Gait	DJ	SH lateral	SH medial
Tib	m1	0.04	0.06	0.17	0.11
	m2	0.05	0.10	0.11	0.08
PerL	m1	0.06	0.03	0.21	0.12
	m2	0.06	0.07	0.12	0.15
PerB	m1	0.17	0.19	0.22	0.16
	m2	0.04	0.12	0.12	0.12
GasM	m1	0.06	0.06	0.19	0.12
	m2	0.10	0.07	0.11	0.13
GasL	m1	0.02	0.13	0.15	0.14
	m2	0.05	0.09	0.17	0.15
Sol	m1	0.16	0.13	0.17	0.15
	m2	0.07	0.16	0.19	0.10

Table 3.4: RMSE for injured subject 1 across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying RMSE values for the initial measurement (m1) and the follow-up measurement (m2) is provided in Table 3.4. The table shows a decrease in RMSE value for the peroneus longus and peroneus brevis muscles during the lateral side hop movement. For the peroneus longus, RMSE drops from 0.21 (m1) to 0.12 (m2), while for the peroneus brevis, it decreases from 0.22 (m1) to 0.11 (m2).

Conversely, the RMSE values for the drop jump movement tend to remain relatively stable for muscles like the gastrocnemius medialis, showing a minor change from 0.64 (m1) to 0.66 (m2) or showing a slight increase like in the tibialis anterior going from 0.06 to 0.10.

Muscle	m#	Gait	DJ	SH lateral	SH medial
Tib	m1	0.15	0.85	0.12	0.34
	m2	0.30	0.14	0.16	0.15
PerL	m1	0.70	0.87	0.17	0.00
	m2	0.00	0.21	0.00	0.13
PerB	m1	0.03	0.68	0.02	0.00
	m2	0.02	0.07	0.01	0.48
GasM	m1	0.64	0.67	0.04	0.42
	m2	0.04	0.48	0.16	0.30
GasL	m1	0.72	0.83	0.61	0.18
	m2	0.00	0.26	0.14	0.54
Sol	m1	0.57	0.84	0.22	0.28
	m2	0.00	0.46	0.017	0.38

Table 3.5: CoD for injured subject 1 across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Table 3.5 provides an overview of the CoD values for injured subject 1. The Table shows that the CoD values are generally lower during the side hop movements. For instance, the CoD value for the gastrocnemius medialis in the initial measurement decreases from 0.64 during gait to 0.42 in the medial side hop.

This trend of decreasing CoD values is applicable to most muscles from the initial measurement to the follow-up measurement. For instance, the CoD value for the gastrocnemius medialis decreases from 0.67 in the initial measurement to 0.48 in the follow-up measurement. While an increase between measurements is a prevailing trend in certain cases, a notable exception can be observed in the activation of some muscles during certain movements like in the Peroneus Brevis muscle during the medial side hop. In the initial measurement (m1), the CoD value registers at 0.00. However, in the follow-up measurement (m2), this value increases to 0.48.

Muscle	m#	Gait	DJ	SH lateral	SH medial
Tib	m1	0	20.6	34.4	40.3
	m2	0	-5.2	15.3	-35.7
PerL	m1	13.6	2.0	21.6	-8.6
	m2	-25.6	-6.1	-15.6	-3.9
PerB	m1	8.3	5.8	-14.1	22.9
	m2	0	-6.4	5.7	-6.0
GasM	m1	0.7	-0.6	39.4	-0.6
	m2	-24.6	-3.2	-0.7	-13.9
GasL	m1	-4.0	1.8	-11.4	-1.4
	m2	-29.5	-3.9	0.5	-1.5
Sol	m1	9.3	1.7	-2.3	8.2
	m2	20.5	-2.5	-0.5	-9.6

Table 3.6: Difference in onset for injured subject 1 across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement in percentage of the movement cycle. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Table 3.6 presents the difference in muscle onset times between legs for subject 1 during the initial measurement (m1) and the follow-up measurement (m2). The most significant difference in onset values between the mean (± std) difference of healthy subjects and injured subject 1 is observed in the Peroneus Longus lateral side hop during the initial measurement, with values of 21.6 against 3.0 (16.1). Importantly, all onset values for Injured Subject 1 fall within the mean (± std) range of the healthy subjects. Furthermore, a trend is observed in the follow-up measurements where all values are lower than those in the initial measurement in the lateral side hop movement. The most notable change occurs in the gastrocnemius medialis, shifting from 39.4 to -0.7 in the follow-up measurement.

3.1.3 Injured Subject 2

Injured subject 2 is a female 28 years old and exhibited a noteworthy and severe level of injury on her right leg, as evidenced by their impairment in daily activities, including the inability to drive, during both the initial and follow-up measurements. This impairment extended to a level of caution observed in their movements during both the initial and follow-up measurements.

The mean normalized muscle activations for Injured subject 2 are displayed in Figure 3.3, the data for all other muscle groups can be found in Appendix .2 figure 11 to 14.

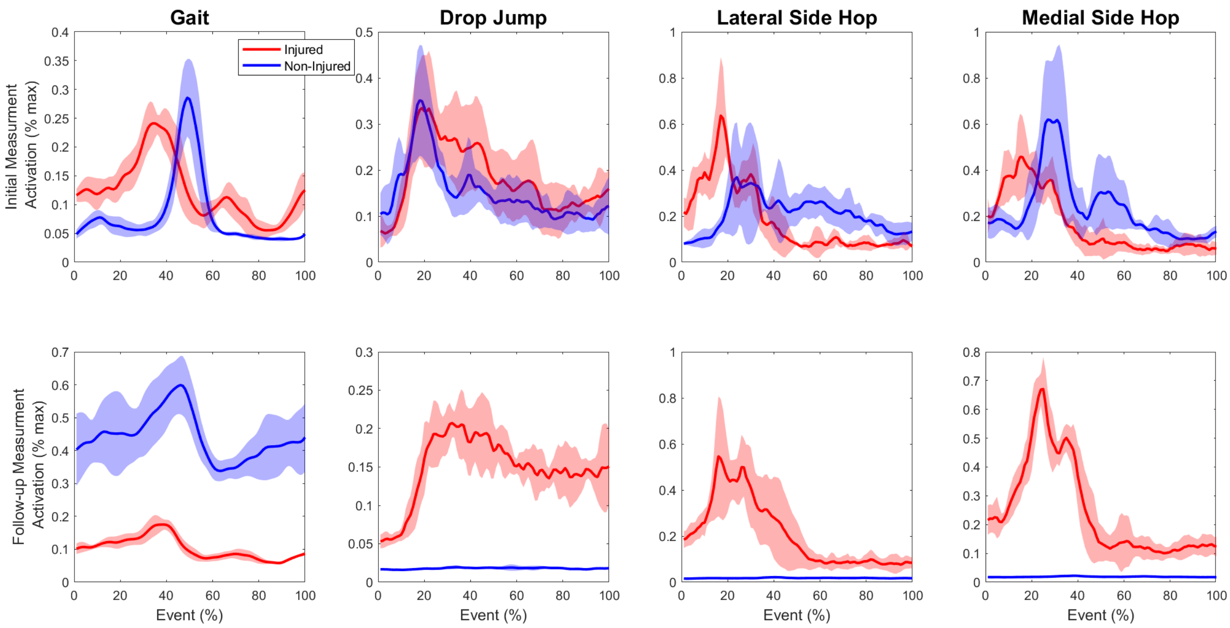

Figure 3.3: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the gastrocnemius lateralis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Figure 3.3 shows the muscle activation of the gastrocnemius lateralis, figure 13 shows the muscle activation of the gastrocnemius medialis, and figure 12 the soleus. All three of these muscles exhibit activation patterns similar to those of healthy subjects. These muscles show a consistent pattern during gait, characterized by either a single peak followed by deactivation or an initial activation, rapid deactivation, and subsequent fast reactivation. Notably, the double-peak activation pattern is more common in the non-injured leg muscles during gait, and the transition from activation to deactivation is much faster in these muscles.

The tibialis anterior activation is shown in 11 and displays a distinct pattern similar to that observed in healthy subjects in the gait movement. However, the peroneus longus and brevis (shown in figure 14 and 15) show more erratic activation patterns with multiple peaks, which are not consistent across legs or measurements. In contrast to the tibialis anterior, the gastrocnemius lateralis (figure 3.3) in the gait movement of the injured leg exhibits activation patterns with smaller peaks in both initial and follow-up measurements. This variation is consistent across the muscle groups in the gait movement for the injured subject.

During the drop jump movement, a consistent pattern is observed across all muscles, with a single activation peak and a gradual decline afterward. The activation peak is wider in the injured leg for all muscles and measurements, except for the peroneus longus (figure 15) and the gastrocnemius lateralis (figure 3.3) in the follow-up measurement. Furthermore, the maximum amplitude of all muscles in the drop jump is lower in the injured leg, except for the gastrocnemius lateralis in the follow-up measurement.

In the side hop movements, a consistent pattern is also evident across all muscles and measurements. This pattern includes either a single peak followed by deactivation or an initial activation, rapid deactivation, and subsequent fast reactivation. The double-peak activation pattern is more common in the non-injured leg muscles, and the transition from activation to deactivation is much faster in the non-injured leg muscles.

Finally, the maximum activation in the peroneus longus (figure 15) during the side hop movements is significantly lower for the injured leg muscles compared to the non-injured leg muscles, especially during the initial measurement. Although the activations remain lower for the injured leg muscles during the follow-up measurement, the difference is not as substantial.

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0.08	0.11	0.25	0.21
	m2	0.05	0.06	0.14	0.22
PerL	m1	0.13	0.20	0.33	0.33
	m2	0.07	0.07	0.17	0.20
PerB	m1	0.06	0.08	0.25	0.22
	m2	0.10	0.18	0.15	0.18
GasM	m1	0.15	0.08	0.29	0.17
	m2	0.09	0.08	0.19	0.23
GasL	m1	0.09	0.05	0.16	0.17
	m2	0.34	0.14	0.28	0.24
Sol	m1	0.08	0.04	0.17	0.22
	m2	0.05	0.05	0.26	0.22

Table 3.7: RMSE for injured subject 2 across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying RMSE values for the initial measurement (m1) and the follow-up measurement (m2) for injured subject 2 is provided in Table 3.7.

The table shows that the RMSE values for the peroneus longus displayed higher values of 0.33 in the initial measurement in the side hop movements, a marked difference from the healthy subjects that show a mean (± std) of 0.17 (0.05) in the lateral side hop. These RMSE values drop down in the follow-up measurement, reducing to 0.19 and 0.20. The peroneus brevis also exhibited high RMSE values in the side hop movements, registering 0.22 in the initial measurement for the lateral side hop, which decreased to 0.18 in the follow-up measurement.

In contrast, the soleus muscles during the drop jump movement demonstrated lower RMSE values for injured subject 2 (0.04 in m1 and 0.05 in m2) compared to healthy subjects (0.07 and 0.14).

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0.11	0.45	0.04	0.00
	m2	0.59	0.38	0.08	0.02
PerL	m1	0.02	0.70	0.01	0.04
	m2	0.09	0.68	0.20	0.02
PerB	m1	0.05	0.77	0.02	0.03
	m2	0.51	0.47	0.23	0.02
GasM	m1	0.16	0.63	0.00	0.02
	m2	0.34	0.29	0.02	0.05
GasL	m1	0.02	0.63	0.18	0.002
	m2	0.47	0.64	0.12	0.00
Sol	m1	0.29	0.73	0.09	0.05
	m2	0.28	0.19	0.00	0.1

Table 3.8: CoD for injured subject 2 across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying RMSE values for the initial measurement (m1) and the follow-up measurement (m2) for injured subject 2 is provided in Table 3.8.

the table shows there are fluctuations in CoD values between m1 and m2 across various muscle groups and movements. For instance, the tibialis anterior exhibits a substantial increase in CoD from m1 (0.11) to m2 (0.59) during the gait movement.

Conversely, in the peroneus longus, the CoD values remain relatively stable between m1 (0.02) and m2 (0.09) for the gait movement. This contrasts with the healthy subjects, whose CoD values display more consistent patterns.

When comparing subject 2's CoD values in the drop jump movement to those of healthy subjects for individual muscles, it is evident that subject 2 exhibits lower CoD values in both initial measurement (m1) and follow-up measurement (m2) for several muscles. For instance, the tibialis anterior in subject 2 shows CoD values of 0.00 (m1) and 0.02 (m2) in the lateral side hop, while healthy subjects have mean (± std) CoD values of 0.26 (0.20) in the lateral side hop.

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0	7.3	-12.1	-6.9
	m2	0	-16.3	-17.2	-19.9
PerL	m1	-6.4	0	-18.6	-1.8
	m2	0	-7.9	-30.5	-28.6
PerB	m1	29.0	10.1	-13.7	-1.8
	m2	-6.5	-22.8	-26.6	-16.8
GasM	m1	13.4	4.4	-19.0	0.2
	m2	-23.8	-10.8	-26.4	-19.4
GasL	m1	18.3	2.6	-18.9	-17.6
	m2	-26.1	-11.8	-34.4	-28.1
Sol	m1	17.0	6.3	-20.6	-20.3
	m2	3.7	-11.1	-23.6	-25.7

Table 3.9: Difference in onset times for injured subject 2 between legs across initial measurement (m1) and follow-up measurement (m2) for each muscle and movement in percentage of the movement cycle. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying the difference in onset values between both legs for the initial measurement (m1) and the follow-up measurement (m2) for injured subject 2 is provided in Table 3.9.

The onset values for tibialis anterior movement in the gait measurements for the initial measurement and the second measurement show a difference in onset values of 0 between legs. The largest disparity between the injured subject 2 and healthy subjects is observed in the initial gait measurement for the tibialis anterior, with a mean (± std) difference of -36.1 (-37.9) for healthy subjects and 0 for Subject 2. In the initial measurement for the gait, there is a consistent trend of lower values on the lateral side hop movement compared to the follow-up measurement across all muscles. For instance, gastrocnemius lateralis exhibits a decrease from -18.9 to -34.4. The majority of values in the table appear to be negative.

3.1.4 Injured Subject 3

Injured subject 3 is a male of 25 years old and experienced a lateral ankle injury on his left leg. In contrast to the challenges faced by the other subjects, injured subject 3 exhibited a markedly different scenario. Notably, this subject was not impaired in their daily life by any means. Furthermore, they were further along in the physiotherapy recovery process, having already practiced the requisite movements multiple times during their physiotherapy sessions. This advanced state of rehabilitation was reflected in the subject's demeanor, appearing confident and swift when performing the movements during both the initial and follow-up measurements.

The mean normalized muscle activations for Injured subject 3 are displayed in Figure 3.4, the data for all other muscle groups can be found in Appendix .2 figure 16 to 19.

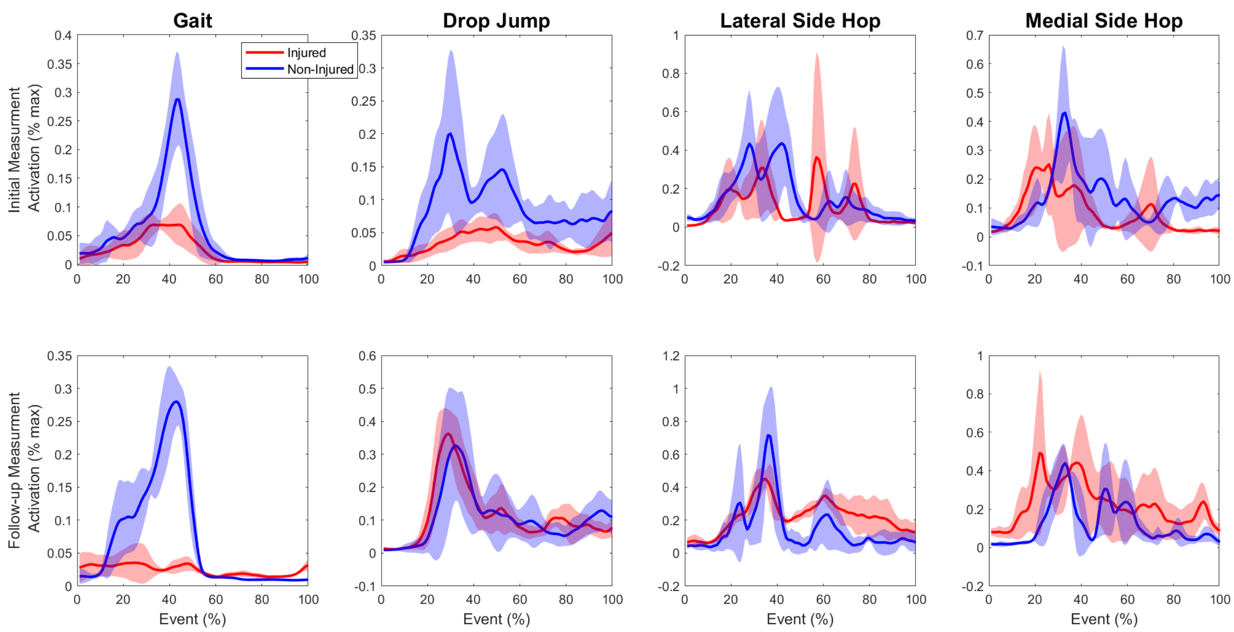

Figure 3.4: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the gastrocnemius lateralis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Figure 3.4, 18, and, 7 shows that the gastrocnemius medialis, gastrocnemius lateralis, and soleus, show a consistent pattern of a single activation peak. This consistency is maintained across both legs and measurements, with the exception of the gastrocnemius lateralis muscle activation in the injured leg during the follow-up measurement. It's notable that the muscle activation peak in the injured leg is generally wider for all these muscles in various movements.

Figure 16 shows the tibialis anterior muscle exhibits a consistent activation pattern during the Gait movement, which closely resembles the pattern seen in healthy subjects. This pattern consistency is observed across both legs and measurements.

On the other hand, figure 19 and figure 20 show the peroneus brevis and peroneus longus muscles exhibit a more erratic pattern during Gait, which is distinct from the regularity seen in healthy subjects. While these muscles sometimes display a single activation peak, akin to healthy plantar flexors during Gait, they also reveal patterns more akin to the tibialis anterior Gait pattern at times.

In the drop jump movements, all the muscles exhibit patterns that are relatively consistent across both legs and movements. However, a notable exception is observed in the non-injured leg muscles, where the peroneus brevis and peroneus longus display a more parabolic-like figure, deviating from the activation patterns seen in the healthy subjects.

The side hop movements reveal more complex and less consistent muscle activations. A general pattern of an initial activation followed by a decrease can be observed, but certain muscles, such as the gastrocnemius lateralis (figure 3.4), display two-peak activations, particularly evident in the non-injured leg muscles. The presence of multiple prominent peaks is more pronounced in the measurements of the non-injured leg muscles.

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0.08	0.08	0.14	0.16
	m2	0.06	0.09	0.21	0.11
PerL	m1	0.11	0.24	0.19	0.14
	m2	0.12	0.20	0.30	0.24
PerB	m1	0.06	0.11	0.11	0.13
	m2	0.11	0.17	0.21	0.17
GasM	m1	0.04	0.05	0.23	0.19
	m2	0.05	0.10	0.14	0.09
GasL	m1	0.06	0.06	0.13	0.10
	m2	0.09	0.04	0.13	0.14
Sol	m1	0.09	0.13	0.25	0.25
	m2	0.02	0.09	0.08	0.12

Table 3.10: RMSE values for injured subject for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying RMSE values for the initial measurement (m1) and the follow-up measurement (m2) for injured subject 3 is provided in Table 3.10.

The table shows differences in RMSE values between the initial measurement (m1) and the follow-up measurement (m2). For instance, the tibialis anterior muscle shows a decrease in RMSE from 0.08 (m1) to 0.06 (m2) during the Gait movement. Similarly, the peroneus brevis exhibits a decline in RMSE values from 0.06 (m1) to 0.11 (m2) during the Gait movement, suggesting a significant increase in variability between m1 and m2.

During the Gait movement, the tibialis anterior RMSE values for injured subject 3 (0.08 in m1 and 0.06 in m2) differ from healthy subjects (0.10 with a standard deviation of 0.07). Conversely, the peroneus brevis RMSE values for the injured subject (0.06 in m1 and 0.11 in m2) in the Gait movement contrast with the healthy subjects (0.07 with a standard deviation of 0.03).

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0.52	0.65	0.32	0.23
	m2	0.55	0.41	0.23	0.33
PerL	m1	0.15	0.76	0.13	0.11
	m2	0.41	0.01	0.01	0.32
PerB	m1	0.54	0.89	0.28	0.28
	m2	0.34	0.23	0.31	0.43
GasM	m1	0.76	0.67	0.041	0.13
	m2	0.76	0.14	0.05	0.52
GasL	m1	0.76	0.60	0.11	0.12
	m2	0.27	0.78	0.53	0.31
Sol	m1	0.72	0.77	0.28	0.21
	m2	0.81	0.01	0.76	0.49

Table 3.11: CoD values for subjects 03 for each muscle and movement. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

The table displaying CoD values for the initial measurement (m1) and the follow-up measurement (m2) for injured subject 3 is provided in Table 3.11.

Table 3.11 shows a consistent increase in CoD values across various muscles and movements between m1 and m2. For example, the tibialis anterior exhibits this trend during the Gait movement, with CoD values rising from 0.52 (m1) to 0.55 (m2).

Notable changes in CoD values are observed between the initial measurement (m1) and follow-up measurement (m2). For instance, in the drop jump movement, the peroneus brevis and longus exhibit decreases in CoD values, transitioning from 0.89 (m1) to 0.0.23 (m2) and the peroneus longus shows a decrease from 0.76 (m1) to 0.01(m2). The CoD does not seem to increase or decrease consistently during measurements as shown for example in the peroneus longus that increases in the gait (0.41 in m1 to 0.41 in m2) and the lateral side hop (0.11 in m1 and 0.32 m2), but showing a decrease in the CoD values in the drop jump (0.76 in m1 to 0.01 in m2) and the medial side hop (0.13 in m1 and 0.01 in m2) between measurements.

When comparing the CoD values of subject 3 in Table 3.11 to those of healthy subjects in Table 3.2, notable differences emerge. Specifically, the CoD values for the peroneus longus and peroneus brevis are higher, particularly in the lateral side hop, during the follow-up measurement. In the follow-up measurement, the peroneus longus exhibits a CoD value of 0.32, while the Peroneus Brevis has a CoD value of 0.43. In contrast, healthy subjects display lower CoD values, with a mean (± std) of 0.13 (0.15) for the peroneus longus and 0.13 (0.16) for the peroneus brevis.

Muscle	m#	Gait	DJ	SH medial	SH lateral
Tib	m1	0	-0.1	3.8	-2.2
	m2	0	-8.6	16.0	33.1
PerL	m1	-2.3	4.0	-7.5	-16.3
	m2	60.2	-27.2	0.3	-6.5
PerB	m1	-1.8	7.7	-26.4	-24.9
	m2	68.3	-3.8	-4.5	-6.1
GasM	m1	-0.4	4.9	-18.6	14.0
	m2	-8.5	-7.0	-14.0	-6.45
GasL	m1	-20.1	4.6	-18.5	-6.3
	m2	0	-4.2	-12.8	-2.1
Sol	m1	-4.4	22.3	-7.6	-20.2
	m2	0.5	-14.8	1.9	-1.8

Table 3.12: Difference in onset values for injured subjects 03 between legs for each muscle and movement in percentage of the movement cycle. Where m1 is the initial measurement (sub31), m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

In Table 3.12, the disparities in onset timing between legs for Injured Subject 3 are shown. The tibialis anterior exhibits a consistent 0 value in the gait movement during both the initial and follow-up measurements.

Distinct patterns emerge in the lateral side hop movement. In the initial measurement, the peroneus longus shows a value of 16.3, and the peroneus brevis registers -24.9. In contrast, the follow-up measurement reveals a shift, with the peroneus longus at -6.5 and the peroneus brevis at -6.1. Showing a decrease in between measurements for the lateral side hop for these muscles. Notably, more than half of the values in the table present a negative trend.

3.2 Suggested Protocol

3.2.1 Introduction

In the preceding sections of the results, various movement metrics and muscle activations have been elucidated, providing physiotherapists with possible indicators to assess a patient's readiness to return to sports. However, the practical application of this information necessitates the formulation of a structured protocol. This protocol serves as a guide for physiotherapists, aiding them in efficiently incorporating the identified metrics into their clinical assessments.

To ensure the protocol's feasibility in real-world physiotherapy settings, certain key requirements must be met. Recognizing that physiotherapists typically have limited time slots, either 25 minutes or 50 minutes, the protocol should ideally be designed to fit within these constraints. This time-efficient approach allows physiotherapists to conduct the necessary measurements while still accommodating other essential tasks within the given time frame.

Moreover, the protocol should be adaptable to regular gym settings or open spaces. Cost considerations are also paramount, as the protocol should be designed with sensitivity to the financial constraints faced by healthcare practitioners. Minimizing the use of expensive materials ensures accessibility and applicability in a variety of clinical settings. The patient must undergo a physical examination by a qualified physiotherapist or other medical expert to assess their readiness and eligibility to perform the prescribed tests. Clearance for specific tests should be based on the professional judgment and evaluation of the physiotherapist or medical expert.

Addressing the challenges identified by Laura McManus et al. in 2020, the protocol should prioritize simplicity to bridge the gap between EMG data and practical application in physiotherapy. A significant barrier highlighted in the research is the limited familiarity of physiotherapists with EMG data. To overcome this hurdle, the protocol should ensure that the measurements generate outcomes that are straightforward and require minimal additional education for interpretation.

Ensuring a balance between efficiency, practicality, and cost-effectiveness is paramount, all the while upholding a high level of accuracy in outcomes that are easily interpretable by physiotherapists. Striking this balance is essential to provide physiotherapists with a reliable tool that aids in determining a patient's readiness to return to sports, contributing to the enhancement of clinical practices within the constraints of real-world rehabilitation scenarios.

In the application of this protocol, it is recommended to integrate it towards the concluding phases of the patient's treatment, serving as an additional objective measurement tool for physiotherapists. This protocol is envisaged as an extension of the existing tools utilized by physiotherapists and not as a replacement. Its purpose is to furnish physiotherapists with an extra layer of objective assessment as they approach the decision-making process regarding a patient's readiness to return to sports. By incorporating this protocol into the comprehensive treatment plan, physiotherapists can gain nuanced insights, contributing to a more well-rounded evaluation of a patient's rehabilitation progress.

3.2.2 Materials

Several materials are needed to guarantee precise data collection and create an optimal environment for executing this protocol. The primary instrumentation includes three Inertial Measurement Units (IMUs) sourced from Xsens (MVN Link, Xsens, Enschede, the Netherlands), proficient in recording data at a frequency of 100 Hz. To secure these IMUs onto patients, three neoprene Velcro bands are required, ensuring a comfortable and adjustable fit during various movements.

In tandem with motion tracking, muscle activation data will be acquired using two bi-polar surface electromyography (sEMG) sensors. to secure these imu's to the patient neoprene velcro straps or tape can be used.

Matlab software (Matlab 2018a, MathWorks, Natick (MA), USA) is necessary for processing the data collected by the sensors, with compatibility extending to newer versions. Additionally, a computer or laptop is needed to run this software seamlessly.

To facilitate specific tasks outlined in the protocol, a platform with a height of 25 cm for standardizing conditions during drop jumps. Furthermore, two lines spaced 30 cm apart are required on a grippy floor to execute the side hop.

Lastly, an unobstructed room should provide patients with ample space to perform the prescribed movements without hindrance. The minimum requirement is an unrestricted space of one by two meters, although a larger area is preferred for optimal maneuverability and safety.

3.2.3 Method

The initial step involves placing three IMUs on the patient's body. Two sensors are affixed to the feet, and one sensor is positioned on the sacrum. The recommended placement is illustrated in Figure 3.5, utilizing either neoprene Velcro straps or the patient's shoe laces.

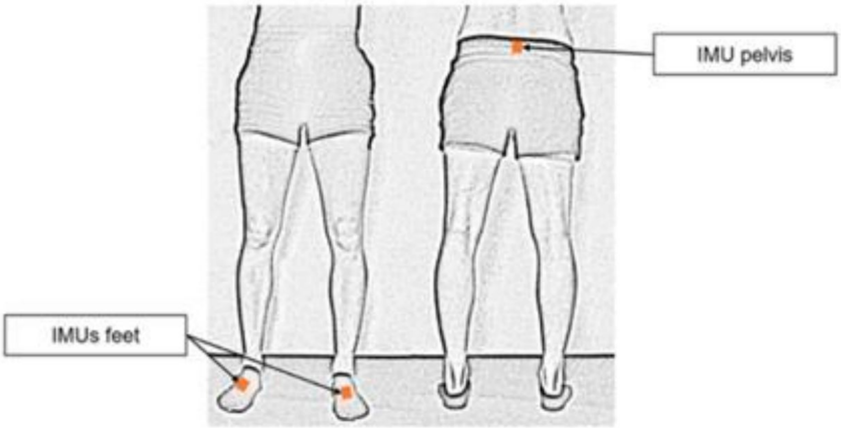

Figure 3.5: IMU Placement for the Protocol. Adapted from [1].

For IMU calibration, a combined methodology inspired by Bonnet et al. (2009) [29] and C.R. Derla et al. (2023) is employed. The calibration phase includes the following steps:

1. **Initial Standing Still Position:** patients stand still with their feet shoulder width apart for 10 seconds.
2. **Bending Forward:** patients are then instructed to bend forward, facilitating the estimation of the orientation of the Y-axis of the pelvis.
3. **Gait:** The patient is guided to walk 10 steps, stop, and then walk backward.

The duration and repetitions of these calibration movements may vary, but the system will notify the physiotherapist when the calibration process is complete.

Following IMU placement and calibration, the subsequent step involves positioning two bi-polar sEMG sensors. These sensors are placed on the peroneus longus muscles for both the left and right leg following the steps shown below.

patient Positioning:

- Have the patient lie in a supine position.

Landmark Identification:

- Mark the lateral malleolus and the fibula head on the leg.
- Make a third mark at 25% of the distance from the fibula head to the lateral malleolus, following SENIAM guidelines as shown in Figure 3.6.

Clean-Up:

- Clean the skin of any residue and wipe with an alcohol wipe before affixing the EMG sensor.

Placement:

- Affix the EMG sensor between the two marks on the third marked spot.
- Orient the sensor in the longitudinal direction of the shank and peroneus longus muscle fibers.

Secure sensors:

- Use tape or neoprene Velcro straps to secure the EMG sensor to minimize potential movement artifacts.

Functional Testing:

- Test the EMG signal by having the patient perform eversion while standing on the opposite leg from the leg with the previously placed EMG sensor.
- Test for the interference of the tibialis anterior by letting the patient perform dorsal flexions.

Quality Check:

- Ensure satisfactory signal quality during functional testing.

- If low to no signal change is observed during the eversion or if high signals are observed in the dorsal flexion, remove the sensor, wipe the location clean, and reapply the sensor.

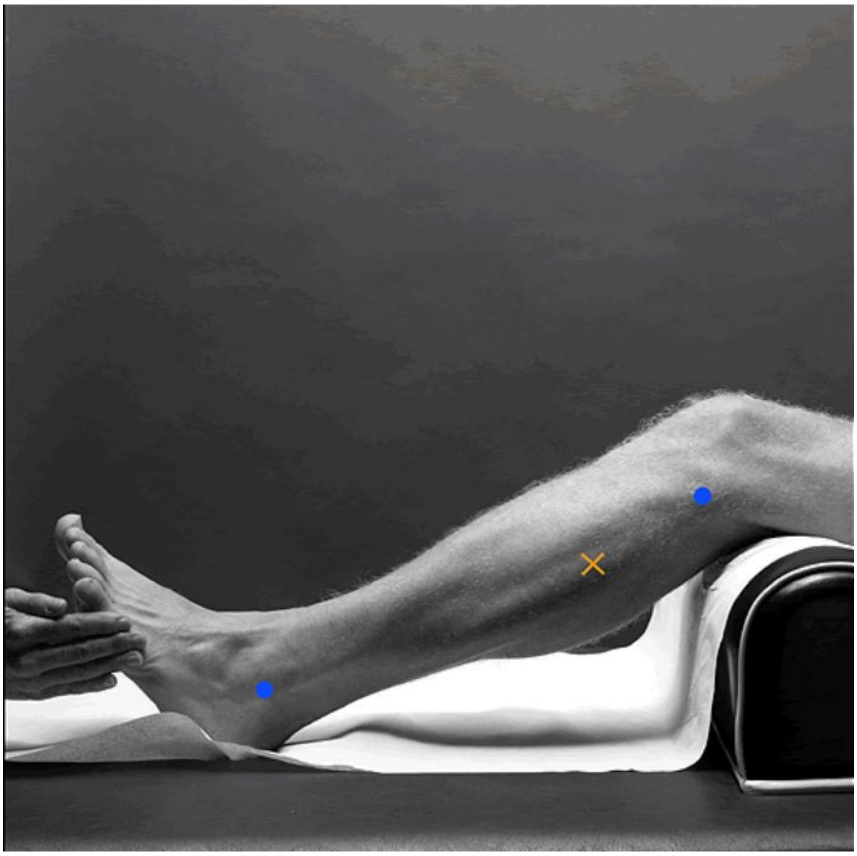

Figure 3.6: EMG Placement for the Protocol. Adapted from the SENIAM guidelines [2].

Once all the sensors are placed correctly, and calibrations are completed, the physiotherapist guides the patient on how to execute the drop jump. Providing a clear example of both correct and incorrect movements, the physiotherapist communicates clearly, when a test is considered either correct or incorrect.

Subsequently, the patient performs one set of five well-executed repetitions of the drop jump using the injured leg. A brief rest period of around 60 s follows, allowing the patient to recover if needed, before proceeding with one set of five repetitions of the drop jump movement using the non-injured leg. The physiotherapist, in collaboration with the software, promptly identifies and communicates any deviation from the standard in the patient's movements. This protocol is iterated through a total of three sets for each leg.

Following the drop jump assessment, the same procedure is repeated for the side hop movement. The physiotherapist takes the time to explain to the patient the criteria for a good repetition and provides clear examples of both acceptable and unacceptable movements if necessary.

Subsequently, the patient embarks on one set of ten repetitions for the side hop, comprising five lateral hops and five medial hops for the injured leg. After completion, a brief rest period is allowed if required before progressing to one set of ten side hop repetitions for the non-injured leg. This sequence is replicated for a total of three sets per leg. The physiotherapist will communicate to the patient and the software when a repetition is deemed incorrect.

The sets, repetitions, and rest periods are shown in Table 3.13. A summary of the protocol is shown in Table 3.14.

Table 3.13: Overview of Drop Jump and Side Hop sets and repetitions.

Movement	**Leg**	**Sets**	**Repetitions**	**Rest Interval (if needed)**
Drop Jump	Injured	3	5	± 60 s
Drop Jump	Non-Injured	3	5	± 60 s
Side Hop	Injured	3	10 (5 lateral, 5 medial)	± 60 s
Side Hop	Non-Injured	3	10 (5 lateral, 5 medial)	± 60 s

Note that the sets, reps, and rest periods mentioned in this protocol are suggestions. The physiotherapist holds the authority to determine the appropriate workload based on the patient's condition. If the physiotherapist deems the patient fatigued or observes any factors that warrant premature cessation, the physiotherapist has the final say. It is important to acknowledge that a lower number of repetitions might impact the accuracy of the outcome.

Table 3.14: Drop Jump and Side Hop Protocol Overview

Step	Action
1	Drop Jump with the Injured Leg (5 reps)
	Rest if needed
2	Drop Jump with the Non-Injured Leg (5 reps)
	Rest if needed
3	Repeat Steps 1 and 2 for a total of 3 sets
4	Side Hop with the Injured Leg (10 reps: 5 lateral, 5 medial)
	Rest if needed
5	Side Hop with the Non-Injured Leg (10 reps: 5 lateral, 5 medial)
	Rest if needed
6	Repeat Steps 4 and 5 for a total of 3 sets

3.2.4 Data Processing

The processing of collected data involves several key steps to ensure meaningful and accurate results:

1. **Filtering and Normalization:** The acquired data will undergo filtering and normalization procedures as detailed in the Signal Processing section in 2.0.7 Metrics for Determining return-to-sports level of the methodology report. This ensures that the data is refined and standardized for subsequent analysis.

2. **Cycle Detection:** The estimation of Ground Reaction Forces (GRF) from the IMUs will be utilized for cycle detection during the drop jump. This involves identifying the moment of impact to detect drop jump cycles accurately. The estimated GRF, coupled with the vertical movement of the sacrum, enables the detection of distinct phases such as loading, push-off, flight, and landing. This approach parallels the methods outlined in the Drop Jump Cycle Detection and Side Hop Cycle Detection sections of the methodology. However, in this protocol, IMUs are employed to estimate ground reaction forces instead of using force plates and to detect vertical sacrum movement instead of retro-reflective markers.

3. **RMSE:** RMSE value will be calculated based on the procedures described in 2.0.7 Metrics for Determining return-to-sports level section of the methodology.

3.2.5 Output and Clinical Application

The protocol's outcomes provide insights, primarily conveyed through RMSE values, with a specific emphasis on the peroneus longus muscle during lateral and medial side-hop, as well as drop-jump movements. To complement the numerical data, visual representations in the form of mean EMG signals per leg will be presented. These signals illustrate the percentage of repetitions on the x-axis and amplitude values ranging from 0 to 1 on the y-axis. This visual representation aims to offer a better understanding of muscle activity throughout each movement. These visual representations closely resemble the figures presented in the preceding section of the results.

3.2.6 Clinical Application

The RMSE values act as precise quantitative measures, delineating the amplitude disparities between the injured and non-injured legs throughout specific movements. To enhance interpretability, the RMSE values will be colour-coded, each colour signifying a different level of significance as shown in figure 3.7. In the context of the drop jump, an RMSE value below 0.08 is represented by the colour green, indicating no difference compared to healthy subjects. For values falling between 0.08 and 0.13, the colour transitions gradually from yellow to red, signifying RMSE values at the higher end of occurrence within healthy subjects. An RMSE value equal to or exceeding 0.13 is denoted as red, highlighting values surpassing the typical range observed in healthy subjects. The colour representations for the lateral and medial side hop movements follow the same scheme, with distinct value ranges for each. Similar to the drop jump, the specific RMSE value thresholds for colour transitions are adjusted to match the characteristics of each movement.

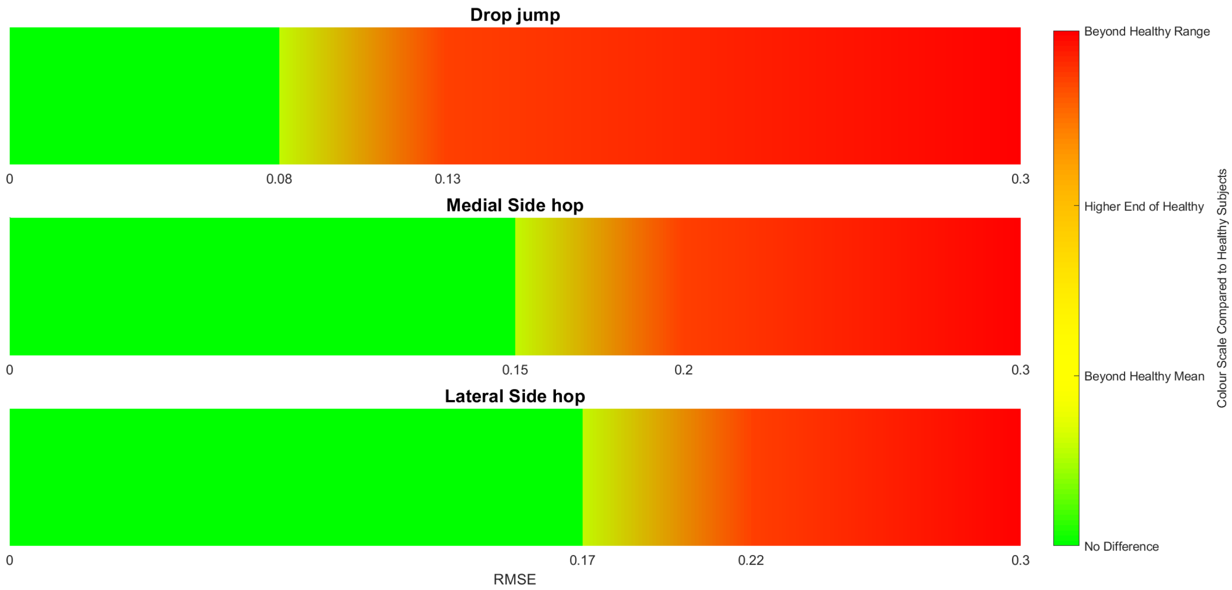

Figure 3.7: Visual indication of the colour coding for the RMSE values

Accompanying the numerical metrics, a mean (± std) signal plot per leg is presented, providing physiotherapists with an additional semi-subjective assessment tool. This visual representation aids in comprehending the overall muscle activation patterns during the prescribed movements.

Physiotherapists can integrate these RMSE values and plot assessments with other subjective evaluations currently in use, such as the Ganganalyselijst Nijmegen (GALN) [11]. This integration provides a comprehensive and more objective perspective to assess a patient's readiness for a return to sports activities. Additionally, EMG data provides the physiotherapist with more insights into the patient's muscle control.

Chapter 4

Discussion

This research was guided by two primary objectives. The first was to assess the feasibility of sEMG as a diagnostic tool for determining a patient's readiness to return to sports following lateral ankle sprains. The second objective aimed to investigate the baseline left-right differences in muscular activation among healthy individuals, establishing a normative range for a scientifically sound and practical threshold for evaluating a patient's readiness for return to sports.

Root Mean Square Error (RMSE) has emerged as a potentially valuable metric in the context of injury detection and recovery assessment. While further research is necessary to firmly establish its utility, preliminary indications suggest that RMSE may hold promise for evaluating a patient's readiness to return to sports. Notably, the consistency of muscle activation patterns between the injured and non-injured limbs appears to be a significant marker in this regard. This conclusion aligns with the findings of Sole et al. (2011), who observed that "decreased strength and EMG activation in a lengthened hamstrings range for athletes with prior hamstring injury suggested a change in neuromuscular control" when employing RMSE to assess strength disparities between injured and non-injured legs [30]. This finding is also consistent with the findings of Kollmitzer et al. (1999), who reported that their data revealed highly reliable short-term and acceptably reliable long-term EMG measurements in both the amplitude (RMSE) and frequency domains when looking at the reliability of sEMG measurements [31].

In contrast, the Coefficient of Determination (CoD) exhibited variability that made it less reliable as an indicator of injury or recovery. While a peak matching approach could potentially address this issue, our research did not provide sufficient evidence to support its feasibility. To the best of our knowledge, CoD values for comparing EMG patterns between injured and non-injured legs have not been utilized before this study.

The difference in muscle onset between legs does not appear to be a reliable indicator of injury or injury recovery, as there is a lack of consistent patterns observed between healthy subjects and injured subjects, as well as between the initial measurement and the follow-up measurement. In some instances, a difference in onset times of 0 was observed in the tibialis anterior in the gait movement, after looking at the individual onset times it showed that the onset occurred immediately from the start of the movement cycle for both legs. This occurrence suggests that the applied onset threshold might be too low or not suitable for the detection of the tibialis anterior pattern in the gait movement. The elevated standard deviation in the healthy subjects' data poses a challenge when comparing values with those of the injured subjects. The wide variability makes it difficult to discern clear trends or significant differences. A notable observation is that a majority of onset values for injured subjects are negative, indicating a delay in activation in the non-injured leg compared to the onset. This contradicts existing research consistently demonstrating that injured muscles typically exhibit a delay in onset compared to their healthy counterparts[18, 19, 20, 21, 22, 23]. The discrepancy suggests the need for careful consideration and potential refinement of the onset determination methodology for accurate assessments.

The research suggests that the most effective movement for detecting differences in muscle activation patterns related to ankle injuries is the drop jump. Future studies should consider the use of this movement to enhance the accuracy of assessments and their clinical relevance. This finding aligns with the research conducted by Fransz et al. (2018), Herb et al. (2018), and Pedley et al. (2020) all of which emphasize the value of the drop jump as a diagnostic tool for predicting ankle injuries and assessing ankle instability [32, 33, 34].

The side hop also holds potential, but it would benefit from more trials and additional time for subjects to practice this challenging movement, ensuring more consistent data. This observation is consistent with the findings of Yoshida et al. (2018), which identified differences in EMG signals in the leg affected by an ankle sprain during the side hop movement. [35]

Furthermore, the Peroneus Longus and Peroneus Brevis muscles have shown promising indications as potential indicators of muscle injury and recovery, particularly in side hop movements. This observation aligns with the study conducted by Palmieri-Smith et al. (2009), in which differences in activation patterns were identified in both peroneus muscles of patients with lateral ankle injuries compared to healthy subjects [36]. This observation aligns with the findings of Yoshida et al. (2018), which indicate a decrease in peroneus longus activity during the side hop in individuals with injured ankles [35].

The Plantar Flexor muscles, especially in the drop jump movement, have demonstrated potential as valuable indicators for muscle injury and recovery, and, consequently, readiness to return to play. This finding is consistent with the study conducted by Yoshida et al. (2018), where the side hop movement revealed differences in activation patterns in both gastrocnemius muscles [35]. However, it is noteworthy that Yoshida's research also demonstrated differences in tibialis anterior activation, which were not as pronounced in this study.

4.0.1 Limitations of the Study

Limitations during the measurement

In the course of our study, several limitations in the measurements warrant discussion. These limitations have implications for the interpretation of the results and the broader applicability of our findings.

First and foremost, the limited number of subjects, specifically four healthy individuals and three injured subjects, poses a significant constraint. This constrained sample size resulted in a notably high standard deviation in the mean across all the healthy subjects. Consequently, it became challenging to discern whether small deviations observed between the legs of the injured subjects were primarily due to their injuries or within the realm of normal deviations seen in healthy individuals. A larger and more diverse subject pool could have provided more robust and generalizable insights into the differences in muscle activation between the injured and unaffected legs.

Another noteworthy limitation pertains to the use of two different systems for the measurement of EMG data. The application of a garment for the non-dominant or injured leg and the Delsys system for the dominant or non-injured leg introduced a degree of variability. While it is theoretically expected that both systems should yield similar muscle activation readings after processing, the use of two distinct systems raises concerns regarding the consistency of the measurements. A more consistent approach, involving a single system, might have enhanced the precision and reliability of the data.

Furthermore, the study incorporated a setup in which subjects wore a backpack with the TMSI SAGA, and several cables extended from this backpack. This configuration, while essential for data collection, had the potential to impede the natural movement of the subjects during the assessments. Such impediments may have influenced the measurements by altering the subjects' gait and movement patterns.

Additionally, the requirement for subjects to walk with one foot on one force plate and the other foot on a separate force plate introduced variability in gait patterns. This was particularly evident in the forced and unnatural appearance of some subjects' gait. The inconsistency in gait patterns between subjects and even within gait cycles for the same patient may have affected the measurements' reliability. A more standardized and natural gait assessment approach, without a predetermined location for subjects to place their feet, could have mitigated this source of variability.

Moreover, it is important to recognize that, despite the existence of guidelines for when measurements were to be taken, not all injuries are created equal. Lateral ankle injury, while commonly categorized under a single term, encompasses a spectrum of injury types and severities. This inherent diversity makes it challenging to directly compare the different injured subjects in our study. The variation in injury characteristics, such as the location, extent, and nature of the damage, could introduce additional nuances and complexities to the interpretation of the results. Furthermore, it is worth noting that the four-week interval between measurements might not provide sufficient time to detect meaningful differences, especially given the limited number of trials that could be conducted in this study.

Finally, it is important to highlight that the study did not differentiate between dominant and non-dominant leg injuries among the injured subject group. This distinction could be significant, as there may be variations in muscle activation and recovery patterns between these two subgroups. Recognizing the potential differences in muscle activation and recovery trajectories in dominant versus non-dominant leg injuries is essential for a more comprehensive understanding of lateral ankle sprains and the role of EMG in the rehabilitation process.

Signal Analysis

In the realm of data processing, certain limitations must be addressed to provide a comprehensive understanding of the study's methodology and its potential impact on the results.

Firstly, the normalization of EMG signals in the study was executed by identifying the maximum activation across all trials. However, a noteworthy consideration arises from the fact that, at times, subjects executed movements between repetitions that achieved the maximum muscle activation for a specific muscle. For example, during activities such as stepping back onto a platform after a drop jump, subjects were not provided specific instructions on how to perform this action. Consequently, variations could occur in the normalization factors between both legs if, for instance, a subject primarily employed their dominant leg for stepping up. These nuances introduce complexities in comparing amplitude values between legs, as the variations in the normalization process could influence the results.

Furthermore, an observation pertains to the gait patterns of the peroneus longus and the peroneus brevis muscles, which sometimes resembled the activation pattern of the tibialis anterior. However, it's important to note that this similarity was not consistent across all patients or legs. One plausible explanation for this inconsistency may be the suboptimal placement of EMG sensors. It's conceivable that the signals from the peroneus muscles might have been subject to interference from the tibialis activation due to sensor placement variations. Therefore, the interpretation of EMG data pertaining to these specific muscles should be undertaken with caution.

Lastly, the method of repetition detection in our study, while generally effective, is not without limitations. Each subject has unique movement patterns, and these patterns may differ between the two legs. While the repetition detection algorithm generally works well, it occasionally demonstrates a subtle translation between the signals of both legs. This translation might be attributed to the subjects' slightly distinct execution of exercises between legs, resulting in signal variations. Consequently, the CoD may appear low even when the EMG signals exhibit similar shapes.

4.0.2 Suggested protocol

This section aims to provide insight into the rationale behind the major choices made in the development of the protocol. The collaborative effort with physiotherapists from TopVorm Twente played a crucial role in establishing the requirements that form the foundation of this protocol. By engaging with these physiotherapists, the protocol was sought to align with real-world physiotherapy practices and ensure its relevance and feasibility in clinical settings. The ensuing discussion will shed light on key considerations and decisions, illustrating the thought process that guided the development of this protocol.

The decision to conduct three sets of five trials each was made in consultation with the physiotherapist to align with their typical patient strain and rehabilitation practices. The specific instructions and techniques for performing the drop jump and side hop were provided by the physiotherapist at TopVorm Twente, ensuring consistency with established rehabilitation protocols.

The choice of utilizing three IMUs in this specific configuration is grounded in findings from relevant research studies. Reh et al. (2021) demonstrated the efficacy of this configuration in detecting various phases of the gait cycle [37]. Additionally, insights from a study by C.R. Derla et al. (2023) and Bonnet et al. (2009) supported the use of this configuration including the calibration method as a cost-effective and simplified method for estimating ground reaction forces (GRF) [1, 29]. While past applications of this setup haven't specifically focused on cycle detection in a drop jump, the configuration is anticipated to be proficient in capturing the impact with the floor after a drop jump, given the substantial increase in GRF during this phase.

The integration of estimated GRF and vertical acceleration data from the sacrum IMU is anticipated to facilitate the identification of distinct phases in the side hop movement. These phases include the loading phase, air phase, and landing phase. While specific research on cycle detection for the side hop is currently lacking, it is assumed that the effectiveness of this configuration in discerning various phases of the gait cycle could extend to the detection of high impacts with the floor and vertical accelerations of the sacrum in the side hop as well. This assumption is further supported by the findings of this report. This report demonstrates that the vertical displacement of the sacrum serves as a proper metric for detecting side hop cycles. Therefore, the integration of data from the sacrum IMU, coupled with the established efficacy in gait cycle phases, is expected to provide a comprehensive basis for anticipating successful cycle detection in the side hop movement.

Pressure insoles could be considered as an alternative for the use of IMUs, however, when assessing the most effective method for detecting side hop cycles, this report found that force plate data lacked the consistency needed for cycle determination of the side hop movement. If future research demonstrates the feasibility of using pressure insoles for this purpose, they could potentially replace the IMUs in the protocol.

The selection of bi-polar sEMG sensors stems from their user-friendly nature for physiotherapists, minimal invasiveness, relatively affordable cost, and extensive research supporting their efficacy. The sensor placement protocol follows the guidelines outlined in the Surface EMG for a Non-Invasive Assessment of Muscles (SENIAM) [2]. Additionally, the placement of sensors on the peroneus brevis muscle was cross validated using the research conducted by Reeves et al. in 2019 [38], ensuring a clear signal without interference from neighboring muscles.

In Table 4.1, the RMSE values of the peroneus longus muscle are detailed for both the drop jump and lateral side hop movements.

Mus/Mov	Healthy	Sub 1m1	Sub1m2	Sub 2m1	Sub2m2	Sub3m1	Sub3m2
SH lat	0.17 (0.05)	0.21	0.12	0.33	0.17	0.19	0.30

Table 4.1: RMSE Values for peroneus longus in the drop jump (DJ) and lateral side hop (SH lat) Movements

Peroneus longus was selected in conjunction with the lateral side hop due to its observed mean (±std) for healthy subjects being 0.17 (0.05) in this movement. The initial measurements for injured subjects revealed values of 0.21 (subject 1), 0.33 (subject 2), and 0.19 (subject 3), all indicating slight to significant elevations. These values align with the observed injury severity, as subject 2, the most severely injured, demonstrated the highest difference, while subject 3, the least injured, exhibited the lowest value. Additionally, Peroneus longus displayed a discernible reduction in subjects 1 and 2 between the initial and follow-up measurements, underscoring its sensitivity to variations in muscle activity during the rehabilitation process, particularly in conjunction with the side hop movement.

The selection of Peroneus longus in conjunction with the drop jump is motivated by the findings in injured subjects 2 and 3. In the initial measurement, injured subject 2 exhibited a substantial increase with an RMSE value of 0.20 compared to the healthy mean (±std) of 0.08 (0.05). Similarly, subject 3 showed an elevated value of 0.24 in the initial measurement. These values also demonstrated a decrease in the follow-up measurements, with injured subject 2 registering an RMSE value of 0.07, and injured subject 3 measuring 0.20. This highlights the sensitivity of Peroneus longus to alterations in muscle activity during the rehabilitation process, when combined with the drop jump movement.

The inclusion of the medial side hop in the protocol stems from its alignment with the current practices of physiotherapists, where a continuous jump alternating between medial and lateral jumps is employed. Despite potentially yielding less clear-cut indicators compared to previously mentioned movements, the medial side hop provides insights into the patient's readiness for a return to sports while its integration does not impose additional time, financial, or spatial burdens on both patients and physiotherapists.

The integration of colour-coded RMSE values into the protocol was a collaborative decision made during discussions with the physiotherapist from Topvorm Twente. This enhancement addresses the challenges identified by L. McManus (2020) by providing a more intuitive interpretation of RMSE values for physiotherapists [3]. In this colour-coding system, a green RMSE value is considered when it falls below the mean value of healthy subjects. Yellow to orange indicates values above the mean of healthy subjects, while orange to red signals values exceeding the mean plus standard deviation of healthy subjects. It's important to note that as further research is conducted with increased trial data, these threshold values may be subject to adjustment.

The decision to exclude the plantar flexors, such as the gastrocnemius lateralis, gastrocnemius medialis, and soleus, from the assessment in the drop jump is based on the lack of a consistent correlation between RMSE values and injury improvement or injury presence. Although there appears to be an increase in the width of the EMG signals for the initial measurements of injured subjects, this increase is not yet reflected in the metrics values.

The exclusion of the tibialis anterior from the assessment was based on the observation of minimal differences between healthy and injured subjects, as well as the lack of consistent variations in initial and follow-up measurements for injured subjects. Consequently, there was insufficient evidence to suggest that the tibialis anterior serves as a reliable indicator for injury detection or improvement.

The exclusion of CoD values from the analysis is based on the absence of a consistent correlation between these values and both injury detection (difference in CoD values between healthy and injured subjects) and injury recovery (improvement of CoD values between the initial and follow-up measurements). The decision not to utilize CoD reflects the empirical findings that suggest limited relevance or predictive value of these particular metrics in the context of the current study.

4.0.3 Recommendations for Future Research

In light of the insights gleaned from our study and the inherent limitations, several recommendations can inform and guide future research. First and foremost, expanding the scope of patient participation and increasing the number of trials conducted is paramount. This approach will yield a more precise understanding of deviations in muscle activation patterns, providing a comprehensive view of the intricate dynamics at play. A larger and more diverse pool of patients, along with an expanded number of trials, will enhance the statistical robustness of the findings and lead to more reliable outcomes.

Equally important is the adoption of a uniform measurement system for both legs. The use of a single, consistent system is instrumental in minimizing potential sources of variability, thereby facilitating accurate comparisons between the injured and non-injured limbs. This harmonization will greatly enhance the reliability and validity of the insights gained into muscle activation patterns during the rehabilitation process.

To achieve a more nuanced analysis, future studies should prioritize obtaining detailed injury profiles for the patients involved. Understanding the specific characteristics and severity of lateral ankle injuries is vital for contextualizing the data and identifying pertinent indicators of recovery. This level of detail is crucial for enhancing the depth of analysis.

Consideration should also be given to extending the duration between assessments. A longer timeframe allows for a more comprehensive exploration of the recovery process and its impact on muscle activation patterns. By taking a broader temporal perspective, future research can elucidate the trajectory of recovery more distinctly. An alternative concept involves implementing a variable timeframe, which would be contingent on the anticipated total recovery duration, thereby factoring in the injury's level of severity.

In addressing the challenge of translations between signals and the associated variations in the CoD, future studies could implement a peak value matching approach before calculating the CoD. This refinement will mitigate potential artifacts and ensure that similar signal shapes are not penalized due to translation discrepancies.

Moreover, providing clearer movement guidelines is essential. Detailed instructions that encompass all facets of movements, including actions like stepping back onto the box in the drop jump exercise, are indispensable for maintaining consistency in movement execution. Such clarity will reduce the risk of variations in muscle activation patterns due to ambiguities in movement instructions.

Finally, the muscle onset threshold should be revisited, with an emphasis on adjustment to a higher threshold or incorporation of a more sophisticated variable. This revision will enhance the accuracy of muscle activation onset detection, furnishing valuable insights into the timing of muscle activation within rehabilitation settings.

Chapter 5

Conclusion

5.1 Conclusion

This study offers preliminary insights into the potential of sEMG in assessing muscle activation patterns in the context of lateral ankle injuries. While there are promising findings that suggest its utility in evaluating a patient's readiness to return to sports, it is essential to approach these results with caution. The limited number of subjects participating in this study hindered the establishment of a stringent baseline between the injured and non-injured legs. Despite this constraint, the initial indications regarding the application of sEMG as a diagnostic tool for readiness assessment are noteworthy. However, to validate these observations and refine our understanding, further research involving a larger and more diverse subject pool is imperative. The groundwork laid here sets the stage for future investigations aimed at enhancing the diagnostic and evaluative tools within the realm of sports medicine and rehabilitation.

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Chapter 6

Appendix

.1 Subject Characteristics

Subject	Gender	Age	Injured/ Non-Dominant leg	Non-Injured/ Dominant leg	Time Injury to m 1	Time m 1 to m 2
sub 2	female	21	Right	Left	N/A	N/A
sub 3	Female	26	Left	Right	N/A	N/A
sub 4	Male	20	Left	Right	N/A	N/A
sub 5	Male	20	Right	Left	N/A	N/A
sub 6	Male	21	Right	Left	N/A	N/A
sub 7	Female	26	Left	Right	N/A	N/A
Injured sub 1	Male	23	Right	Left	5 weeks	4 weeks
Injured sub 2	Female	28	Right	Left	8 weeks	4 weeks
Injured sub 3	Male	25	Left	Right	1 week	4 weeks

Table 1: Subject Characteristics

.2 Muscle Activation Graphs, Healthy Subjects

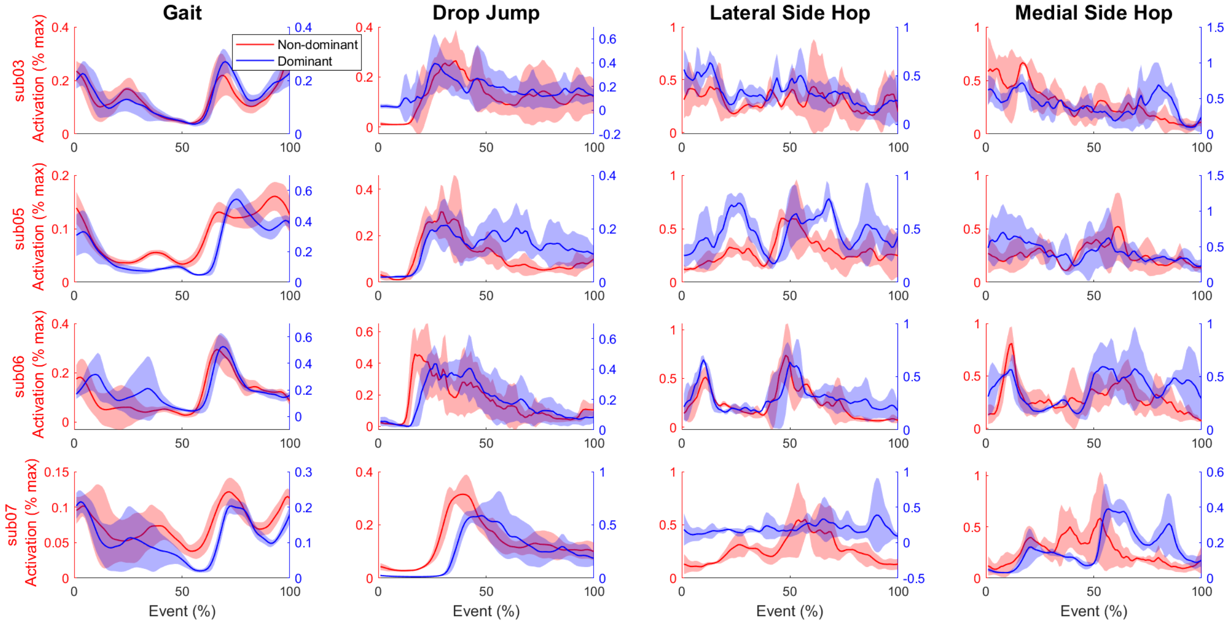

Figure 1: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the tibialis anterior. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

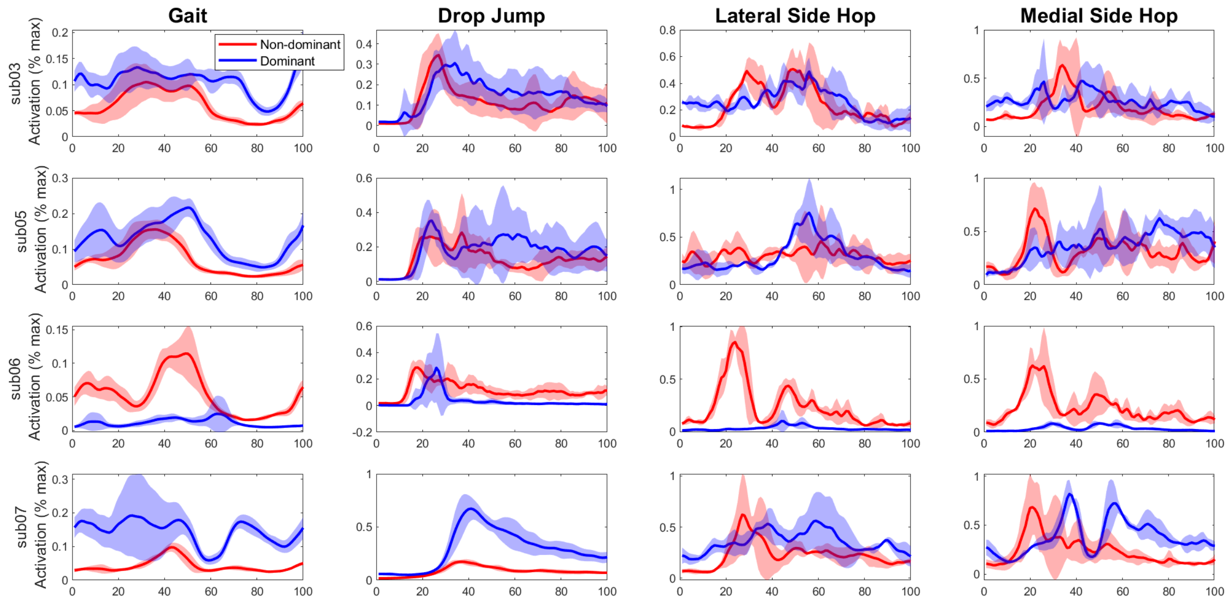

Figure 2: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the peroneus brevis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

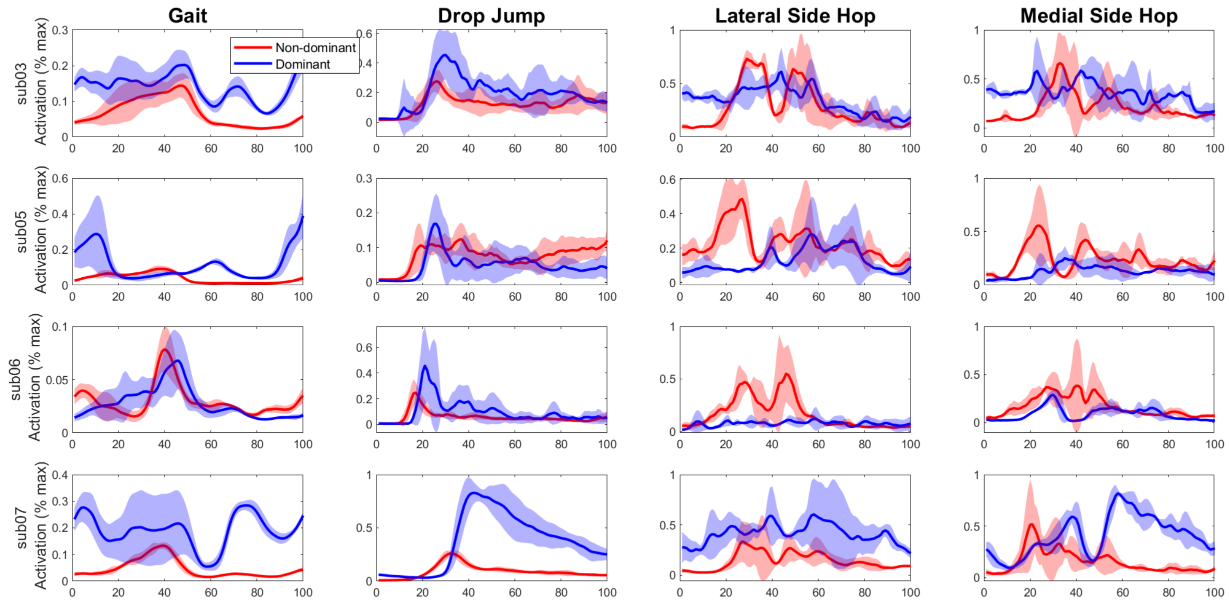

Figure 3: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the peroneus longus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

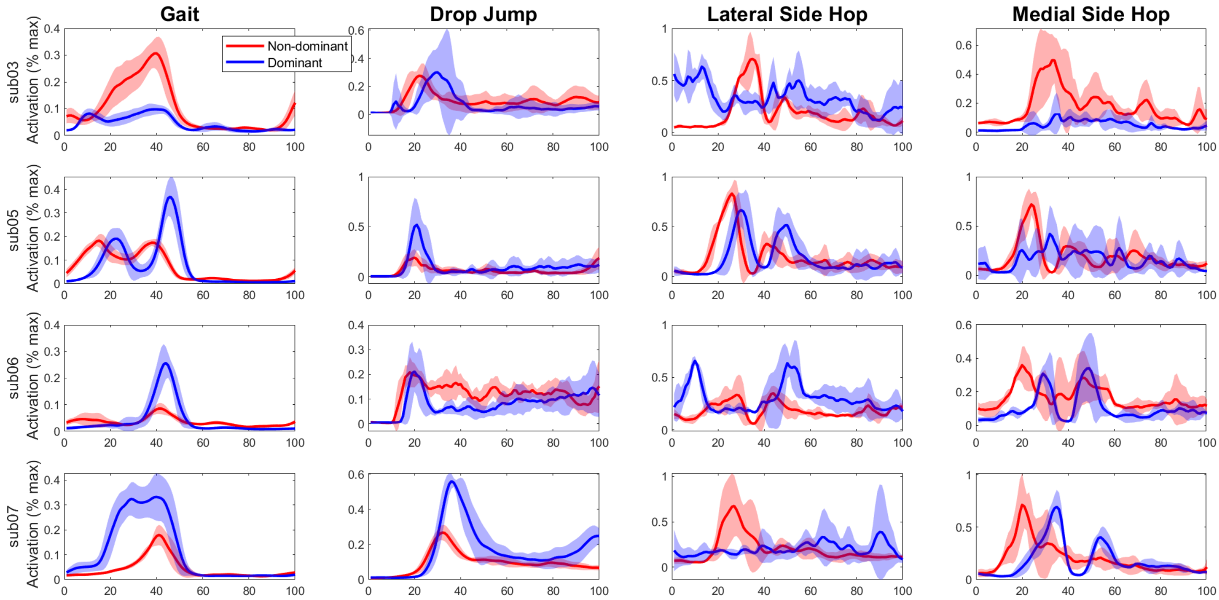

Figure 4: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the gastrocnemius medialis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

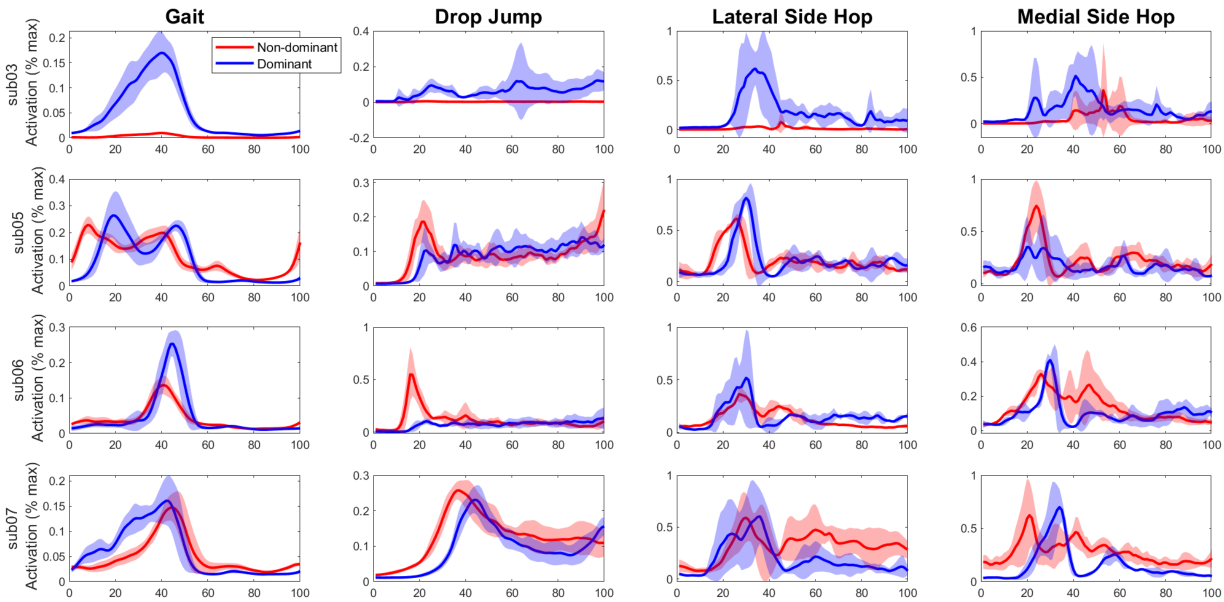

Figure 5: Mean muscle activation for dominant (blue line) and non-dominant (red line) leg for all healthy subject 3, 5, 6, and 7 from the soleus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Appendix 3: RMSE Tables, Healthy Subjects

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.029619	0.067164	0.098945	0.18324
PerL	0.078342	0.099882	0.1739	0.20979
PerB	0.050722	0.068764	0.10879	0.15614
GasM	0.086754	0.074871	0.2574	0.15964
GasL	0.062892	0.023087	0.070922	0.11954
Sol	0.070666	0.065543	0.22065	0.14111

Table 2: RMSE values for subject 03 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.18492	0.066484	0.23275	0.21531
PerL	0.11874	0.041539	0.14902	0.16537
PerB	0.065423	0.086463	0.13784	0.17657
GasM	0.088712	0.081223	0.19773	0.15805
GasL	0.20207	0.12942	0.18079	0.096378
Sol	0.071089	0.037379	0.15337	0.12342

Table 3: RMSE values for subject 05 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.11615	0.10301	0.11637	0.17556
PerL	0.012199	0.08903	0.1707	0.12101
PerB	0.05028	0.096086	0.28412	0.23453
GasM	0.048468	0.055112	0.18941	0.10054
GasL	0.066504	0.069031	0.12285	0.14075
Sol	0.037965	0.11371	0.081156	0.079897

Table 4: RMSE values for subject 06 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.052019	0.19301	0.1358	0.1787
PerL	0.15764	0.37505	0.28355	0.34278
PerB	0.10705	0.25753	0.17278	0.25582
GasM	0.11086	0.12095	0.16953	0.17992
GasL	0.047989	0.062956	0.10994	0.16169
Sol	0.030145	0.051889	0.18806	0.2003

Table 5: RMSE values for subject 07 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Appendix 4: CoD Tables, Healthy Subjects

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.79537	0.65708	0.37086	0.36312
PerL	0.46691	0.59386	0.3225	0.028086
PerB	0.43568	0.46604	0.40968	0.052229
GasM	0.74534	0.20966	0.030054	0.38468
GasL	0.94331	0.58917	0.80957	0.17097
Sol	0.98365	0.37631	0.33972	0.20552

Table 6: CoD values for subject 03 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.67962	0.38291	0.13777	0.097482
PerL	0.0037586	0.28657	0.0037933	0.001821
PerB	0.5135	0.32474	0.32149	0.049956
GasM	0.15961	0.52528	0.12995	0.042806
GasL	0.1591	0.00020684	0.23959	0.24571
Sol	0.36259	0.38136	0.21519	0.40337

Table 7: CoD values for subject 05 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.60329	0.46679	0.57165	0.15879
PerL	0.44691	0.2301	0.11042	0.22643
PerB	0.20015	0.33059	0.032313	0.1722
GasM	0.74206	0.37987	0.033959	0.19828
GasL	0.5378	0.50004	0.73418	0.62577
Sol	0.7353	0.0070115	0.48565	0.26896

Table 8: CoD values for subject 06 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0.6675	0.41833	0.11455	0.014163
PerL	0.015575	0.12392	0.29448	0.0055266
PerB	0.13446	0.82818	0.2131	0.0099855
GasM	0.67922	0.59429	0.023427	0.092737
GasL	0.5467	0.47471	0.44086	0.14892
Sol	0.64969	0.65471	0.2189	0.098662

Table 9: CoD values for subject 07 across all muscles and movements. Where m1 is the initial measurement, m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Appendix 5: Onset Tables, Healthy Subjects

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	-68.2	1.6	0	0
PerL	-18.94	-0.3	18.9	4.0
PerB	-74.4	-6.7	19.3	23.3
GasM	-5.4	4.0	24.7	1.0
GasL	4.4	0.3	-0.1	2.4
Sol	-6.8	-41.5	1.7	4.1

Table 10: OnSet values for subject 03 across all muscles and movements. Where m1 is the initial measurementin percentage of the movement cycle. m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	-69.4	-11.6	23.7	44.5
PerL	5.1	-6.7	4.3	-6.9
PerB	2.7	-5.7	17.1	-2.9
GasM	-9.7	-2.1	-1.0	18.5
GasL	0	-0.8	4.7	2.9
Sol	-8.3	-5.0	-6.0	-0.7

Table 11: OnSet values for subject 05 across all muscles and movements. Where m1 is the initial measurementin percentage of the movement cycle. m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	-6.7	-5.1	-1.8	4.1
PerL	-18.3	-2.5	10.3	-0.4
PerB	-1.9	-1.3	-26.0	-15.1
GasM	-12.0	-2.8	13.2	-12.6
GasL	-4.5	-1.9	-4.0	-7.3
Sol	-26.2	-5.3	-5.3	-16.6

Table 12: OnSet values for subject 06 across all muscles and movements. Where m1 is the initial measurementin percentage of the movement cycle. m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Muscle	Gait	DJ	SH_lateral	SH_medial
Tib	0	-9.0	-16.9	-37.4
PerL	-56.3	-12.9	-16.8	-23.9
PerB	8.2	-4.7	-15.3	-22.4
GasM	18.7	-3.9	-47.5	-16.2
GasL	-8.9	-9.1	2.0	-10.7
Sol	21.3	-10.3	0.2	-24.3

Table 13: OnSet values for subject 07 across all muscles and movements. Where m1 is the initial measurementin percentage of the movement cycle. m2 is the follow-up measurement, (DJ: Drop Jump, SH: Side Hop).

Appendix 6: Muscle Activation Graphs, Injured Subject 1

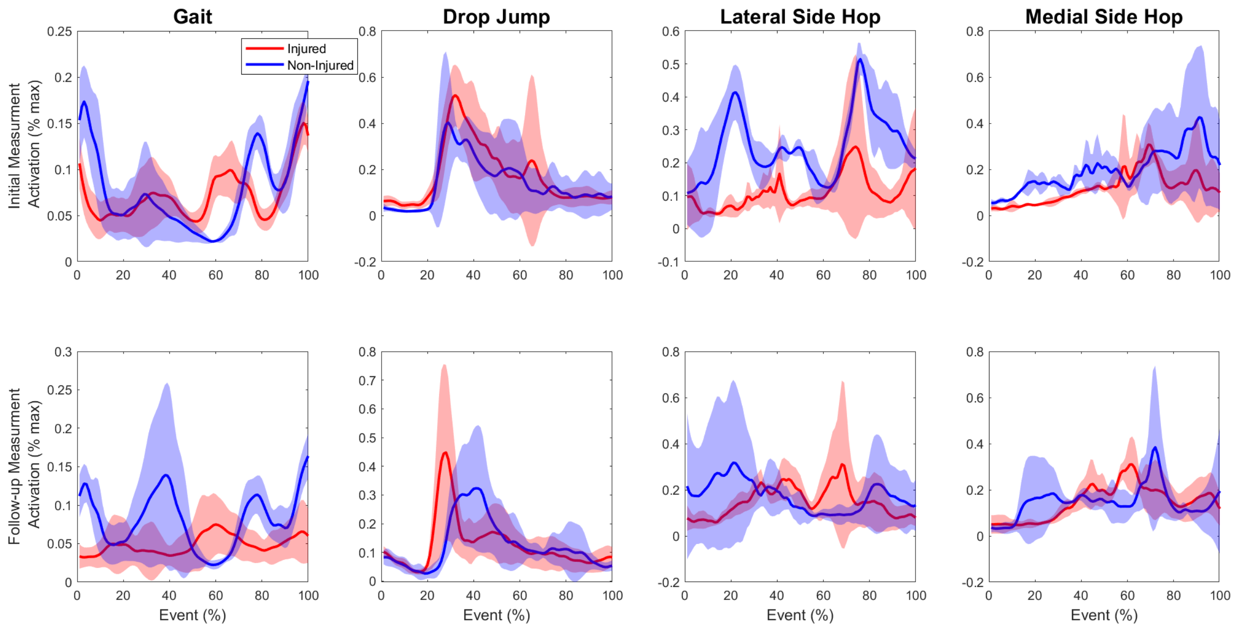

Figure 6: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the tibialis anterior. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

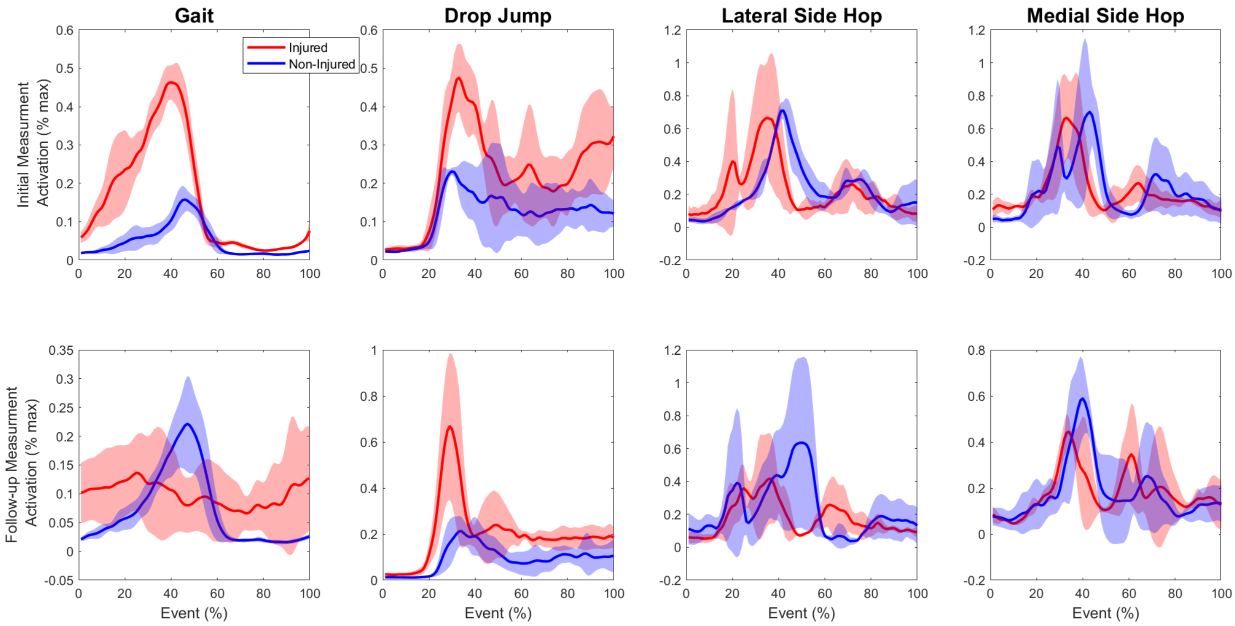

Figure 7: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the soleus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

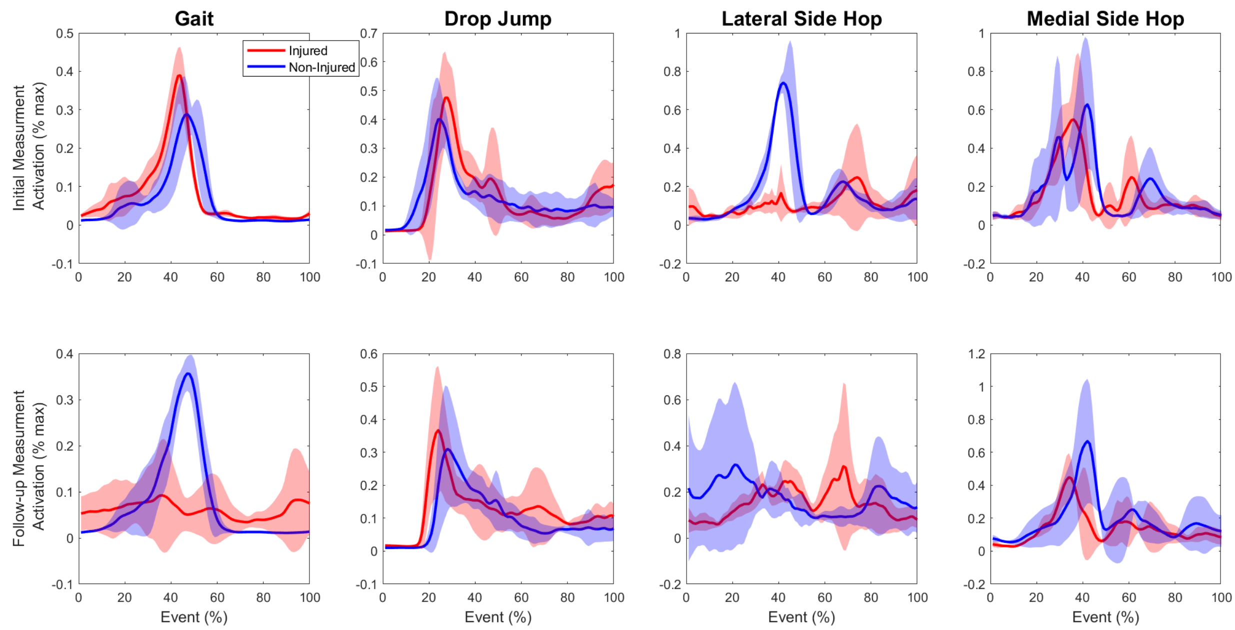

Figure 8: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the gastrocnemius medialis.The continuous line indicates the mean value, while the shaded area represents the standard deviation.

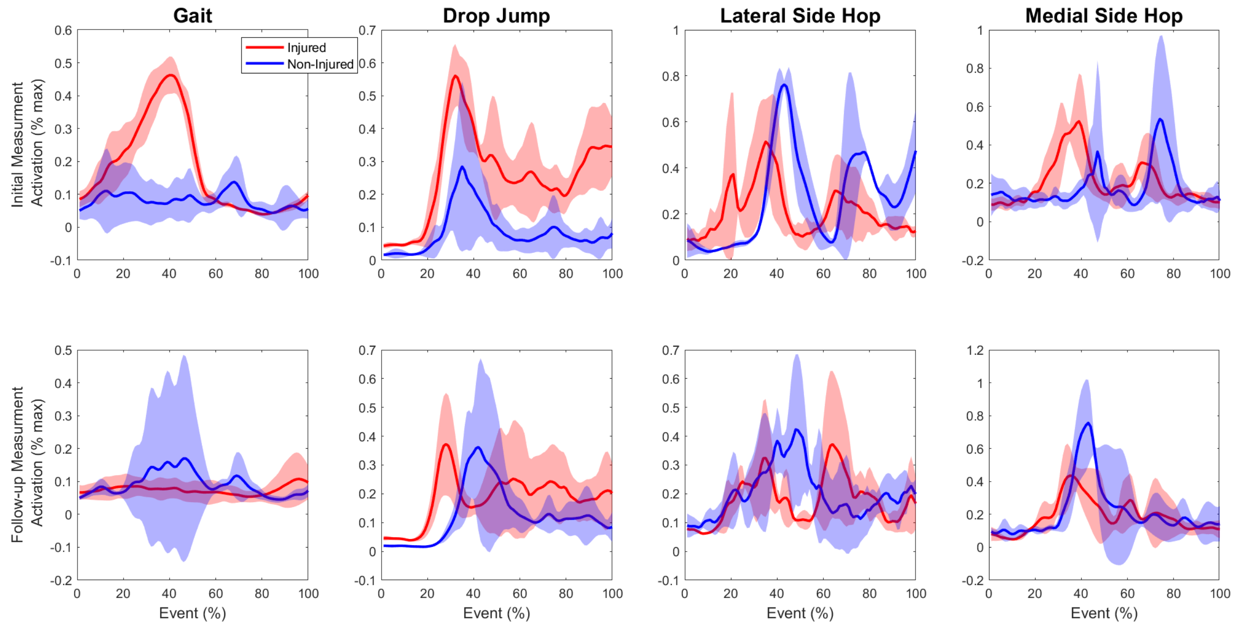

Figure 9: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the peroneus brevis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

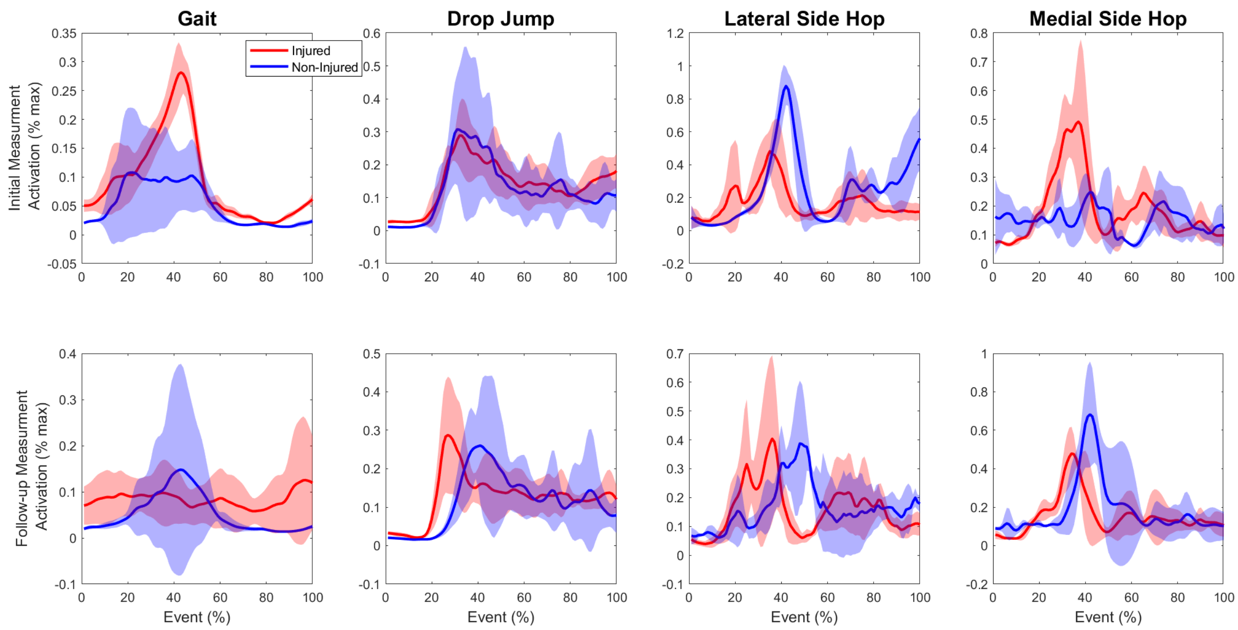

Figure 10: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 1 from the peroneus longus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Appendix 7: Muscle Activation Graphs, Injured Subject 2

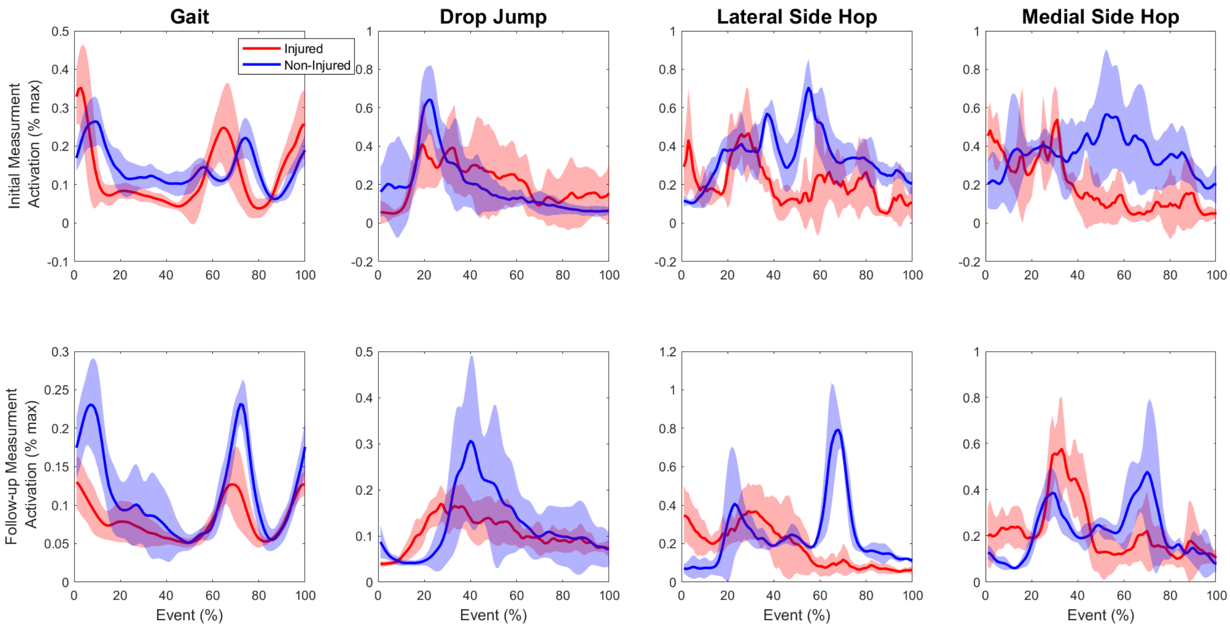

Figure 11: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the tibialis anterrior. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

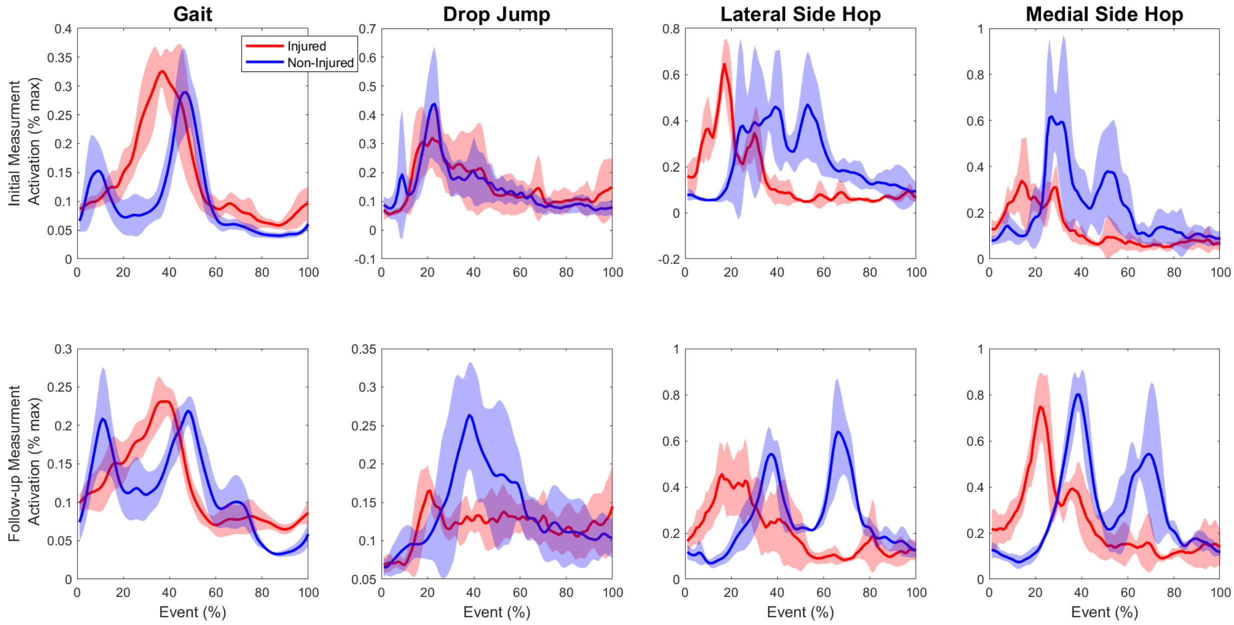

Figure 12: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the soleus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

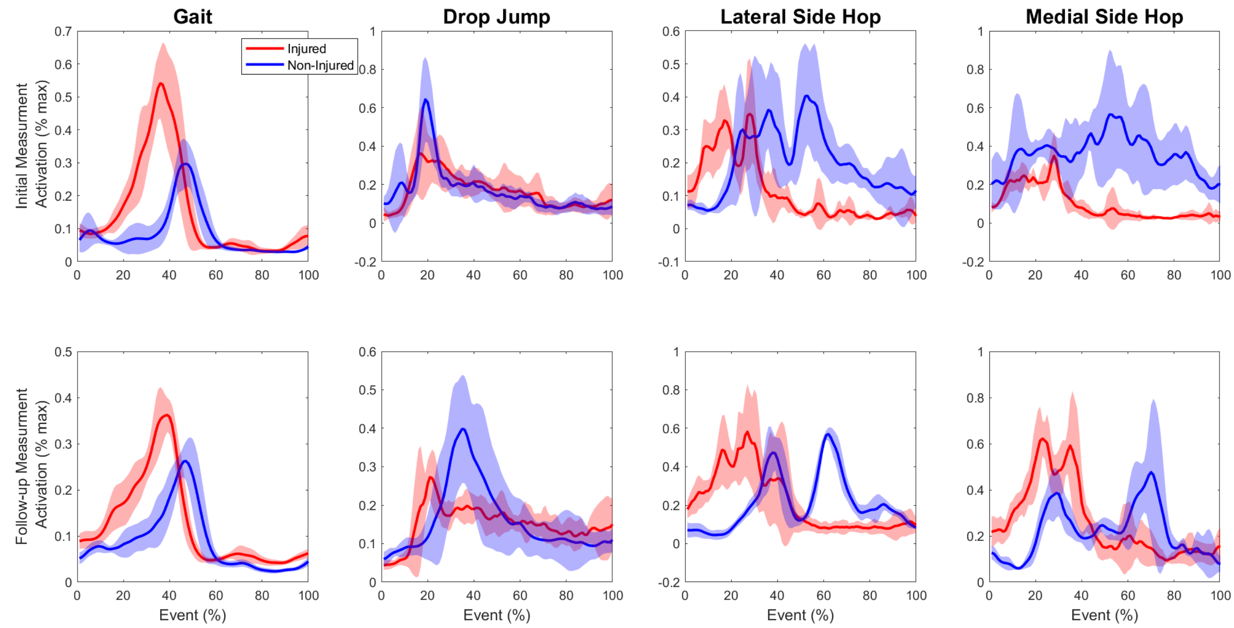

Figure 13: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the gastrocnemius medialis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

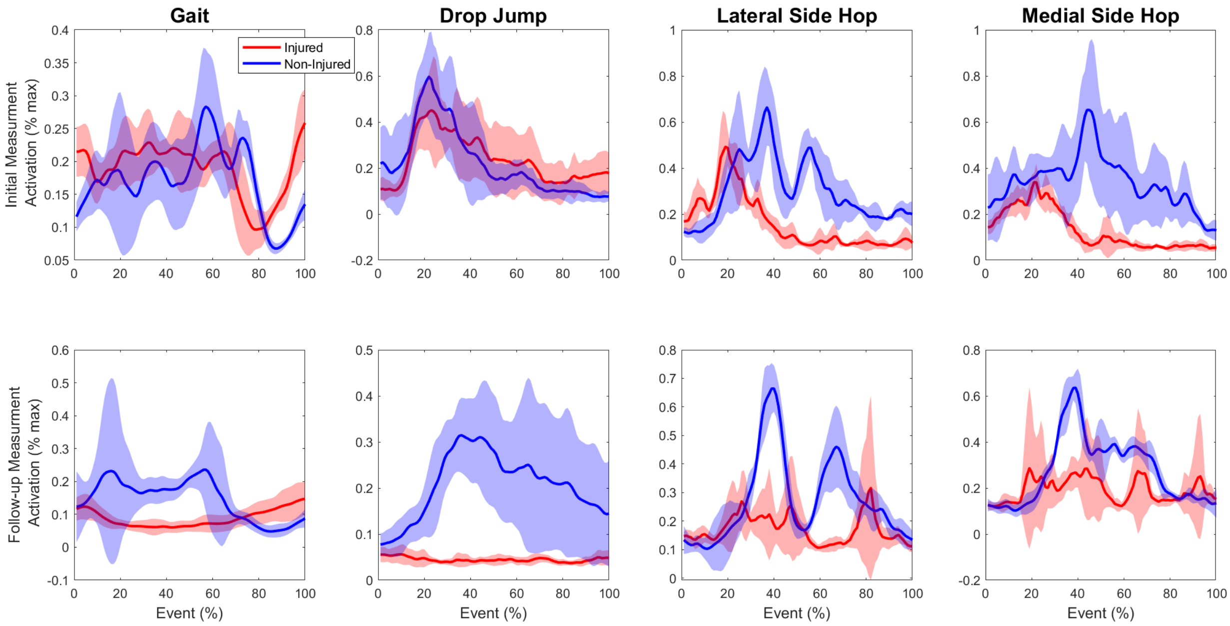

Figure 14: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the peroneus brevis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

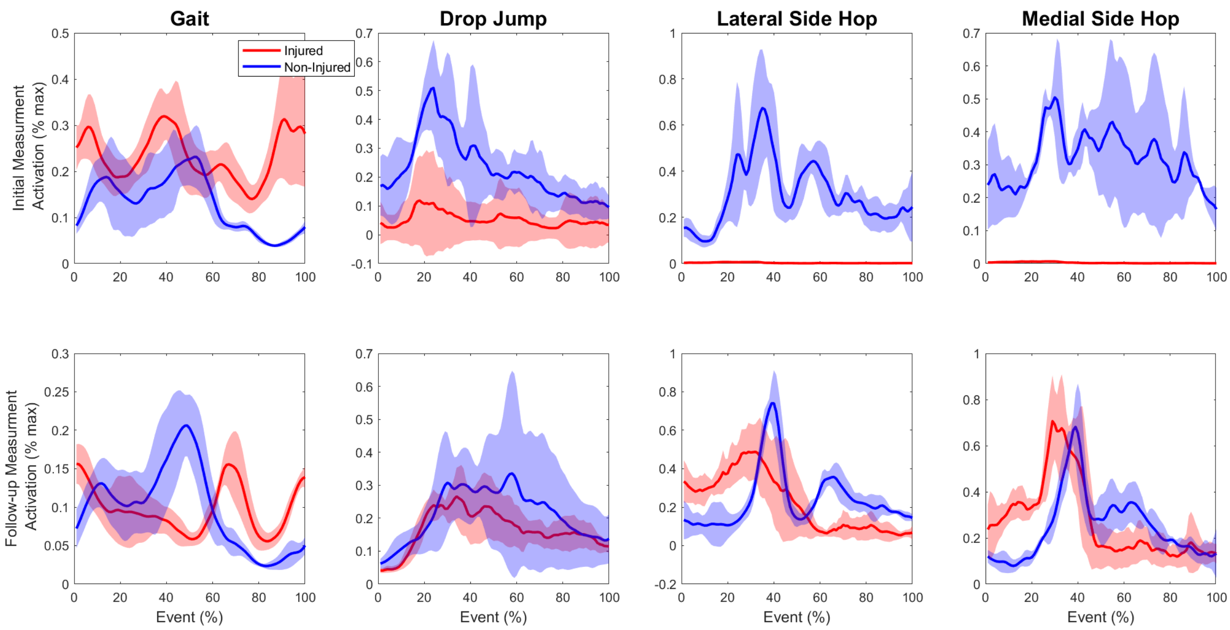

Figure 15: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 2 from the peroneus longus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

Appendix 8: Muscle Activation Graphs, Injured Subject 3

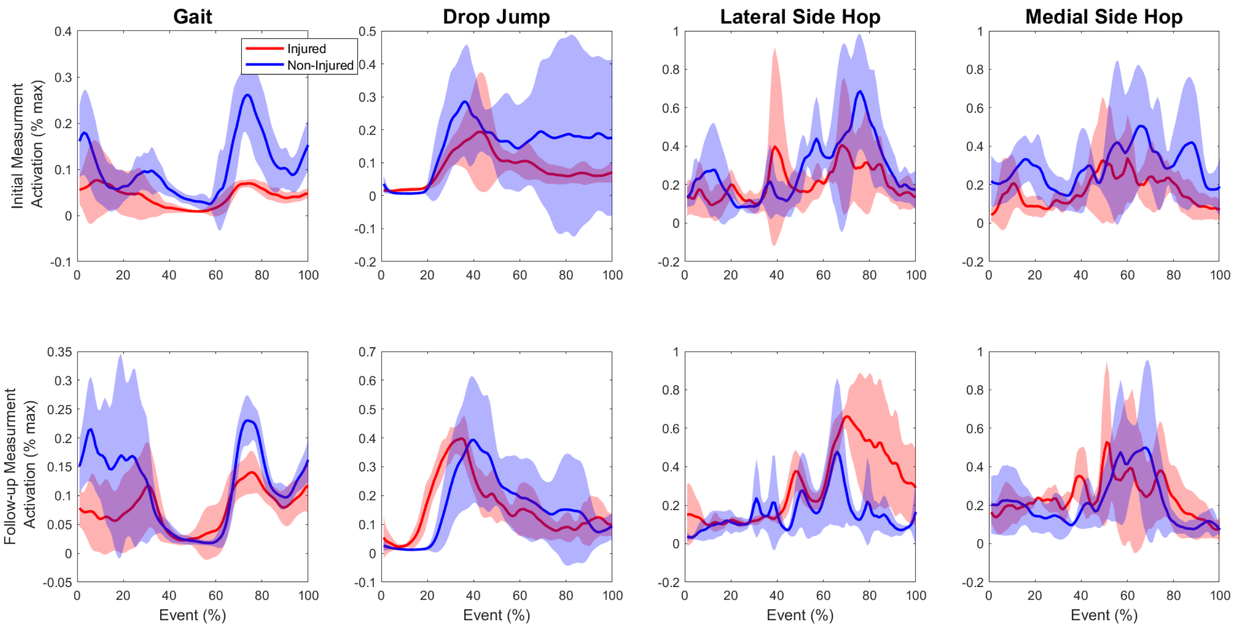

Figure 16: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the tibialis anterior. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

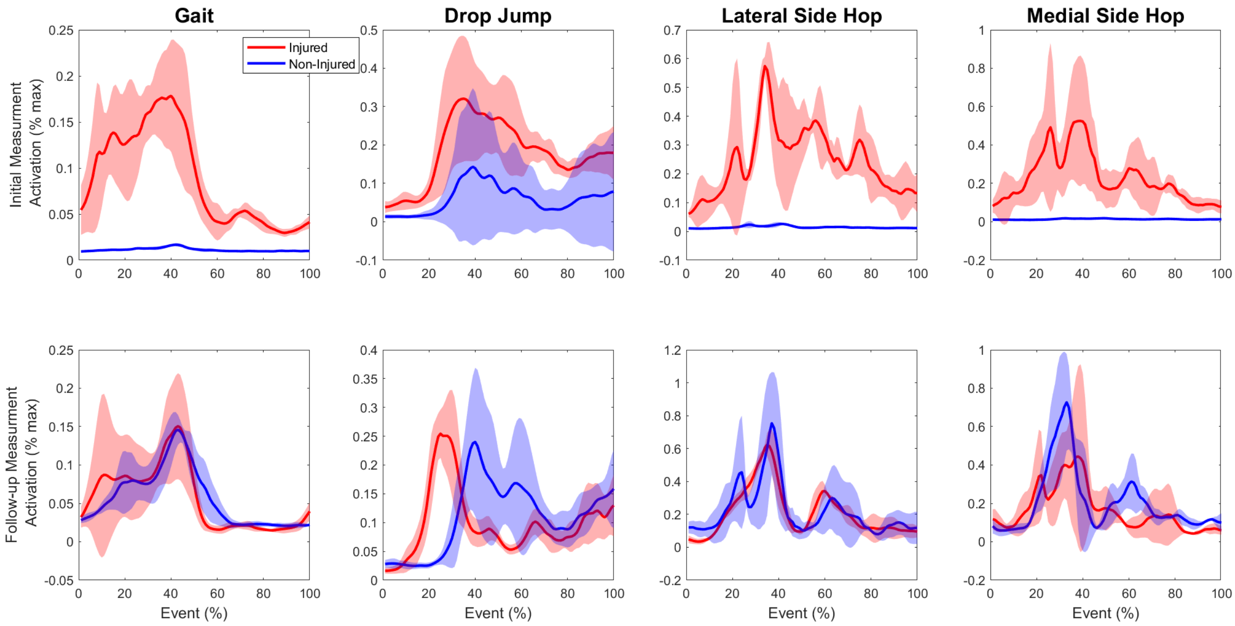

Figure 17: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the soleus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

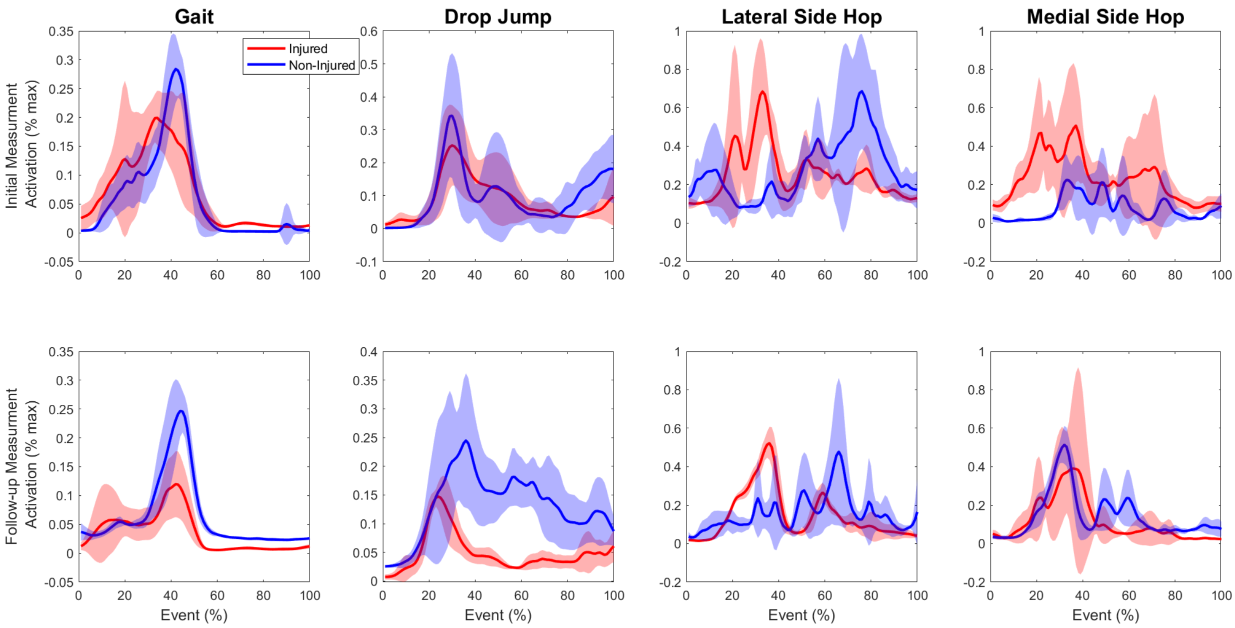

Figure 18: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the gastrocnemius medialis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

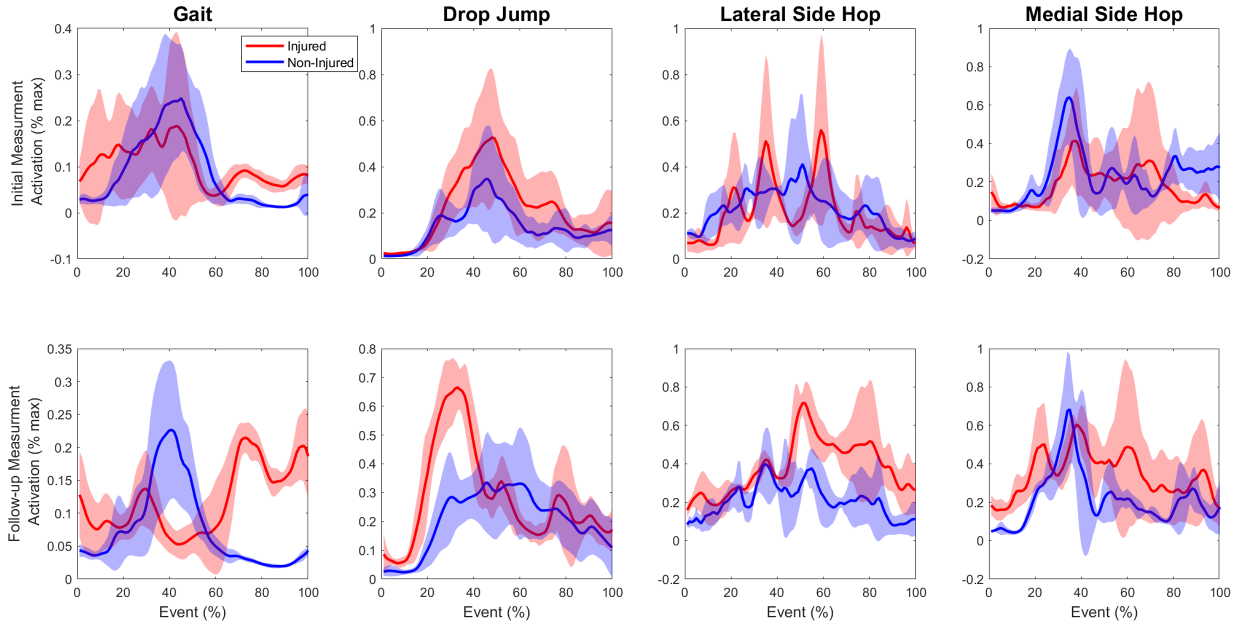

Figure 19: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the peroneus brevis. The continuous line indicates the mean value, while the shaded area represents the standard deviation.

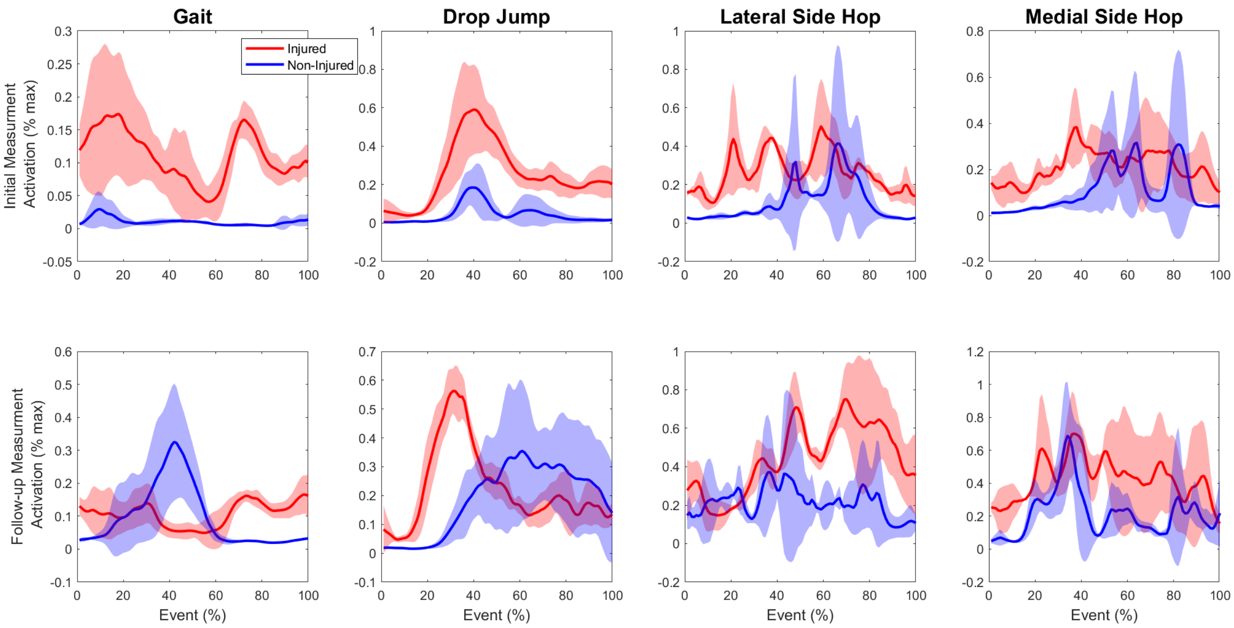

Figure 20: Mean muscle activation for injured (red line) and non-injured (blue line) leg for Injured Subject 3 from the peroneus longus. The continuous line indicates the mean value, while the shaded area represents the standard deviation.