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EMG Analysis in ACLR Athletes: for Enhanced Rehabilitation Strategies

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Abstract

Presently Anterior Cruciate Ligament (ACL) ruptures account for over 50% of all knee injuries. An ACL Reconstruction (ACLR) is recommended for those aiming to return to their sports at a higher level, followed by a structured rehabilitation, that can take up to 12 months. The clinical analysis of the rehabilitation mainly consists of clinicians performing assessments of athletes' performances and subjective evaluations, that do not always show sufficient results. Thus, this thesis aims to investigate Electromyography (EMG) data of the knee muscles of ACLR athletes in comparison to healthy athletes and highlight the impact EMG sensors can have on rehabilitation. The results of this research show that ACLR athletes still deviate greatly from healthy subjects at the time of discharge from rehabilitation. Furthermore, evidence suggests that, even though athletes only injure the ACL in one leg, the other leg can suffer from bilateral effects. The median frequency has been reported to provide valuable insights into muscle activity, including changes in muscle activation following an ACLR. Ultimately this research provides evidence of the importance of looking at muscle ratio within muscle groups to ensure that one muscle does not assume a greater role than what is normal.

Keywords

Anterior Cruciate Ligament, Electromyography, EMG index, Median Frequency, Muscle Ratio, Rehabilitation

Sammanfattning

För närvarande står främre korsbandsskador (ACL) för över 50% av alla knäskador. En ACL-rekonstruktion (ACLR) rekommenderas följt av en strukturerad rehabilitering som kan ta upp till 12 månader för dem som siktar på att kunna återgå till att idrotta på en hög nivå. Den kliniska analysen av rehabiliteringen består huvudsakligen av att sjukgymnaster utför bedömningar av idrottarnas prestationer samt individuella utvärderingar. Men dessa ger inte alltid ett tillräckligt bedömningsunderlag. Därför syftar denna avhandling till att undersöka elektromyografidata (EMG) från knämusklerna hos ACLR-idrottare jämfört med friska idrottare och belysa den påverkan EMG-sensorer kan ha på rehabiliteringen. Resultaten av denna forskning visar att ACLR-idrottare fortfarande avviker avsevärt från friska försökspersoner vid tidpunkten för utskrivning från rehabiliteringen. Vidare tyder bevisen på att även om idrottare bara skadar ACL i ett ben kan det andra benet drabbas av bilaterala effekter. Medianfrekvensen har rapporterats ge värdefulla insikter om muskelaktivitet, inklusive förändringar i muskelaktivering efter en ACLR. Slutligen ger denna forskning bevis på vikten av att titta på muskelförhållandet inom muskelgrupper för att säkerställa att en muskel inte får ta en större roll än vad som är normalt.

Nyckelord

Främre korsband, Elektromyografi, EMG-index, Medianfrekvens, Muskelförhållande, Rehabilitering.

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"If at first, you don't succeed, call it version 1.0" - unknown

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Acronyms

ACL	Anterior Cruciate Ligament
MCRs	Mechanoreceptors
CNS	Central Nervous System
PCL	Posterior Cruciate Ligament
ACLR	ACL Reconstruction
EMG	Electromyography
sEMG	Surface EMG
MVC	Maximum Voluntary Contraction
SLJ	Single Leg Jump
DLJ	Double Leg Jump
SLS	Single Leg Squat
VM	Vastus Medialis
VL	Vastus Lateralis
ST	Semitendinosus
BF	Biceps Femoris
GM	Gluteus Medius
TFL	Tensor Fascia Latae
RMS	Root Mean Square
PSD	Power Spectral Density

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Chapter 1

Introduction

The knee stands as a prevalent injury site among athletes, with the Anterior Cruciate Ligament (ACL) presently accounting for over 50% of all knee injuries [1]. Over 200,000 people are said to rupture their ACL annually in the United States alone [2]. As the ACL ruptures, the knee suffers an instant stability loss along with the possibility of dysfunctions [1]. Such injuries can occur due to both contact and non-contact mechanisms, with the latter rather considered to be preventable. Non-contact ACL ruptures commonly occur during actions such as pivoting, cutting, or jumping. Multiple factors contribute to the likelihood of an ACL rupture, including age and sex. Specifically, females aged 17-18 years represent the demographic at the highest risk of ACL injury and are told to be three times more likely to sustain such injuries overall [2].

Following an ACL rupture, patients are required to follow a structured rehabilitation program. The first weeks of rehabilitation are very similar between patients, irrespective of whether they then undergo an ACL Reconstruction (ACLR) or prompt for conservative management. An ACLR is recommended for younger individuals and those aiming to return to high-level activity training. If not performed, individuals, especially those in high-level activity training, have a higher risk of suffering from continuous "giving-away" episodes, predisposing them to meniscal tears and articular cartilage lesions [2, 3].

The rehabilitation is long and critical after an ACL rupture. For those who decide against an ACLR, the rehabilitation is considered to be around 3 months long, with exercises that focus on strength, stretching, and balance [2, 3]. ACLR is recommended

to be performed after a 12-week pre-operative rehabilitation program, and before 5 months have passed since the injury to avoid additional trauma to the knee [2]. After a reconstruction, the rehabilitation is considered to be around 6-12 months, where the last few weeks focus on return-to-sport assessments [3]. The program focuses on measures to establish a full range of motion, prevent muscle hypotrophy, diminish pain and swelling, and avoid unnecessary stress to the reconstructed ligament [2]. Most athletes have the end goal of returning to sport. Statistics however show that only around 65% return to their pre-injury physical readiness and only about 55% can compete again in their respective, high-demand sports. Additionally, statistics have also shown that 1 out of every 4 ACLR athletes suffer from a re-rupture after having returned to their sport [4].

The most common method to reach the next stage of rehabilitation is when clinicians perform a subjective evaluation, during medical evaluations. Rating scales and questionnaires are examples of these evaluations and, even when performed by experienced clinicians, they may not always show sufficient results [5]. Additionally physical impairment measures are performed, including measures of single-leg hop capabilities, quadriceps strength and anterior knee joint laxity [6]. The gold standard of technology is however a camera-based motion analysis system, either marker-based or markerless, adopted in gait analysis for quantitative movement analysis. This technology is however constrained by costs, access, and practicality of application to the larger subject group [5].

1.1 Aim

This thesis aims to analyse Electromyography (EMG) data of muscles surrounding the knee following an ACLR and its subsequent rehabilitation. The primary goal is to gain deeper insights into the muscular responses during this period and the correlation of the muscles' median frequency to ACLR athletes. EMG data was previously collected from both healthy and ACLR athletes and will be further analyzed and evaluated. A light will be shed on the distinctions between these two groups, as well as to track the progress made by the ACLR athletes over time. The aspiration of this thesis is to provide valuable insights that can aid physical therapists with future evaluations and treatments, and improve the robustness of the clinicians' evaluations following an ACLR. Additionally, it could be further developed as a predictive method to evaluate

the risk of ACL injury from a neuromuscular control standpoint and eventually prevent more ACL injuries.

Research Questions

- Is frequency spectrum analysis from EMG data a feasible method to evaluate the progress following an ACLR operation?
- Is there a linear relationship between the early to late testing in the ACLR athletes?
 - If athletes receive good results in the early stages of rehabilitation, are they expected to receive good results in the late stages?
- Does rupturing the ACL lead to bilateral effects?
 - Can athletes maintain the strength in their healthy leg following an ACL rupture?

Chapter 2

Background

This chapter will introduce the ACL and its role in the human body, along with the muscles surrounding the knees. EMG will be further explained, as well as the signal processing methods commonly used for processing EMG data.

2.1 Anterior Cruciate Ligament

The knee joint is one of the most complex joints in the human body. It consists of many hard and soft tissues that work together to allow movement along three planes. The ligaments are a soft tissue and work as stabilizers in the knee, shown in Figure 2.1.1 [7]. The ACL and Posterior Cruciate Ligament (PCL) are the main stabilizers of the joint, as they limit the anterior and posterior translations [8].

The ACL, as stated, limits the anterior translation of the knee. Its function however is also more complex. The ligament contains Mechanoreceptors (MCRs). The MCRs are a sub-type of somatosensory receptors [8]. Their role is to receive proprioceptive stimuli and convert them to an action potential. The action potential is then transferred to the Central Nervous System (CNS) where it is processed. The CNS receives the action potential in three different stages, at the spine, lower brain, and cerebrum, depending on how fast a response is needed [9].

2.1.1 Proprioception

Proprioception is an important component in injury prevention and preserves the functions of the knee joint. Proprioception is known to have three main functions;

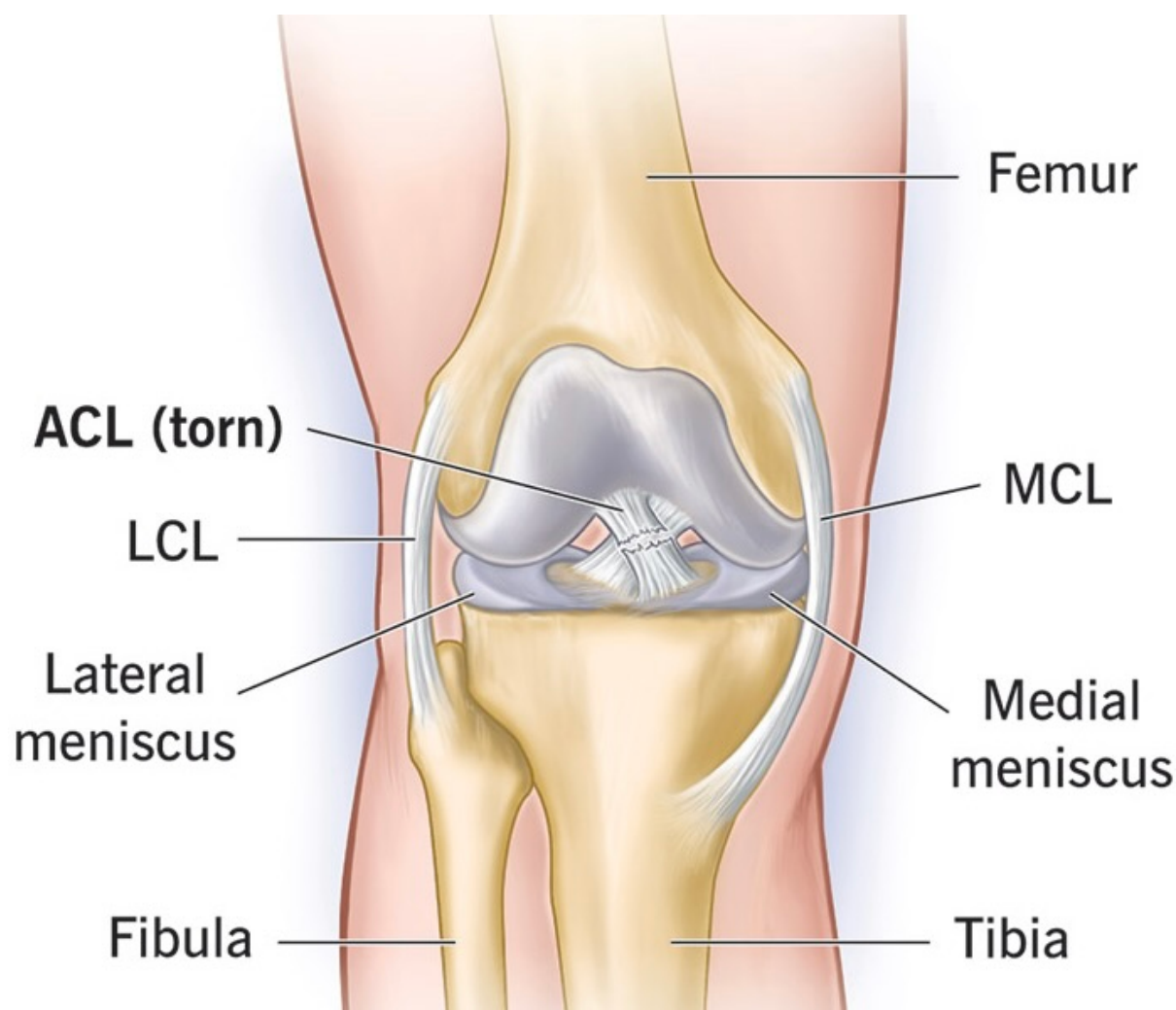


Figure 2.1.1: Anterior view of knee Anatomy, with patella removed and a torn ACL is marked in bold [7]

static awareness of joint position, awareness of joint movement and acceleration, reflex responding, and regulating muscle activity. As before stated, the ACL contains MCRs which are very important in terms of proprioception. The MCRs have four subtypes, all of which have been proven to be present in the ligaments of the knee. The ACL and PCL however are the only ligaments to contain every single one of them, proving their importance [8].

2.2 Skeletal Muscles

Muscular structure is the knees' most important stabilizing factor. The muscle groups that affect the knee the most are the quadriceps. The quadriceps are a 4-component muscle group that attaches to the patella via the quadriceps tendon. The

four components are called; Vastus Medialis (VM), Vastus Lateralis (VL), Vastus Intermedius, and Rectus Femoris. The quadriceps are also known as the knee extensors, as they help the knee with the extending movement along with helping to stabilize the joint [10].

As the ACL ruptures, the quadriceps suffer a near-immediate strength loss. Research has shown that the cause of this sudden strength loss is the chronic suppression of recruitment of high-threshold motor units during voluntary contraction of the quadriceps, which the MCRs in the ACL are responsible for [11].

This strength deficit in the quadriceps ranges from 5% to 40% and has been reported for up to 7 years after a reconstruction surgery. The hamstrings are another muscle group that has been reported to suffer strength loss [12]. Similar to the quadriceps, the hamstrings are a collection of four muscles. The muscles are Semimembranosus, Semitendinosus (ST), Biceps Femoris (BF) long head, and Biceps Femoris short head [13]. The hamstrings are knee flexors, meaning they help the knee flex (bend). Their strength loss has been proven to last up to 3 years after reconstruction and ranges from 9% to 27% [12].

Other muscle groups are also believed to be affected by an ACL rupture and evidence suggests that hips and ankles may grow weaker. However little data exists to support this theory and this will not be further researched in this thesis [12].

2.3 Electromyography

When a muscle contracts, it produces an electrical signal, which is controlled by the nervous system. A collective of these electrical signals is referred to as EMG. As the name Electromyography may point to, an EMG signal refers to the electrical activity of the muscle's motor units. The electrical signals can be subdivided into two groups; Surface EMG (sEMG), which are recorded non-invasively, and intramuscular EMG, which are recorded invasively [14]. The focus of this research will be on the sEMG as sEMG sensors were used to collect all data.

2.4 Signal Processing

Routinely various noise signals accompany the wanted EMG signals, causing disturbance and interference, proving the importance of signal processing. These noise signals can be caused by various sources. They can, for example, be inherent in the electrode, caused by unexpected movement, or electromagnetic radiation from the body [14].

2.4.1 Rectification

A direct averaging of a raw EMG signal results in the cancellation of the negative and positive potentials, that is there would be no measurable response. Therefore, signal rectification is often one of the first steps taken when analyzing an EMG signal. Rectification or other non-linear signal processes are needed to quantify the EMG signal's amplitude, which has been proven to be an indicator of the muscle's strength during a muscle contraction [15].

By rectifying a signal, one cancels out a polarity, creating a single polarity signal. There are two methods to do this, using a half-wave rectifier or a full-wave rectifier. As seen in Figure 2.4.1 [16], using a half wave rectifier only saves half of the signal, erasing all the negative samples [16]. Half of the signals' information would therefore be lost. As muscle movement generates both negative and positive values, using a half-wave rectifier would lead to the loss of important information. Therefore, a half-wave rectifier is not a good fit for this thesis [17]. A full-wave rectifier, as seen in Figure 2.4.2 [16], saves the absolute value of the signal, saving all information generated by the muscles [18]. A full-wave rectifier is therefore evaluated as a much better fit for this thesis.

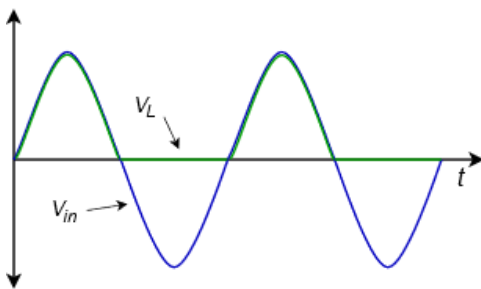


Figure 2.4.1: Half wave rectifier

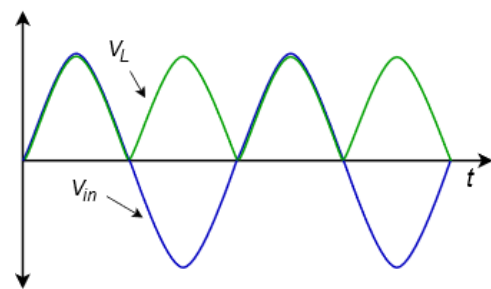


Figure 2.4.2: Full wave rectifier

2.4.2 Root Mean Square

Root Mean Square (RMS) is a similar non-linear process to rectification. It is also used to quantify the EMG signal's amplitude [15]. The RMS is defined as the square root of the mean square value as seen in Equation 2.1 [19, 20].

$$RMS = \sqrt{\frac{1}{N} \sum_{t=1}^N (x(t))^2} \quad (2.1)$$

2.4.3 Filter

Filters are considered a complicated system, where the input enters a transfer function, and out comes a filtered output. Many versions of filters exist, with different transfer functions and their respective transfer properties. The versions are; High-pass, Low-pass, Band-pass, and Band-Stop (Notch) [21]. A filter will have an amplitude response for the frequencies of interest, called pass-band, and a zero elsewhere, called stop-band. Figure 2.4.3 [22] shows pass- and stop-bands of previously mentioned filters as idealized filter-responses [23].

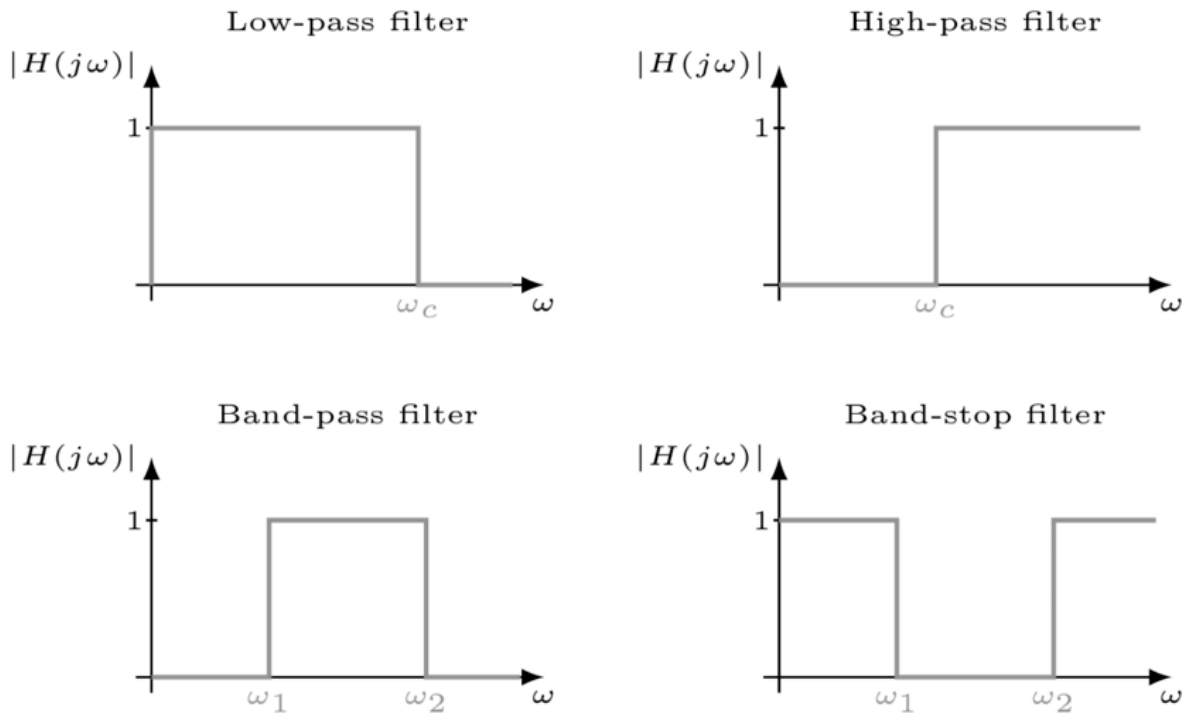


Figure 2.4.3: Idealized filter responses [22]

Furthermore, many types of filters exist. The most known are the Butterworth, Chebyshev, Bessel, and Elliptic filters. Each filter has different frequency responses as shown in Figure 2.4.4 [24].

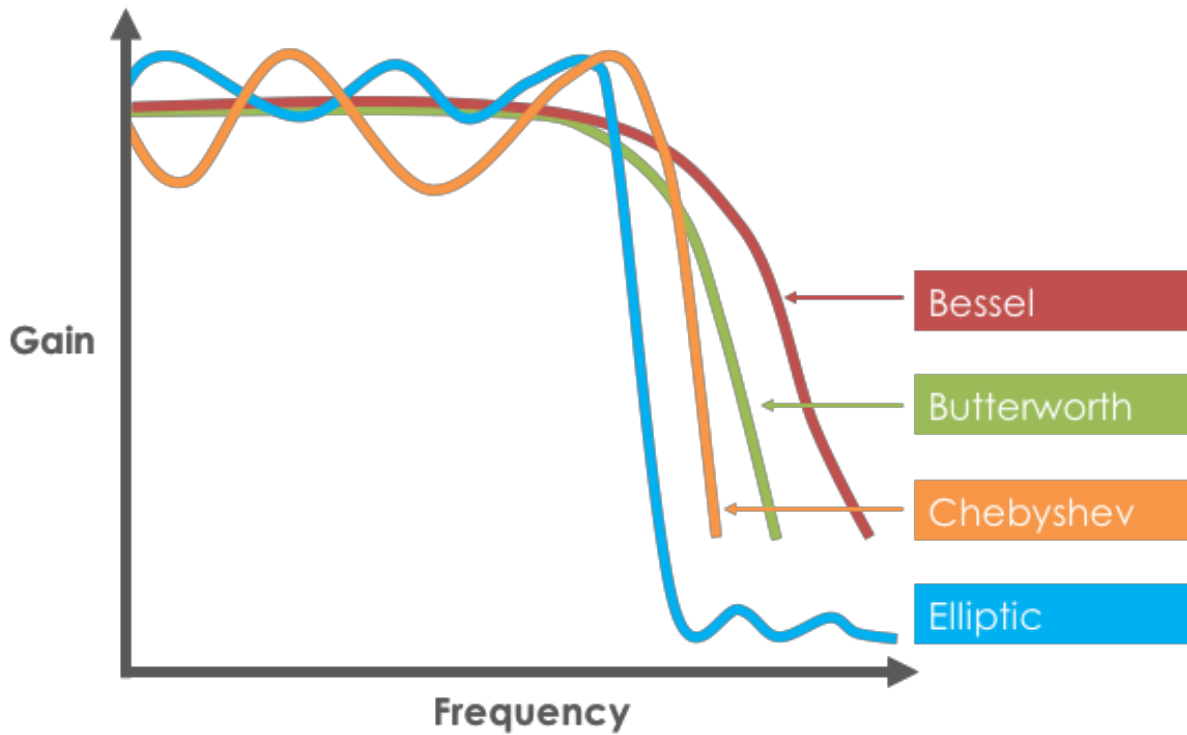


Figure 2.4.4: Various filters' frequency response [24]

Butterworth filter is said to be the best compromise between the attenuation and phase response. As seen in Figure 2.4.4, a Butterworth filter does not have any ripples in either the pass-band or the stop-band, therefore it is called a maximally flat filter [23]. The Butterworth filter is considered to be an ideal filter for conditioning EMG signals, as it best preserves amplitudes in the pass-band region [25].

2.4.4 Frequency Spectrum

All signals can be transformed into the frequency domain through a mathematical function called the Fourier Transform. This function decomposes its input into a series of sinusoidal waves at different frequencies [26]. This is shown in Equation 2.2, where A represents a Direct Current (DC) component that the signal may have (a non-zero mean), and B_n and C_n represent unique coefficients that the cosine and sine signals may have [25].

$$x(t) = A + \sum [B_n \cos(f_n \cdot t) + C_n \sin(f_n \cdot t)] \quad (2.2)$$

From these sinus waves the Power Spectral Density (PSD) can be calculated by squaring the Fourier Transform from each segment of data and averaging them [26].

In 1970 Peter Welch introduced what is known today as the Welch method. The Welch method is another way to compute the Fourier Transform and compute the PSD [27, 28]. The Welch method applies the fast Fourier transform algorithm to the estimation of the power spectrum. It has been proven to include fewer computations and therefore should be more efficient when computing the PSD [27]. Furthermore, the Welch method is said to be more flexible concerning recorded data [29].

2.5 Previous Work

A study from the year 2002, found that combining preoperative EMG deficits with early postoperative strength deficits offered strong predictions of weakness at 6 months post-operation [30]. Another previous study examined median frequencies of the Rectus Femoris muscle post ACLR. Results indicated lower frequencies in injured limbs at 1 and 3 months and decreases in uninjured limbs at higher contraction levels. This suggests altered muscle activation patterns following injury, affecting muscle fiber properties during recovery. [31]. Another study found significant hamstring muscle deficiencies post-fatigue in ACLR athletes [4] and yet another suggested that activation deficits and atrophy contribute significantly to quadriceps weakness following an ACL injury [32]. These include only a few examples of work that has previously been conducted, all of which concluding the great potential EMG has for the future of rehabilitation following an ACLR.

The topic is widely researched, however, there is still a lot to uncover [33]. This thesis will research the median frequency following an ACLR, up to the date of discharge from rehabilitation. Expectations of athletes' performances will be examined and furthermore it will research if an ACL rupture can lead to bilateral effects.

Chapter 3

Methodology

In this chapter, the methodology of the thesis is introduced. It will go through what signal processing methods were chosen and why, and how the data was processed. Furthermore, it will address how the data was analyzed and explain the parameters chosen for the data analysis.

3.1 Flow chart

A schematic flow chart can be seen in Figure 3.1.1. The flow chart introduces a step-by-step guide to the methodology of the thesis and highlights the steps taken during the signal processing, as well as the parameters and goals of the data analysis.

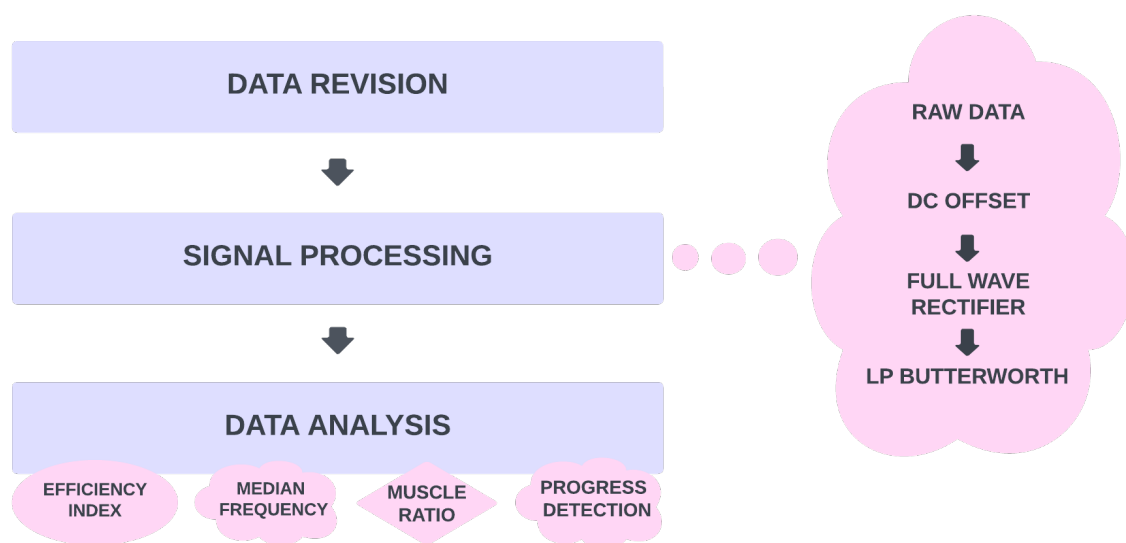


Figure 3.1.1: The thesis' schematic flowchart

3.2 Data and Equipment

All data was previously collected by Einar Einarsson, a Physical Therapist Specialist at the Irish Rugby Football Union. Delsys Trigno EMG sensors were used in the collection of data as well as the Delsys respective software, EMGWorks [34]. The sample frequency is 1926 Hz and bandwidth 20-450 Hz. As the data was all saved as a .hpf file from EMGWorks, the Delsys File Conversion Utility was used to convert the data to a .csv file before any data analysis could be done.

The data consists of two groups, a test group (ACL injured) and a control group (non-ACL injured) subjects. Data was collected from six muscles, two quadriceps muscles; VM and VL, two hamstring muscles; BF and ST, and two hip abductor muscles; Gluteus Medius (GM) and Tensor Fascia Latae (TFL). The control group came in once to perform the tests while the test group was asked to come in three times during their rehabilitation. The three times consisted of early; from 6-12 weeks after an ACLR, mid; from 16-20 weeks after an ACLR, and late; at the time of discharge from rehabilitation.

The tests performed during the data collection were, SLJ, Double Leg Jump (DLJ), Single Leg Squat (SLS), Fatigue, and a Maximum Voluntary Contraction (MVC) test. The exercise protocols are further explained in appendix A. The focus of this thesis will be on the MVC and SLJ.

At the start of every session, each subject began with an MVC test. MVC tests are done to measure the maximum contractions of the muscles each time and are often used as a reference for other tests conducted during the same session. The SLJ tests have been widely recommended for evaluating sport-related performance following an ACLR. They relate to numerous sports and activities and isolate muscular operations of the individual knee joint where the other leg cannot influence the test performance [35, 36]. Along with the EMG data two other parameters were measured that will be further used for the result analysis of the project. The jump height during the SLJ tests was measured for both legs and the subjects' strength was measured in grams during an isometric test.

3.2.1 Group Demographics

Table 3.2.1 presents demographic information for the two groups in question.

21 participants were in the control group, and 13 in the test group. Within the test group, 5 subjects ruptured their left ACL and 8 subjects their right ACL.

For the control group, the mean weight was 70.6kg with a standard deviation (SD) of 8.78kg, mean height was 176cm (SD 6.82), and mean age was 24.3 years (SD 4.27).

In contrast, the Test group had a mean weight of 73.5kg (SD 10.2), mean height of 174cm (SD 6.55), and mean age of 20.3 years (SD 4.83).

Overall, the Test group tended to have slightly higher weight, slightly lower height, and were younger on average compared to the control group. Variability in weight and age was slightly higher in the Test group.

Table 3.2.1: Group Demographics

	Group	Mean	SD
Weight	CTRL	70.6	8.78
	Test	73.5	10.25
Height	CTRL	176.1	6.82
	Test	174.4	6.55
Age	CTRL	24.3	4.27
	Test	20.3	4.83

3.3 Data Analysis

The analysis of this study was performed in Python, version 3.11.4, using the packages listed in Table 3.3.1.

3.3.1 Signal Processing

Figure 3.3.1 shows the signal of the VM muscle during a single SLJ test, before any signal processing is done. The file used and the VM was picked at random and will be shown as a reference throughout this chapter.

Table 3.3.1: Python Packages used in this thesis

Package	Version
Pandas	1.5.3
NumPy	1.24.3
matplotlib	3.7.1
openpyxl	3.1.2
SciPy	1.13.0
Tkinter	8.5

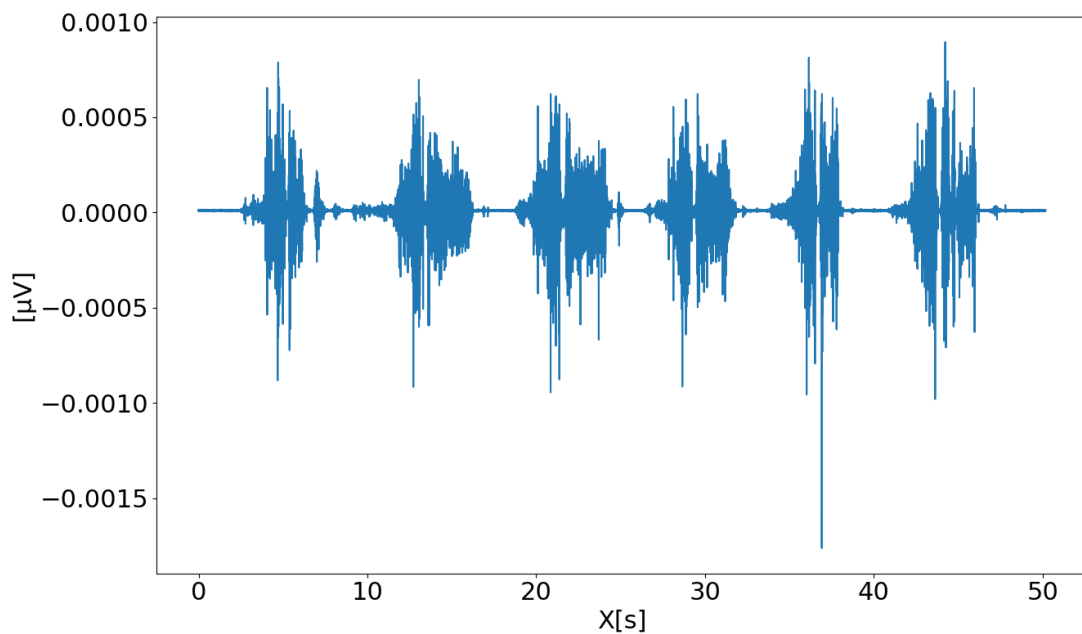


Figure 3.3.1: The raw signal of Vastus Medialis during a SLJ test, before any signal processing

The two methods, discussed in chapter 2 were tested to analyze the signal. For the RMS analysis different window sizes were tested, shown in Figures 3.3.2 and 3.3.3, before eventually picking 2500 ms as seen in Figure 3.3.4.

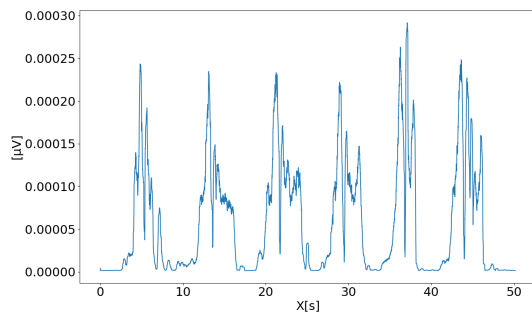


Figure 3.3.2: Signal filtered using Root Mean Square, window size 250 ms

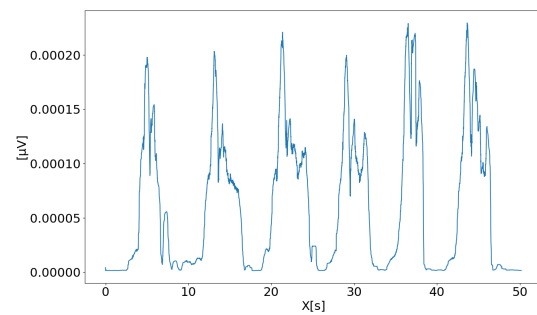


Figure 3.3.3: Signal filtered using Root Mean Square, window size 500 ms

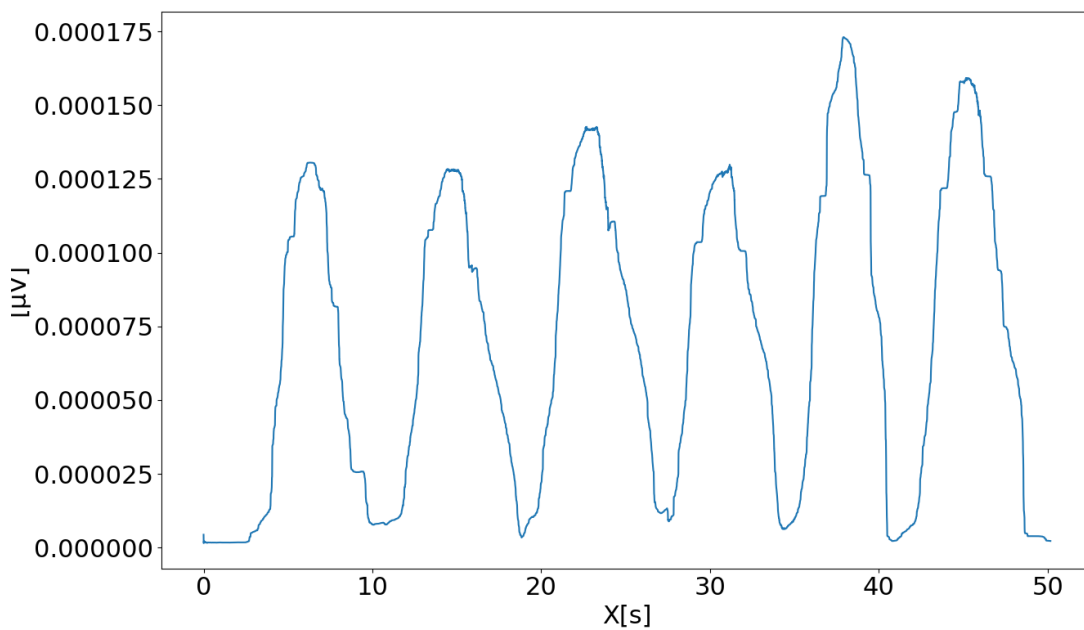


Figure 3.3.4: Signal filtered using Root Mean Square, window size 2500 ms

The second method mentioned was rectifying the signal, using a full wave rectifier, and then applying a Butterworth filter. A few tests were made to conclude which filter version and cutoff frequency to use.

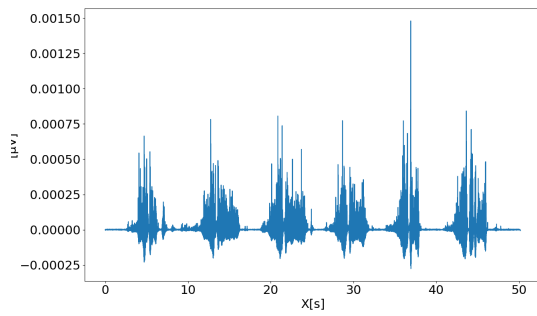


Figure 3.3.5: High-pass filter

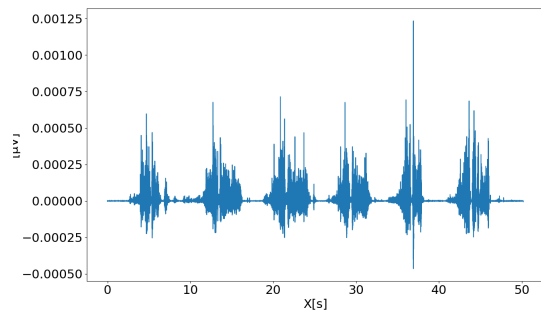


Figure 3.3.6: Bandpass filter

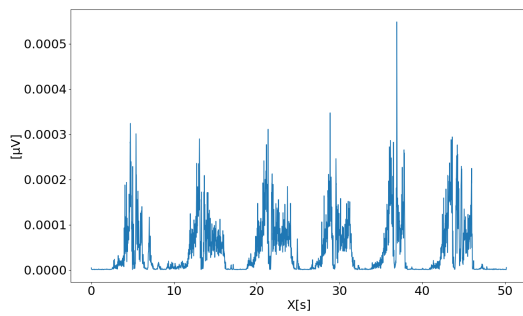


Figure 3.3.7: Filtered signal with a cutoff frequency of 20 Hz

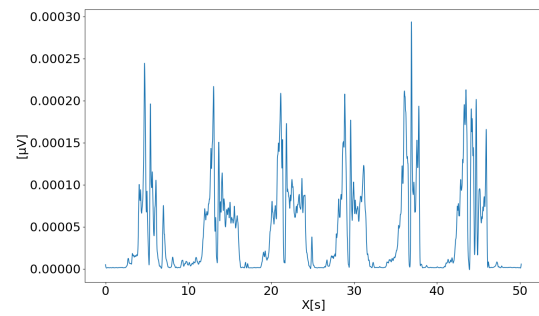


Figure 3.3.8: Filtered signal with a cutoff frequency of 5 Hz

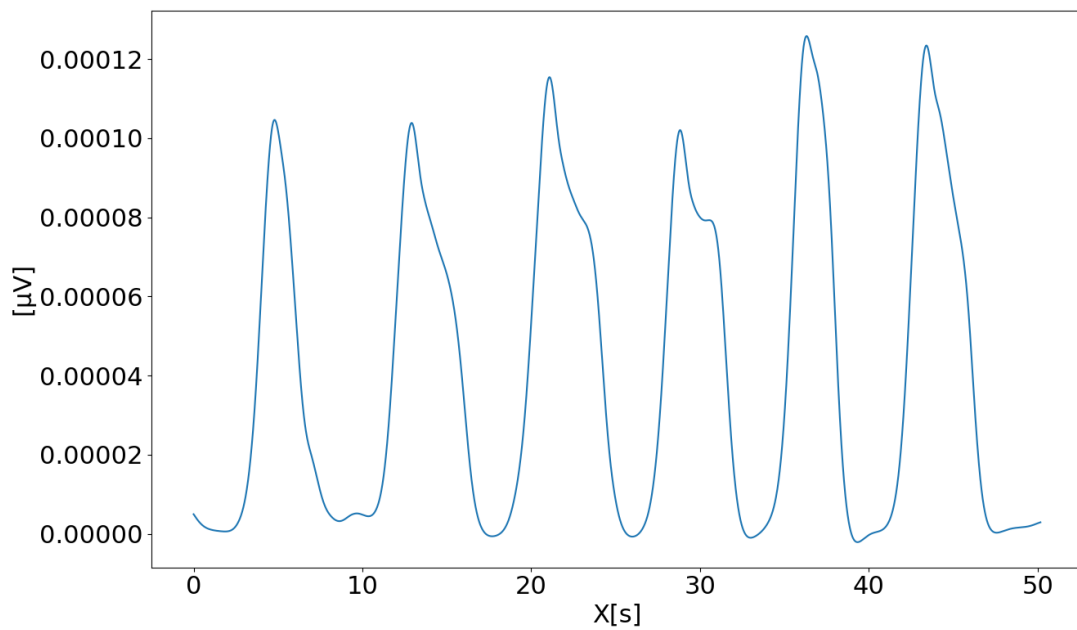


Figure 3.3.9: Signal filtered using a full wave rectifier and a 2nd order Butterworth filter with a cutoff frequency of 0.4 Hz

Figures 3.3.5 - 3.3.8 show different versions of filters and cutoff frequencies. It is noteworthy that the lowpass filter works better than the bandpass and high-pass filters. Ultimately when comparing Figures 3.3.7, 3.3.8 and 3.3.9, one can see that in Figure 3.3.9 the smoothest signal is returned.

Comparing the two methods, from Figures 3.3.4 and 3.3.9, it can be seen that both methods manage to filter the signal well. The latter ended up being chosen as the signal looks smoother in Figure 3.3.9. Furthermore, a second-order Butterworth filter was used and it was concluded that a higher order would not be necessary.

In conclusion, all signals were full-wave rectified and filtered with a low-pass second-order Butterworth filter with a cutoff frequency of 0.4 Hz.

3.3.2 ON/OFF Activation of the Muscles

Single Leg Jump Files

To evaluate each jump of the SLJ, each file was divided based on the ON/OFF activation of the muscle. When a muscle is active, it is said to be ON, and when it is inactive, it is said to be OFF. To divide the files two methods were tested.

The first method consisted of taking a percentage of the maximum voltage produced by the muscle. Three different thresholds were tested 20%, 30%, and 40%. This is shown in Figure 3.3.10. The thresholds were tested for all muscles and a few different files to decide which threshold was the best fit.

After careful consideration and comparisons of different muscles for a few subjects, the 30% threshold was chosen to be the best fit. Figure 3.3.11 then shows how the data was split for each muscle. Each color in the graphs represents one jump, and each graph contains all jumps for its respective muscle.

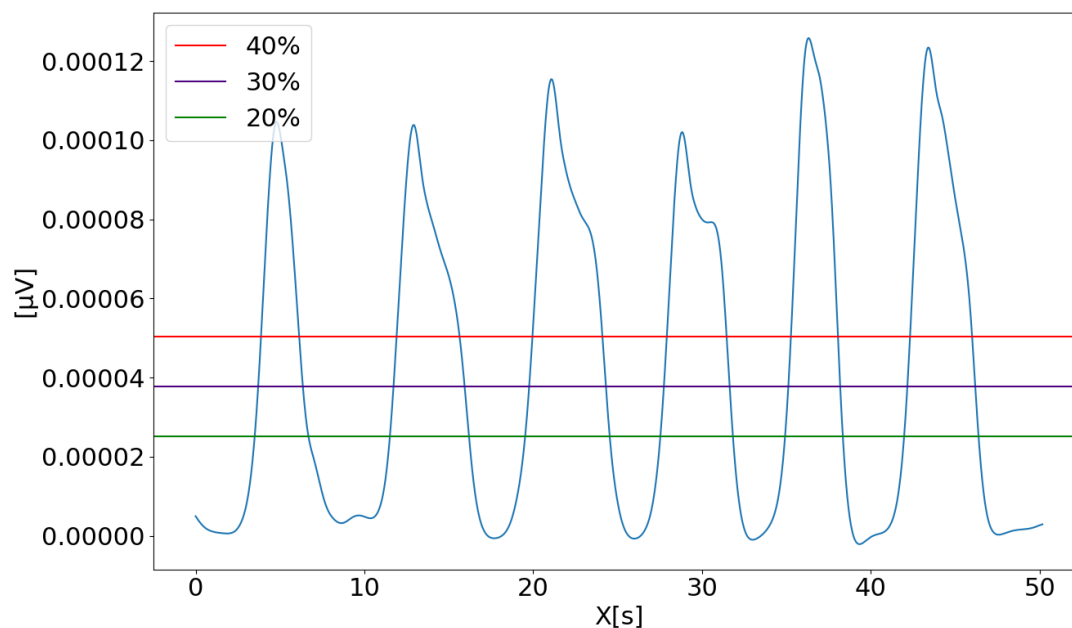


Figure 3.3.10: Different threshold compared

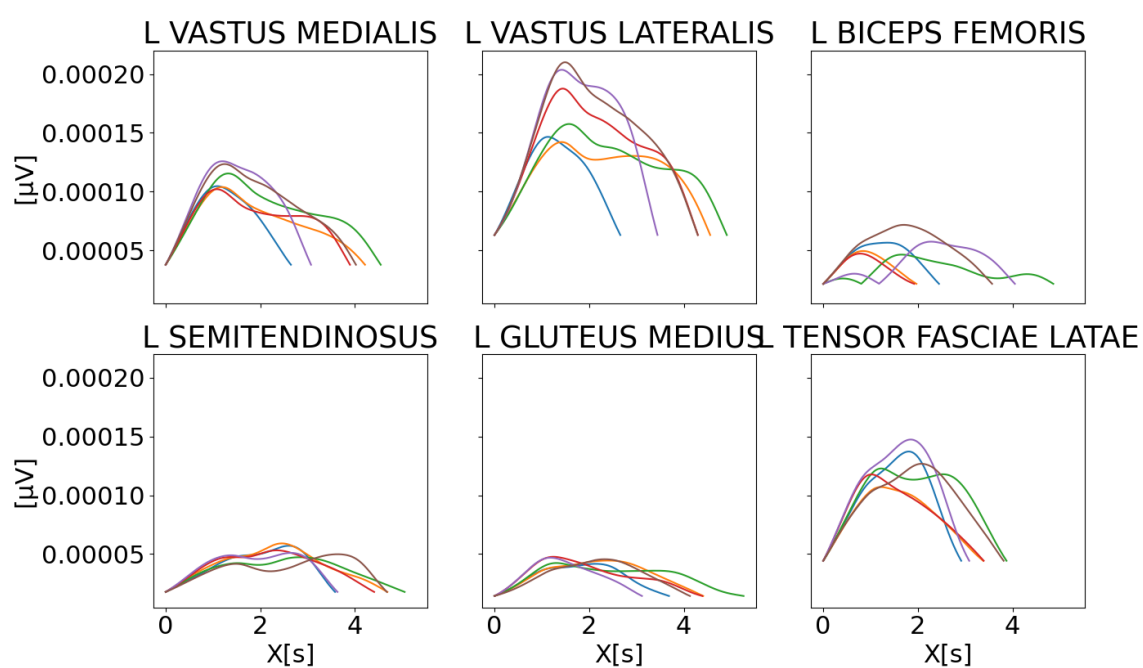


Figure 3.3.11: The muscle data split based on the 30% threshold

The other method was using the `find_peaks` function in Python and saving 5000 samples before and after each peak. As it is known that the subjects each jump 6 times in each SLJ test, the top 6 peaks, along with surrounding samples, are saved and plotted as seen in Figure 3.3.12.

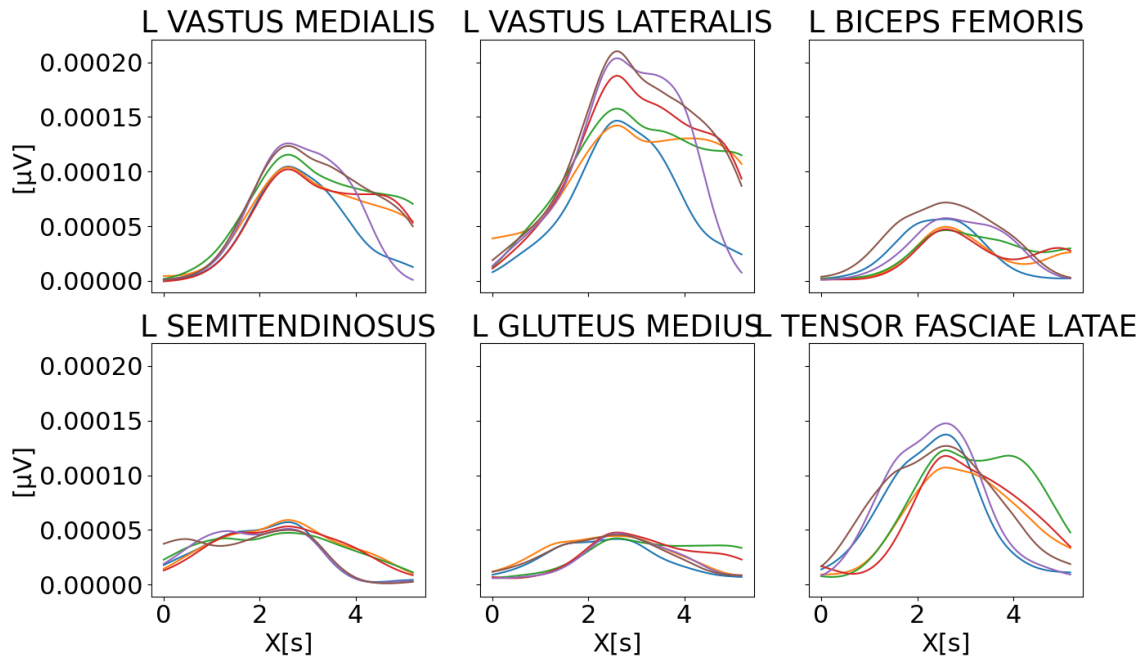


Figure 3.3.12: `find_peaks` function to split the data

When comparing the two Figures; Figure 3.3.11 and Figure 3.3.12 it is noted that they are two very different methods. Both have their pros and cons. However comparing the Biceps Femoris muscle between the two plots, one can see that additional 'bumps' are in Figure 3.3.11 that are not in Figure 3.3.12. After comparing the methods for more subjects, it was decided to use the `find_peaks` method for the continuance of this thesis.

MVC files

The MVC files were not needed in the same manner as the SLJ files. From the MVC files a single peak of the activation was needed. A similar method as before was used, that is the python function `find_peaks` was used to find the top three peaks of each muscle and the mean value from these three peaks saved to get the best results.

3.4 Data Analysis

To answer the research questions stated in chapter 1, the data was transferred to Excel along with the values measured during the data collection for the result analysis. The results were compared both by the injured and healthy legs between the test and control groups. As the injured legs were compared to the control group, the same amount of left and right legs were used and were picked at random.

An EMG index was defined as seen in equation 3.1.

$$\text{EMG index} = \frac{\text{grams}}{\text{EMG amplitude}} \quad (3.1)$$

Where grams is the weight tolerated by the subjects during isometric testing for each muscle group. The muscle groups being quadriceps (VM and VL), hamstrings (BF and ST) and hip abductor muscles (GM and TFL). The EMG amplitude then stands for the sum of the peak amplitudes of the muscles within the muscle group in question.

As the index uses the sum of each muscle group, the ratio of the muscles within each muscle group was further examined. Equation 3.2 shows how the ratio was computed.

$$\text{Muscle Ratio} = \frac{\text{Muscle 1}}{\text{Muscle 1} + \text{Muscle 2}} \quad (3.2)$$

Each muscle group contains two muscles, Muscle 1 and Muscle 2 as seen in equation 3.2, where the computation of the ratio of Muscle 1 is conducted.

To assess the progress made, the correlation was computed for the EMG indices. Correlation coefficients were calculated using the "CORREL" function in Excel. The significance of the correlation coefficient was assessed at the $\alpha = 0.05$ level. The coefficients were used to assess the progress made by the test groups, between the early and late test sessions.

3.4.1 Frequency Analysis

For further analysis, each test was converted to frequency spectrum, using the Fourier Transform. The Welch method introduced in chapter 2 was used to calculate the median frequency of each muscle during both the MVC and the SLJ tests. The median

frequency was then further compared to the jump heights of the subjects.

3.4.2 Statistical tests

Finally, to analyze the outcomes of the computations, statistical tests were conducted. Shapiro-Wilks tests were used to test the normality and student's t-tests were used in the evaluations to determine if the results were significant ($p < 0.05$) or not.

Chapter 4

Results

4.1 Healthy vs. Injured legs

The t-test, including all test progression, from early to late, from the comparison of the EMG indices of the healthy and injured legs showed no significant results as well as a t-test of the muscle ratio. The t-tests can be seen in Table 4.1.1.

Table 4.1.1: Independent T-test comparing the injured and healthy legs

	Statistics	df	p
Q EMG index	0.4131	76.0	0.681
H EMG index	1.1291	76.0	0.262
ABD EMG index	-0.0358	76.0	0.972
VM ratio	0.5555	76.0	0.580
BF ratio	1.4601	76.0	0.148
GM ratio	-0.2022	76.0	0.840

4.1.1 Early vs. Control Group

The early tests of the test group were compared to the control group. Comparing the EMG indices yielded no significant results. However, comparing the median frequency, significant results were found for the VM ($p = 0.001$), VL ($p < 0.001$) and BF ($p = 0.004$). The comparison is shown in Figures 4.1.1, 4.1.3 and 4.1.5.

4.1.2 Late vs. Control Groups

The late tests of the test group were then compared to the control group in the same manner. The EMG indices, again, yielded no significant results. The median frequency, however, yielded significant results in the same muscles as before. The VM ($p = 0.011$), the VL ($p = 0.017$) and the BF ($p = 0.016$). The comparison is shown in Figures 4.1.2, 4.1.4 and 4.1.6

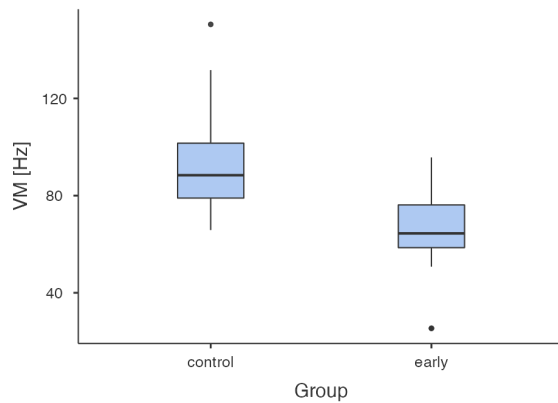


Figure 4.1.1: Injured Vastus Medialis from the early tests compared to the control group

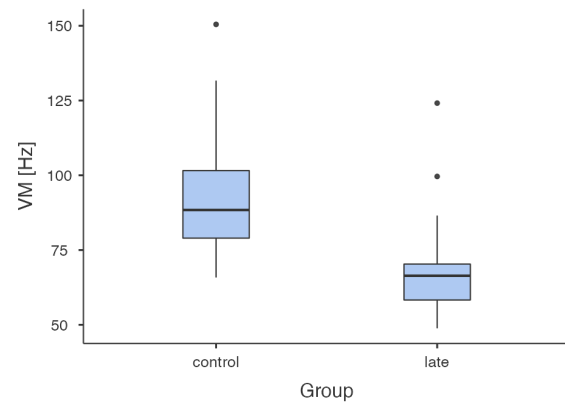


Figure 4.1.2: Injured Vastus Medialis from the late tests compared to the control group

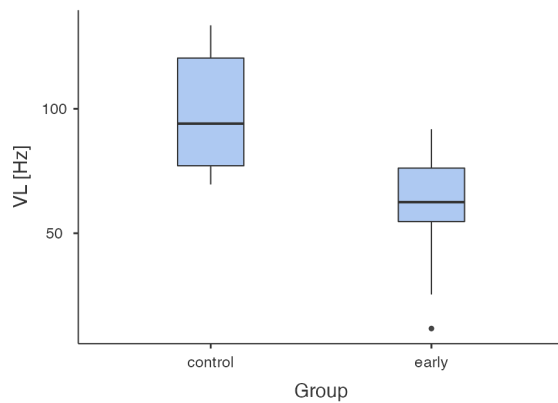


Figure 4.1.3: Injured Vastus Lateralis from the early tests compared to the control group

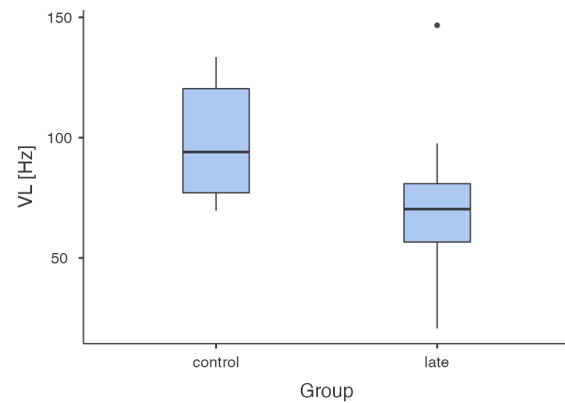


Figure 4.1.4: Injured Vastus Lateralis from the late tests compared to the control group

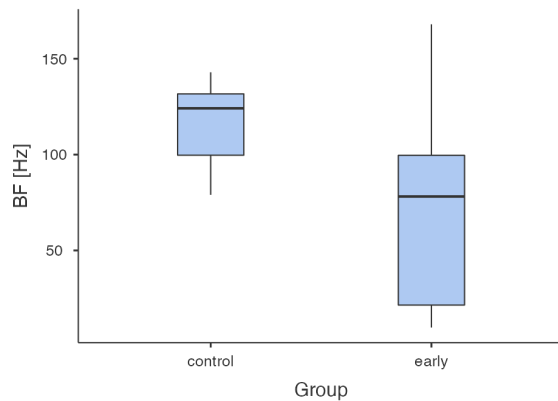


Figure 4.1.5: Injured Biceps Femoris from the early tests compared to the control group

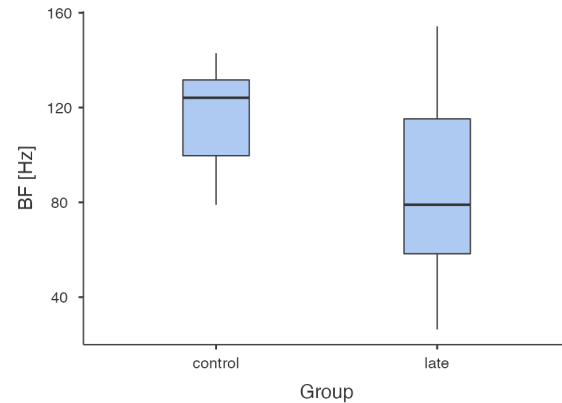


Figure 4.1.6: Injured Biceps Femoris from the late tests compared to the control group

4.1.3 Injured vs. Control Groups

The comparison of the injured, containing all test progressions, from early to late, vs. control groups will now be displayed. The EMG indices of the muscle groups showed no significant result, whether talking about the injured legs or the healthy. However, looking at the muscle ratio within the muscle groups, a different narrative unfolded.

The muscle ratio for both the hamstrings and hip abductor muscle groups showed significant results with $p < 0.001$ for both the injured and the healthy legs. The Quadriceps did not show significant results with $p = 0.385$ (injured) and $p = 0.551$ (healthy) respectively. The muscle ratio of the injured hamstrings is shown in Figures 4.1.7 and 4.1.8. The other muscle groups are shown in appendix B.

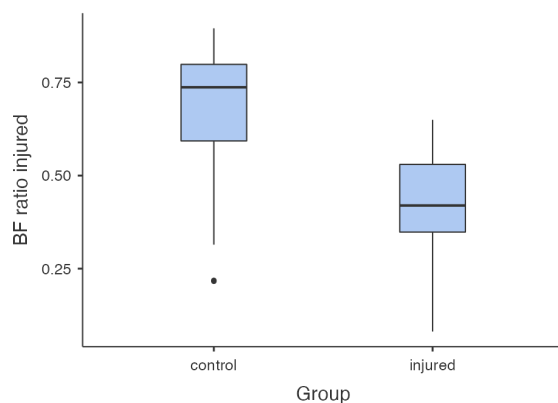


Figure 4.1.7: Biceps Femoris muscle ratio of the injured leg

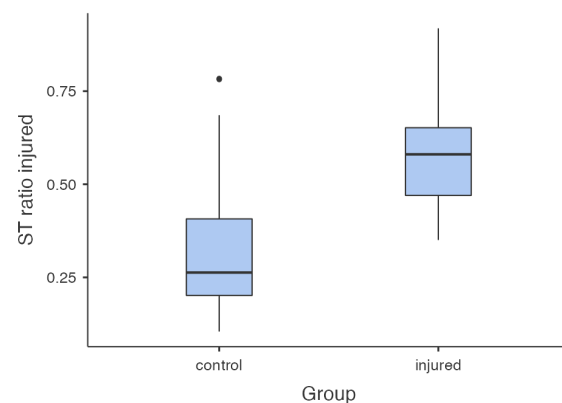


Figure 4.1.8: Semitendinosus ratio of the injured leg

The quadriceps muscle group, however, shows significant results in median frequency for the injured leg ($p < 0.001$ (VM) and $p = 0.002$ (VL)) as well as the VM of the healthy leg ($p = 0.005$). The quadriceps of the injured legs are shown in Figures 4.1.9 and 4.1.10

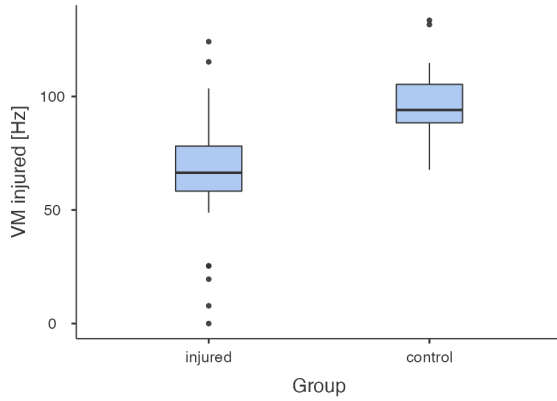


Figure 4.1.9: Median Frequency of the Vastus Medialis of the injured leg

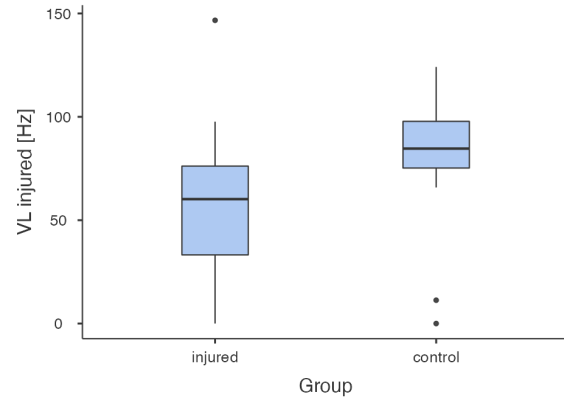


Figure 4.1.10: Median Frequency of the Vastus Lateralis of the injured leg

4.2 Single Leg Jump test

The results for both Median Frequency and Jump heights from the SLJ tests are presented here.

4.2.1 Median Frequency

During the SLJ tests the median frequency was compared for the healthy and injured groups. The median frequency was reported to be lower for all muscles during the test, however only the VL showed significant results for both the injured ($p < 0.001$) and healthy ($p < 0.001$) legs. This is shown in Figures 4.2.1 and 4.2.2.

4.2.2 Jump Heights

Significant results were found for both injured ($p < 0.001$) and healthy ($p = 0.013$) legs for the jump height tests. The mean difference between the control and injured group was found to be 7.2 cm on the injured leg and 5.3 cm on the healthy leg. The injured leg jumped 3.3 cm lower on average compared to the healthy leg. Figures 4.2.3 and 4.2.4 show the height difference between the groups.

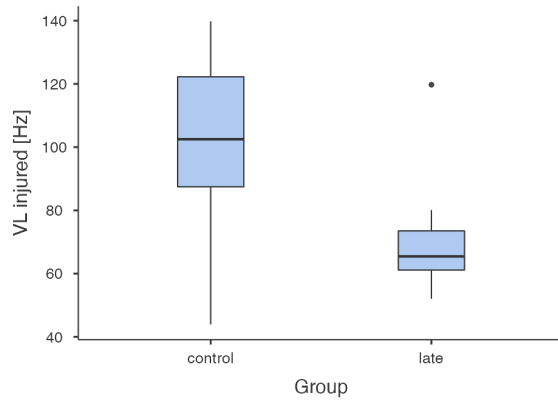


Figure 4.2.1: Median Frequency of the Vastus Lateralis of the injured leg during Single Leg Jump

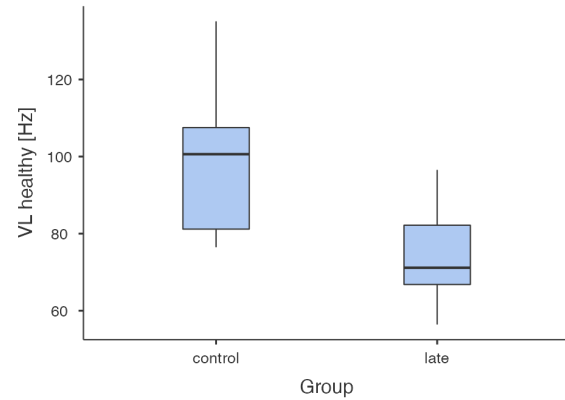


Figure 4.2.2: Median Frequency of the Vastus Lateralis of the healthy leg during Single Leg Jumps

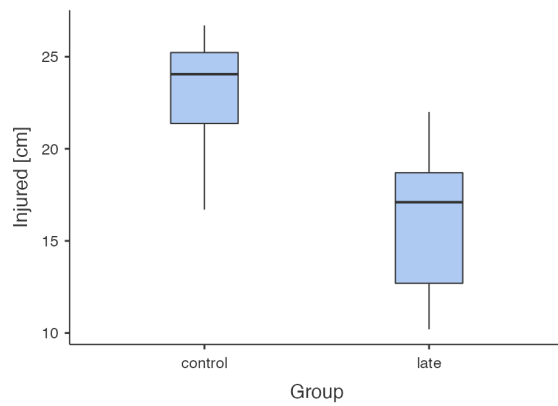


Figure 4.2.3: Jump height of the Injured leg

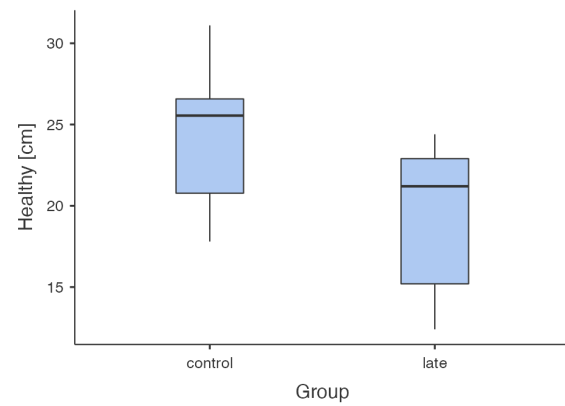


Figure 4.2.4: Jump height of the healthy leg

4.3 Progress Detection

Figures 4.3.1 and 4.3.2 show the EMG indices from the early to late MVC tests of the quadriceps for all subjects. The blue line, highlighted in the images, shows the mean value of the indices over all the subjects.

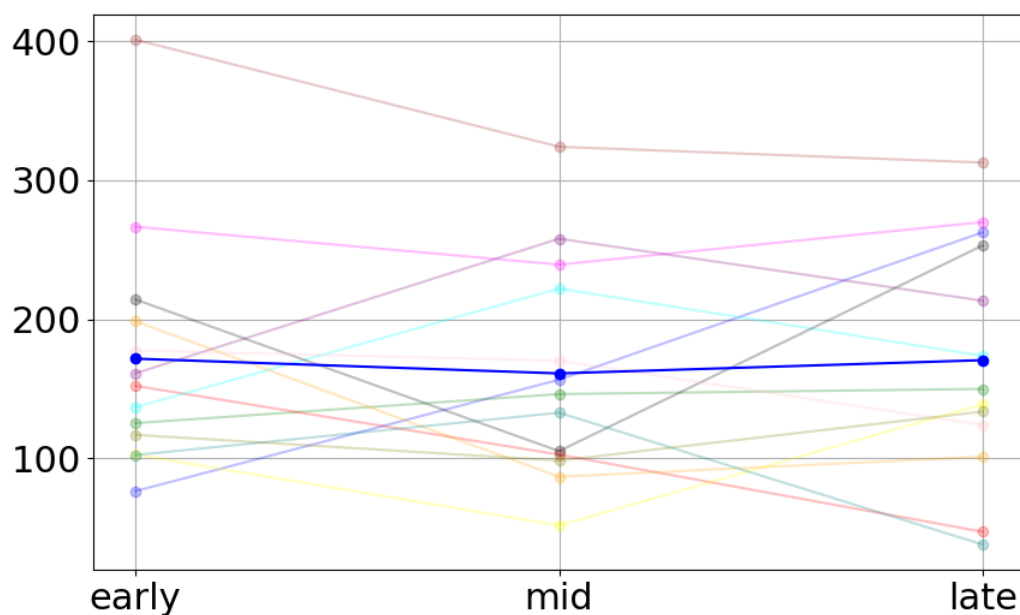


Figure 4.3.1: EMG indices for the Quadriceps muscles of the injured leg for all athletes. The blue highlighted line is the mean value of all athletes

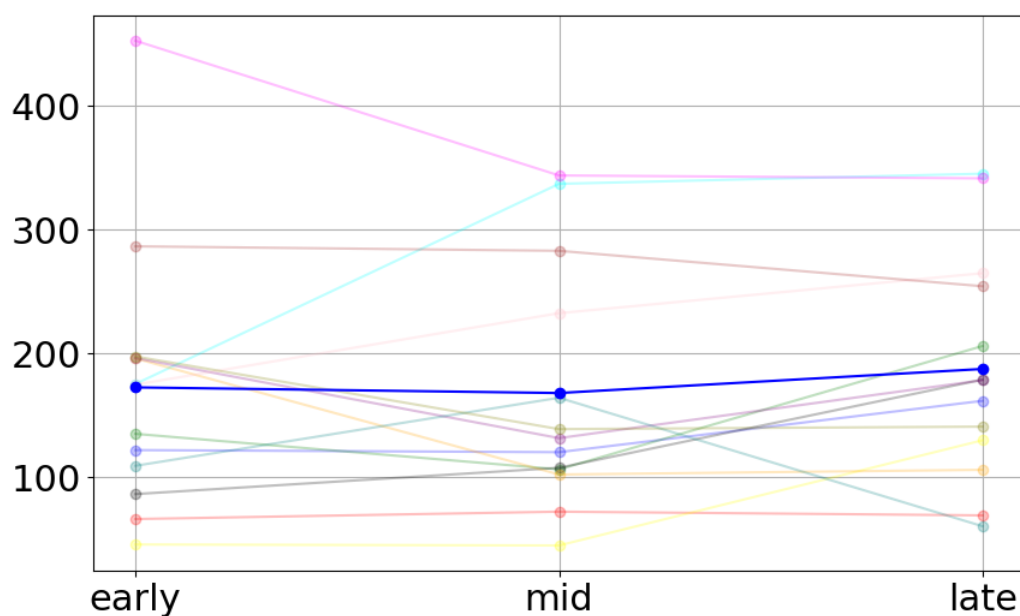


Figure 4.3.2: EMG indices for the Quadriceps muscles of the healthy leg for all athletes. The blue highlighted line is the mean value of all athletes

The correlation coefficients, shown in Table 4.3.1 were calculated between the early and late groups, for each muscle group on both the healthy and injured legs.

Table 4.3.1: Correlation Coefficients for progress detection

	Injured	Healthy
Quadriceps	0.57	0.65
Hamstring	0.33	0.16
Hip Abductors	0.64	0.70

Chapter 5

Discussion

The results presented in the previous chapter will be further analyzed and discussed in this chapter. The chapter will follow the same structure and offer criticism and thoughts on what happens in the lower body when an ACL is ruptured. Finally, the limitations of the study are introduced.

5.1 Healthy vs. Injured legs

The first test conducted was an independent t-test to compare the healthy and injured legs of the test group. As mentioned in section 4.1 the t-test showed no significant results for neither the EMG indices nor the ratio between muscles within the muscle groups. These findings indicate that the occurrence of an ACL rupture could result in bilateral effects as reported in previous research [32].

As the results from these tests did not show any significant results, the control group was used as a reference for the test group in further comparisons.

Comparing the early tests to the control group as well as the late tests to the control group showed no significant results from the EMG indices as stated in section 4.1. However, from both of these comparisons, significant results were found in the median frequency. VM, VL, and BF were all found to have significantly lower median frequency in the test group compared to the control group. This indicates changes within the muscle activation patterns and that an ACLR impacts the activation patterns. This has also been reported in previous research [31, 37], although further research is needed to gain full understanding.

Furthermore, the whole progression of the test group was compared to the control group. The EMG indices, again, showed no significant results, but looking deeper into the muscle groups, a different narrative was unfolded. The ratio between the muscles within the muscle group exhibits a mirroring effect. This can be seen in the hamstrings and the hip abductors, the quadriceps did not show significant results, although exhibiting the same pattern.

This indicates that in the case of an ACL rupture the ST assumes a greater role between the two hamstring muscles examined, deviating from the control group where the BF typically bears a higher load. Prior research has suggested a deficiency in the medial hamstring in ACLR athletes, leading to a change in knee kinematics and stability. This could explain the change in muscle ratio, however, further research is needed for a better understanding [38].

The median frequency showed significant results for the VM of both the healthy and injured legs and the VL of the injured leg. This indicates that although the amplitude of the muscles is not significant, there is still a difference in the quadriceps. As mentioned, the significant difference can indicate different activation patterns but further research is needed.

5.2 Single Leg Jump test

As not all subjects were able to perform SLJ until the last test session, the SLJ tests were only compared between the late and control groups.

As reported in section 4.2, the median frequency was lower for all muscles in the test group, compared to the control group. This can indicate that the muscles of the control group are more activated during the jumps, leading to the jump height results.

When examining the results of the jump heights, the findings suggest significant differences between ACL-injured and healthy subjects. The ACL-injured group showed significantly lower jumps for both legs. This can again imply that injuring an ACL in one leg can lead to bilateral differences.

5.3 Progress Detection

To be able to track the progress of the athletes, the EMG indices were plotted over time. This can be seen in Figures 4.3.1 and 4.3.2.

As explained in section 3.4, the EMG indices are defined as the grams lifted divided by the EMG amplitude of the muscle group in question. As the rehabilitation progresses, the goal would be to lift more weight while using less muscle, meaning the EMG amplitude should decrease evenly as one lifts the same weight or more. That is, the dream scenario would be that the EMG indices decrease with time.

As seen in the Figures, this is not always the case. For some subjects, the decrease is somewhat linear and for others, the indices only change slightly. Cases of increase can also be found as well as changes with no patterns.

As seen in table 4.3.1, the correlation between the early and late is somewhat linear, although, not perfectly. It is noted that the hamstrings exhibit the least linearity in both the healthy and injured legs. These findings are not surprising as there is a lot of variability in EMG amplitude and many variables, such as skin and temperature, that can affect it. Therefore it might be more important to understand the ratio between the synergist muscles in these tests and how it changes with ACLR.

5.4 Limitations

Inherent in any research are limitations that limit the findings of the thesis. This section will list limitations found thus far and suggest changes and different directions to be considered in future work.

To begin with, limitations can be found in how the signals are processed. Filtering out all artifacts was found to be time-consuming, therefore some artifacts made it through the filters and were included in the computations of the thesis. To name an example when the data was split based on the ON/OFF activation of the muscles, the top peaks were found. In a few instances, some of these peaks have now been found to have been an artifact. To fix this the code could be changed to check if the data around the peaks drops in an instant. This would indicate that the peak is an artifact. That specific peak could be excluded as an ON activation of the muscle in question and, therefore, excluded from further calculations.

Another notable limitation is the timing of when the tests are taken for the test group. As mentioned in section 3.2, the first test is taken in the span of 6 weeks, the second in the span of 4 weeks, and the last one at the time of discharge, depending greatly on the subjects themselves. 'We are all as different as we are many' is an Icelandic phrase and is very fitting in this context. The subjects are as different as they are many and all have different times of discharge. The timings of the tests will therefore not showcase everyone's progress the same. There are examples of subjects discharging at around 20 weeks and other examples of subjects discharging around 48 weeks following an ACLR. The mid-test can therefore be taken very close to their discharge timing or around mid-rehabilitation. As is the 6-week time-span in the early test very long, the progress made between week 6 and week 12 can increase exponentially in these weeks. This is something to consider in the case of another research. Tests could be taken more frequently, resulting in more data, and less difference between subjects. However, test-timing can never be both progress-based and equal in time for everyone.

It's important to note the limitations posed by the control group in this study. The control group comprised competitive athletes who underwent the same tests as the test group. However, since they were volunteers, they could choose not to participate in certain tests. Some participants only did the MVC tests and skipped the SLJ tests. As a result, there's more data available for comparing MVC than for SLJ. For future works, this is something to consider. It could be considered to pay the control subjects, rewarding them might make them more willing to put in the work. Another idea would be to make sure that these tests were taken in the off-season of the subjects, or directly following their season, so games and competitions cannot be of disturbance.

In summary, while this thesis provides valuable insights regarding ACLR and rehabilitation, it is important to acknowledge its limitations. By doing so, future researchers will be guided toward new directions and methods, enhancing the robustness of the field.

Finally, ChatGPT version GPT-4 [39] and Grammarly Free, version 1.71.2.0 [40] were used in order to improve the grammar and language in this thesis.

Chapter 6

Conclusions

This thesis researched EMG data of muscles surrounding the knees following an ACLR. Deeper insights were gained into the muscular responses during the period of rehabilitation following an ACLR. Questions such as if the frequency spectrum is a feasible method to evaluate the rehabilitation progress and if there is a linear relationship between different stages of the rehabilitation were answered.

The frequency spectrum has been reported to give good insights into muscle activation and to be a valuable factor when evaluating the rehabilitation progress following an ACLR. Further research is still needed to evaluate whether the frequency spectrum is a feasible method to evaluate rehabilitation progress. It, however, serves as a way of understanding how the muscles function and react to the injury and can give good insights into how the muscles respond to rehabilitation.

Based on the findings in this thesis, there is a slightly linear relationship between the different stages of rehabilitation. Indicating that if an individual has good results in the early stages, they tend to have good results in the later stages, although it is not guaranteed. The same can be said if an individual has poor results in the early stages, at the time of the late stages their test results are rather expected to be poor. This relationship might improve with a bigger cohort. It is important to know that, despite poor early results, late results will still be possible.

As the healthy and injured legs were compared, results displayed that there was not a big difference between the two legs. Indicating bilateral effects from rupturing an ACL. Athletes are therefore not expected to maintain strength in their healthy leg, following an ACLR. The results from the SLJ tests indicated the same effects as the ACLR athletes

had significantly lower jump heights on both legs compared to the healthy group.

In conclusion, this thesis has provided good insight into the field of ACL injuries. There are already great tools and applications on the market today designed to be used in rehabilitation that should be more recognized and used especially by physical therapists. The author believes that EMG sensors are the future of rehabilitation. EMG sensors not only provide insight into muscle activity but are also low in cost and easily tractable, making them economically and ecologically sustainable. They are being developed today to connect to the next smart device via Bluetooth, and are therefore becoming a good out-of-lab solution. The sensors can have a great societal impact as they give insights that can shift the focus of athletes' rehabilitation, discharging them at a stronger level than before. In the long run, this can result in more athletes returning to their respective sports, and some even sooner than before, saving money for both the athletes and their teams. In other words, EMG sensors, are not only considered to be a good and an informative solution regarding rehabilitation, providing informative feedback and deeper insights to physical therapists, but they can also be considered as a sustainable solution.

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Appendix A

Test Protocol

EMG and clinical assessment measurements after ACLR

Information about the procedure and the objectives of the assessment are provided verbally to the subject. Instructions about each task are given in detail immediately before the task is executed, and the patients are asked to perform one trial without recording to ensure they understood the task.

Before recording any sEMG, the participant is requested to perform a 10-minute warm-up on a static bicycle. For electrode placement, skin is shaved and cleaned with alcohol swabs (70%), and electrodes are placed according to the direction of muscle fibers, following SENIAM guidelines.

EMG data is collected from the VL, VM, BF, ST, GM and TFL on both legs as subject performed the before-mentioned tasks in the following manner.

- 3 repetitions of double leg squat for EMG signal test and inspection.
- 3 repetitions of maximal voluntary isometric contraction (MVC) for each muscle group with 1 minute rest in between each repetition, with strength measured with a handheld dynamometer attached to a belt, to encourage the exertion of more force in the following attempt.
 - For the quadriceps muscle group, subjects are sitting with the knee at 60° flexion and exerted force towards extension.
 - For the hip abductors group, subjects were in standing position and performed the movement towards abduction.

- For the hamstrings, subjects are lying in prone position with the knee in 60° flexion and perform the movement towards knee flexion. This last one was performed against manual resistance.
- 6 repetitions of SLS: subjects were instructed to squat on one leg as low as possible, with 10 seconds rest in standing position in between each repetition.
- 6 repetitions of SLJ: subjects were instructed to jump on one leg as high as possible, with 10 seconds rest in standing position in between each repetition. Jump height was measured with Optojump Next and respective software.
- 3 repetitions of DLJ: subjects were instructed to jump with two legs as high as possible and land on one leg, with 10 seconds rest in standing position in between each repetition. Additionally, jump height was measured with Optojump Next and respective software.
- 30 seconds SLJ: subjects were instructed to jump on one leg as high as possible and as fast as possible during 30 seconds. Jump power was measured using Optojump Next and respective software.

Each procedure above was executed according to status of the athlete, and if the athlete is already performing these tasks during the rehabilitation sessions. The assessment is ceased if there is any pain performing the described tasks.

For the control group, all procedures are executed provided that subjects were healthy and pain-free for the last three months.

Appendix B

Results

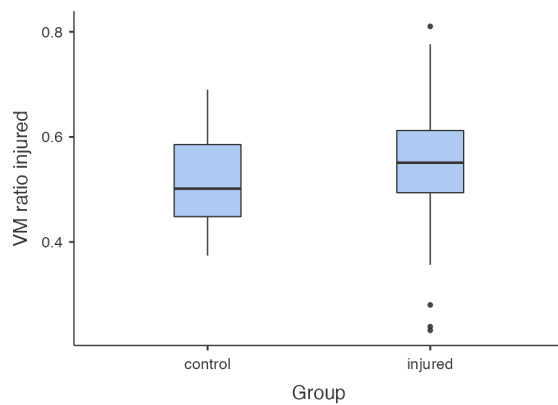


Figure B.o.1: Vastus Medialis muscle ratio of the injured leg

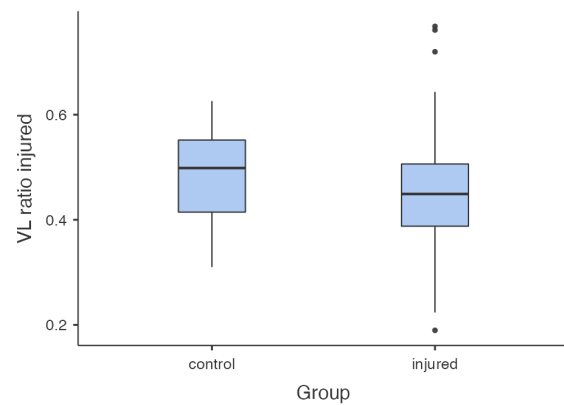


Figure B.o.2: Vastus Lateralis ratio of the injured leg

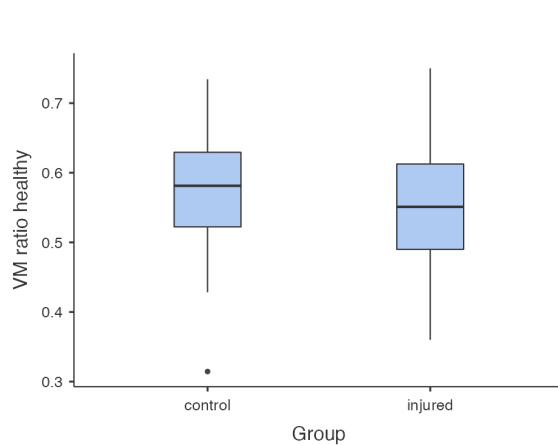


Figure B.o.3: Vastus Medialis ratio of the healthy leg

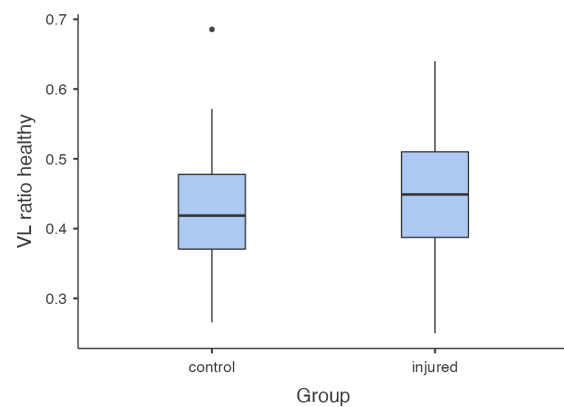


Figure B.o.4: Vastus Lateralis ratio of the healthy leg

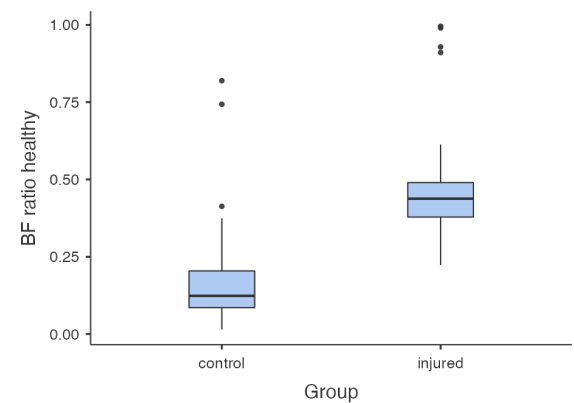


Figure B.o.5: Biceps Femoris muscle ratio of the healthy leg

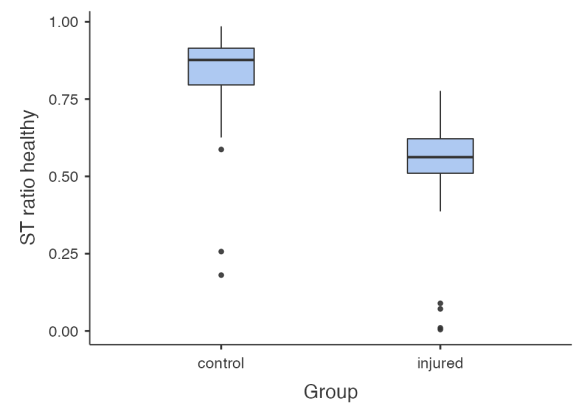


Figure B.o.6: Semitendinosus muscle ratio of the healthy leg

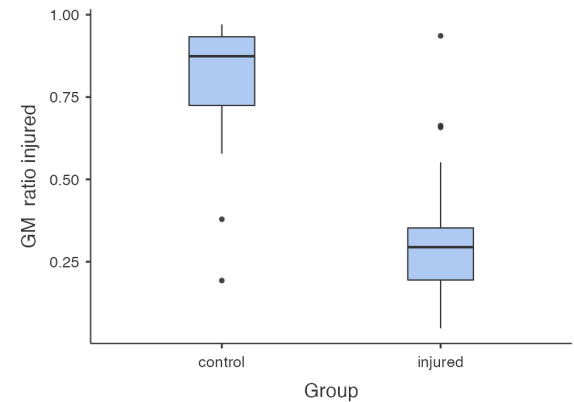


Figure B.o.7: Gluteus Medius muscle ratio of the injured leg

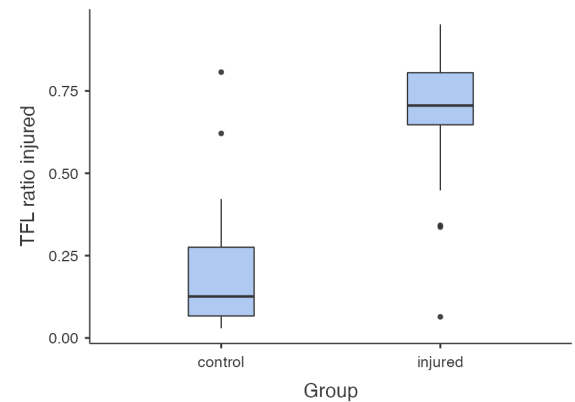


Figure B.o.8: Tensor Fasciae Latae muscle ratio of the injured leg

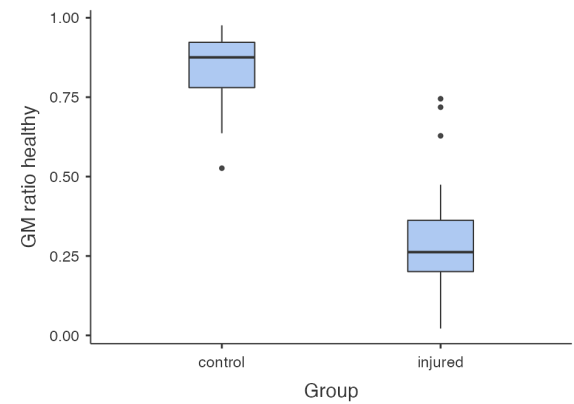


Figure B.o.9: Gluteus Medius muscle ratio of the healthy leg

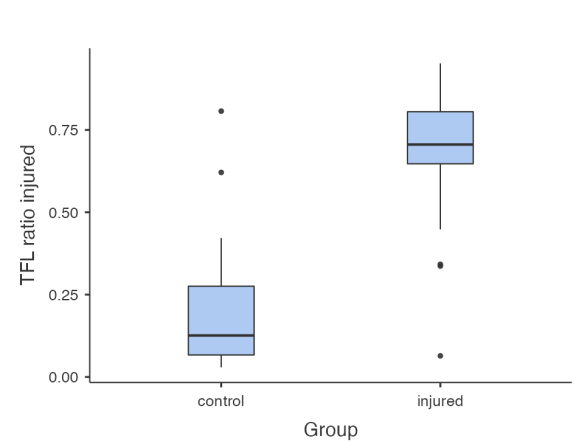


Figure B.o.10: Tensor Fasciae Latae muscle ratio of the healthy leg

