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Towards personalized return to sport decision after ACL-reconstruction

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List of abbreviations

ACL	Anterior cruciate ligament
ACLr	Anterior cruciate ligament reconstruction
IC	Initial contact
IMU	Inertial measurement unit
MMTs	Manual muscle tests
MVICs	Maximal voluntary isometric contractions
OCON	Orthopedisch Centrum Oost Nederland
ROM	Range of motion
RTS	Return to sport
SD	Standard deviation
sEMG	Surface electromyography
SLHDs	Single leg hop for distances
SPM	Statistical-parameter mapping

Summary

An often-discussed topic within the rehabilitation after ACLr is the decision whether a patient is ready to return to sport. Current test batteries do not include neurocognitive load, something that athletes face in real sport situations. As a result, these test batteries may not be specific enough to determine whether an athlete is ready for return to sport. During this graduation internship, a research line has started on the role of neurocognitive load in rehabilitation after ACLr. The main aim of this research line is to evaluate the effect of neurocognitive load on jumping distance, movement patterns and muscle activation patterns in ACLr patients and controls without knee injury.

In the service of this research line, a pilot was first carried out. Participants: Eleven participants (5 Male, 6 Female, 26 ± 4 years, 178 ± 7 cm, 69 ± 10kg) were recruited. Method: Knee kinematics and muscle activation patterns were measured during ten successful single leg hop for distances. Figures with knee kinematics and muscle activation patterns are visually compared with means of the total population. Besides two-tailed SPM paired t-tests were performed to compare the subject-averaged curves for successful and failed trials. The level of statistical significance was set at $p \leq 0.05$ for all analyses. Results: knee kinematics and muscle activation patterns differ minimally within a participant over several jumps in a population without knee injuries. Over the population, however, the differences are large, leading to a wide spread in standard deviations. No differences were found in knee kinematics between successful and failed trials, except for range of motion. During failed trials of the SLHDs, however, participants showed a higher peak activation of the gastrocnemius medialis during take-off. Conclusion: Proposed measurement setup is suitable for evaluating differences within a participant. Based on the higher peak activation of the gastrocnemius medialis, failed jump trials mainly occur when the participant challenges himself. However, including jumping distance of the failed trials should confirm this.

Finally, the research line was started, and first patients and controls were included in the study. Participant: Eight participants were recruited for the ACLr group (6 Male, 2 Female, 24 ± 5 years, 181 ± 13, 76 ± 9 kg) and ten participants were recruited in the control group (7 Male, 3 Female, 23 ± 2 years, 184 ± 10 cm, 80 ± 15 kg). Jumping distance, knee kinematics and muscle activation patterns were measured during standard single leg hop for distances and two singles leg hop distances containing different neurocognitive load. Method: First, two-tailed independent t-tests were performed to assess differences in jumping distance and kinematic outcome parameters between the reconstructed leg of the ACLr group and the dominant leg of the control group. Two-tailed SPM independent t-tests were performed to investigate differences in knee kinematics and muscle activation patterns between the reconstructed leg of the ACLr group and the dominant leg of the control group. Second, two-tailed paired t-tests were performed to assess differences in in jumping distance and kinematic outcome parameters between standard SLHDs and both neurocognitive SLHDs. Besides, two-tailed SPM paired t-tests were performed to compare the subject-averaged curves for the conditions. Results: No differences were found between the reconstructed leg of the ACLr group and the dominant leg of the control group. Overall, this study established that adding a neurocognitive component to standard hop tests influences the jump strategy, according to knee kinematics. Specifically, differences occur in maximal knee flexion during the flight phase in ACLr patients. Conclusion: Statements on whether differences exist between the operated leg of the ACLr patients and dominant leg of the control group are for now omitted and require a larger study population.

The SLHDs presented in this thesis are a first step to clinically incorporate a neurocognitive component to functional testing. For further expansion of the research line, it should be considered to enable synchronization between the measurement techniques. In addition, the measurement setup could be expanded with a force plate. This makes it possible to perform even more detailed analyses. The clinical study is currently running, and a larger study population is required to draw definitive conclusions. With this future refinement, the research line has the potential to guide clinical decision-making by emphasizing deficiencies throughout the duration of a challenging neurocognitive task. This may improve an objective, personalized and more complete return to sport advise, which will contribute to minimizing the currently high incidence of re-ruptures of an ACL and while increasing the RTS ratio.

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GENERAL INTRODUCTION

Anterior cruciate ligament

The anterior cruciate ligament (ACL) is one of the four major ligaments of the knee, providing stability to the tibiofemoral joint. The ACL runs from the medial surface of the lateral femoral condyle, slants at the knee joint from lateral-posterior to medial-anterior and attaches to a broad area of the central tibial plateau (1, 2). The total intra-articular length of the ligament varies throughout the normal range of motion (ROM) of the knee, which is 0 degrees of extension (completely straight knee joint) to 135 degrees of flexion (fully bend knee joint) (3). The ACL consists of two distinct bundles: an anteriomedial bundle and a posterolateral bundle. These two bundles have unique points of attachment within the knee, which lead to a complex dynamic relationship during knee flexion. Both bundles contribute to knee stability by limiting anterior tibial translation and conferring rotational stability (4). Apart from its mechanical role, the ACL also appears to play a role in knee proprioception due to the mechanoreceptors within its substance. These mechanoreceptors transmit information about movement, position, and rotation of the joint, and detect changes in tension within the ligament (5, 6).

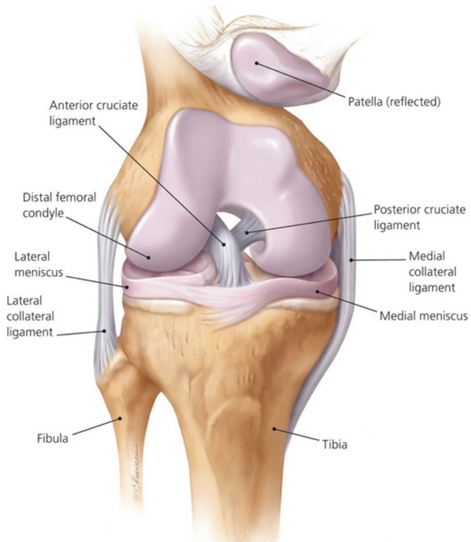

Figure 1.1 Anatomy of the knee, including the ACL.

Anterior cruciate ligament rupture

Rupturing the ACL is a common injury among young athletes during sports (7). Most ACL ruptures occur in men between 15 and 34 years, and women between 14 and 21 years. It is estimated that about 13.5000 people rupture their ACL annually in the Netherlands. ACL injuries predominantly result from a noncontact mechanism (8-10). It often occurs during abrupt landing or due a rapid change of direction with the knee in a semi-flexed position with valgus or varus stress and internal or external rotation. Given the course of the ACL, these movements generate forces that load the passive knee joint structures including the ACL. Symptoms of an ACL rupture include pain, an audible cracking sound during injury, and joint swelling. Depending on the trauma mechanism and the forces that occur during trauma, other injuries in the knee can occur in addition to the ACL injury: for example, meniscal or cartilage injuries and ruptures of other ligaments. These early symptoms usually subside within 2-4 weeks of the injury. In addition, ACL rupture can result in knee instability, during sport but also in daily life.

Treatment of ACL rupture

Treatment of ACL rupture is important to reduce abnormal knee movements, improve knee function, build trust and confidence to use the knee normally again and optimize long-term quality of life following the injury (11). Treatment of an ACL rupture is either non-surgical or surgical and must be determined on an individual basis. Non-surgical treatment of ACL ruptures traditionally involves a physiotherapeutic approach including rehabilitative exercises and physical activity modification. About half of the patients experience residual instability after non-surgical treatment and op to undergo an ACL reconstruction (ACLr). During this operation, a patellar or hamstring tendon is used to reconstruct the native ACL. This operation is mainly performed in athletes who are involved in sports with jumping, pivoting, and cutting movement such as soccer, volleyball, and basketball.

Rehabilitation after ACL reconstruction

ACLr and post-operative rehabilitation attempt to restore normal knee stability and function, and to prevent the development of future pathologies in the joint (i.e., osteoarthritis). Rehabilitation programs typically focus on ROM, balance, strengthening and neuromuscular exercises (12). *"When can I start sports again?"* is a frequently raised question by athletes who suffered from ALC rupture. After ACLr, more than 90% of athletes expect to be able to return to their sport at the same activity level as before the injury (13). An often-discussed topic within the rehabilitation after ACLr is the decision whether a patient is ready to return to sport (RTS) (14), since the risk for a re-injury increases when someone is not ready yet to RTS. Wiggins et al. found that 23% of the athletes under the age of 25 who returned-to-sports will suffer from a new ACL rupture (15). Most of these new injuries occur within two years, of which half of them in the first six months after RTS (15, 16). In view of the above-mentioned numbers, it is necessary to evaluate the functional performance of athletes before they return to their previous level of sports to reduce the risk of new injuries.

Many different functional tests are available to quantify knee function, but no golden standard exists on which the RTS decision can be based (17). Commonly used test batteries consists, among other things, hop tests to evaluate injury recovery (18-20). This includes a variety of single leg jumps where a person jumps as far or as high as possible. These activities challenge knee stability by requiring large knee moments during take-off and landing. A combination of muscle strength, neuromuscular control, confidence in the knee, and the ability to tolerate loads is tested. These tests are attractive since they are easy to perform, repeatable, and have satisfactory reliability.

Neurocognitive load

Although current hop tests provide an indication of an athlete's progress in rehabilitation, its results are not comprehensive. A hop test is a so-called closed skill, which takes place in a predictable and static environment. Various team ball sports such as soccer, basketball, and volleyball, however, are classified as open skill sports. These sports involve unpredictable environments, active decision making, and ongoing adaptability in which athletes must alter responses to randomly occurring external stimuli (21). In this, neurocognitive functions play an important role. This refers to a set of mental processes necessary for processing information. Neurocognitive functions are essential in tasks that require concentration, coordination, and control to suppress internal or external stimuli, such as in the sports environment. Presence of cognitive or visual load is associated with movement strategies which are related to an increased risk of injury (22-24). Recommendations for RTS decision from 2016 states that a test battery should consist of multiple tests that make use of the reactive elements and the decision-making steps as athletes use in real sports situations (25). However, current hop tests do not include such neurocognitive aspects.

Recent research has explored the use of a light system to introduce a reactive cognitive load to traditional functional tests to better simulate the demands of sports (26). In this study, four different hop tests were used, each of which tested a different aspect of neurocognition. These neurocognitive hop tests were found to be more challenging in healthy individuals, resulting in a decreased hop distance and an increased reaction time (27).

Summary

In summary, current hop test battery does not include neurocognitive load that athletes face in real sport situations. As a result, these test batteries may not be specific enough to determine whether an athlete is ready for RTS. Hop tests using a light system to which a person must respond appears to be more challenging and may better represent sport-specific tasks. Scientific research, however, has two important limitations. First, only the jumping distance is assumed. However, neurocognitive load may not only affect jumping distance, but could also have an impact on kinematics and muscle activation patterns. This is important, since altered biomechanics could be a risk factor for ACL re-injury (28, 29). Merely reporting the jumping distance, these effects are missed, while these may be of clinically in value. Yet, the effect neurocognitive load on jumping strategy has never been investigated. Second, the effect of neurocognitive load on SLHDs performance have never been studied in a ACLr patient population.

Primary aim

At the Sports Medicine Clinic of Orthopedisch Centrum Oost Nederland (OCON) a main research focus is on rehabilitation monitoring after ACLr. During this graduation internship, a research line has started on the role of neurocognitive load in rehabilitation after ACLr. The main objective of this research line is to evaluate the effect of neurocognitive load on jumping distance and jumping strategy in ACLr patients and controls without knee injury. The ultimate goal is to reduce the number of re-ruptures whilst increasing the rate of patients returning to their pre-injury level of sports by adapting rehabilitation to target any underlying deficits of an individual patients. In this thesis, the first steps have been taken towards the realization of this 'greater' goal.

Secondary aims

In the service of being able to respond to the primary research aim, two secondary aims were additionally formulated:

- First, a research protocol was developed and validated. Considering this research goal, a minimum of ten controls without knee injury were measured with the defined measurement set-up.
- After that, a clinical study was performed. For this purpose, all steps of an METC application were completed to include ACLr patients and controls without knee injury. Within this thesis the results of the first participants were analyzed.

Thesis outline

First, the importance and limitations of current RTS decision making after ACLr are outlined in the general introduction. Furthermore, several research objectives will be presented. In the second chapter, the results of a pilot study in which the reliability of the measurement set-up was tested in a population without knee injury is described. In the third chapter, the first results of the clinical study are presented. Here, the differences between the control group and the ACLr group are considered, followed by an evaluation of the influence of the neurocognitive load on the performance of the hop tests. Finally, the thesis is concluded with a general discussion – including limitation and recommendations. A well-founded recommendation will be made on how the results of this thesis can contribute to the development of personalized multifactorial RTS decisions.

SECTION I: PILOT STUDY

1. Introduction

Evaluation of movement and muscle activity patterns can help in the distinction between normal and pathological movement. Many studies have been performed measuring knee kinematics and comparing the values of ACL reconstructed legs with contralateral legs, or legs of healthy participants (28-30). However, a large variety in values of the measured parameters have been reported. This is expected to be the result of, among other things, the measurement setup and the technology used. Therefore, the first research goal was to evaluate intrasubject variation in knee kinematics and muscle activation patterns during single leg hop for distances (SLHDs) in a population without knee injuries in our measurement set-up.

In almost all studies investigating jump-landing tasks such as SLHDs, criteria are established to judge whether a jump is "successful" or "failed". For example, someone must land stably, and maintaining balance for at least 2 seconds. SLHDs that do not meet the requirements of a successful trial are usually excluded from the dataset to minimize variation in the dataset and allow better explanation of the datasets. Most sport injuries, however, occur when an athlete is unable to control movement. These movements resulting in injury (e.g., landing from a jump) might possess similar characteristics as a failed trial in a controlled environment. Examining the failed trials could therefore provide new information regarding muscle activation patterns and the resulting knee kinematics during injuries in lower extremities. Therefore, the second research goal was to evaluate differences in knee kinematics and muscle activation patterns during successful and failed SLHDs.

2. Methods

A pilot study including participants without knee injuries was conducted at Orthopedisch Centrum Oost Nederland (OCON) in Hengelo.

2.1 Participants

Participants were eligible for participation if they were aged between 18 and 40 years. Exclusion criteria were walking disabilities in general, current pathologies of the lower extremities that cause hinder in sport or daily life, or pathologies of the lower extremities that needed surgical treatment within the last year. Prior to participation, oral informed consent was obtained from all participants. The following information was documented: gender, age, length, weight, and limb dominance defined as the preferred leg to kick a ball.

2.2 Instrumentation and data acquisition

<u>2.2.1 Knee kinematics:</u> Kinematic measurements of the pelvis and lower limbs during SLHDs were obtained from each participant. Therefore, each participant was equipped with eight wireless Xsens MTw Awinda IMU's (Xsens, Enschede, The Netherlands). Six IMU's were placed bilaterally on different segments of the lower extremities: the foot, the lower leg, and the upper leg. Pelvic movement was measured by additional sensors on the sacrum and sternum (Figure 2.1). The IMU's were fixated to the body using the provided strap holders and sport tape. The motion analysis system was calibrated according to manufacturer recommendations. Data was recorded with a sample frequency of 100 Hz and was registered using the Xsens MT manager on a computer, where it was received by the Awinda

station. Raw data from the IMUs were exported in the MVNx file format and imported into a Matlab (MATLAB version 2020b) workspace.

<u>2.2.2 Muscle activation patterns:</u> Simultaneous surface electromyographical (sEMG) activity of the gastrocnemius lateralis, gastrocnemius medialis, vastus lateralis, vastus medialis, biceps femoris and semitendinosus of the dominant leg were measured. Disposable, self-adhesive Ag/AgCl surface electrodes were applied over these muscles as recommended by the SENIAM European Recommendations for Surface Electromyography (Figure 2.1). A reference electrode was attached to the lateral malleolus of the dominant leg. Electrodes were connected to the Mobita amplifier (TMSI, Oldenzaal, the Netherlands). Cables were fastened using the strap holders of the IMUs to prevent them from swinging and causing movement artefacts. Data was recorded with a sample frequency of 2000 Hz and was registered using Polybench software. Raw data from the sEMG was exported in CSV file format and imported into a Matlab workspace.

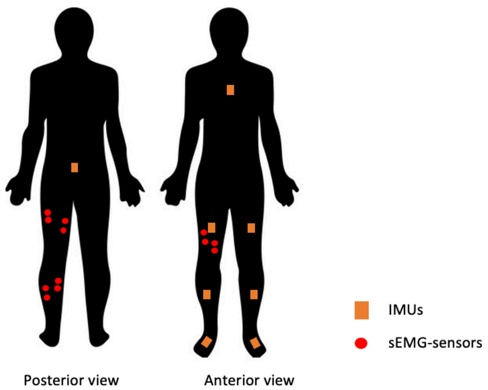

Figure 2.1 Schematic representation of the subject' leg with the attached sEMG sensors in red and IMUs in orange. sEMG = surface electromyography, IMUs = inertial measurement units.

2.3 Testing procedure

All measurements of each participant were done in a single session. Prior to testing, participants performed a warming-up consisting of five minutes of cycling on a home trainer with preferred speed and resistance.

The warming-up was followed by three repetitions of maximal voluntary isometric contractions (MVICs) or manual muscle tests (MMTs), depending on the muscle, to obtain the maximum sEMG signal. This was needed to normalize the amplitude of the sEMG signal.

MVICs were performed to retrieve the maximum sEMG signal of the vastus lateralis, vastus medialis, biceps femoris and semitendinosus. Participants were seated in an isokinetic dynamometer (Isoforce, Tus, Rostock, Germany) with straps secured over the torso, thigh, and leg to isolate knee flexion and extension. The knee was positioned in 55° flexion, and the lever arm was adjusted so that the ankle strap was two finger widths above the medial malleolus. The participant checked whether the knee could flex and extend properly, and minor adjustments were made if necessary. Participants were instructed to flex/extend the knee with maximum force and hold it for 3-5 seconds. A bar indicating the force delivered during the session was shown as visual feedback.

MMTs were performed to retrieve the maximum sEMG signal of the gastrocnemius lateralis and gastrocnemius medialis. Participants were positioned in prone position on a table with the knee of the dominant leg at approximately 90°. Participant were instructed to push their toes toward the ceiling, plantar flexing the ankle. During MMTs, counterforce was provided by two investigators. Three trials of MVICs/MMTs were conducted for each muscle group with 30 seconds' rest between trials. During both MVICs and MMTs the participants were encouraged to pull or push harder, according to standardized instructions.

Next, SLHDs were performed. The researcher introduced the SLHD and performed an example: 1) stand behind the line on the dominant leg, 2) jump as far as possible, 3) land on the same leg maintaining balance for at least 2 seconds and 4) place your other leg next to your dominant leg. All these requirements must have been met for a successful trial. If one of these requirements was not met, the trial was defined as failed. Participants were given two practice trials to familiarize themselves witch the SLHDs. In total, ten successful SLHDs were collected with a maximum of fifteen attempts.

2.4 Data analyses

Data analyses were performed using MATLAB R2020B (The MathWorks, Inc., MA, USA). Intrasubject analysis was determined based on the successful jumps of all participants. In addition, a comparison was made between successful and failed jump trials. For this, participants who had a total of five or more failed jumps were included in the analysis.

<u>2.4.1 Knee kinematics:</u> The parameters of interest were the flexion angles of the knee during SLHDs. Knee angles were calculated using Xsens algorithms. The moment of initial contact (IC) was identified using peak detection, as IC results in a peak in the acceleration data of the lower leg, Figure 2.2A. During failed trials, two peaks in the signal could be visible, due to an extra jump and thus an extra landing. In this case, the first peak was selected as IC, Figure 2.2B. Two seconds before, and two seconds after IC were analyzed to segment the complete jump.

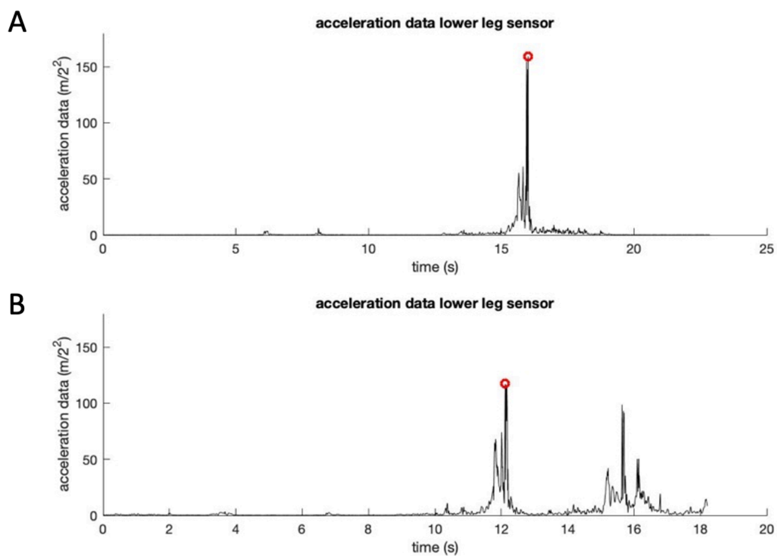

Figure 2.2 Accelerometer data plotted for the sensor located on the lower leg. The circle indicates the peak used for detection of initial contact. A) acceleration data during a successful trial, B) acceleration data during failed trial.

Figure 2.3 shows a typical example of how a SLHDs is performed. The task is split in three phases, 1) take-off, 2) flight phase and 3) landing. The phase transitions are marked by the toe-off (TO) and IC. This movement results in the flexion/extension angles showed in Figure 2.4. Here, the numbers indicate moments of interest during the analysis namely, 1) maximal knee flexion during take-off, 2) minimal knee flexion during take-off, 3) maximal knee flexion during flight phase, 4) minimal flexion just before IC, 5) knee flexion at IC, 6) maximal knee flexion during landing. In addition, the range of motion during the landing is determined, defined as the difference between minimal flexion just before IC and maximum flexion during the landing (ROM during landing = moment 6 - moment 4).

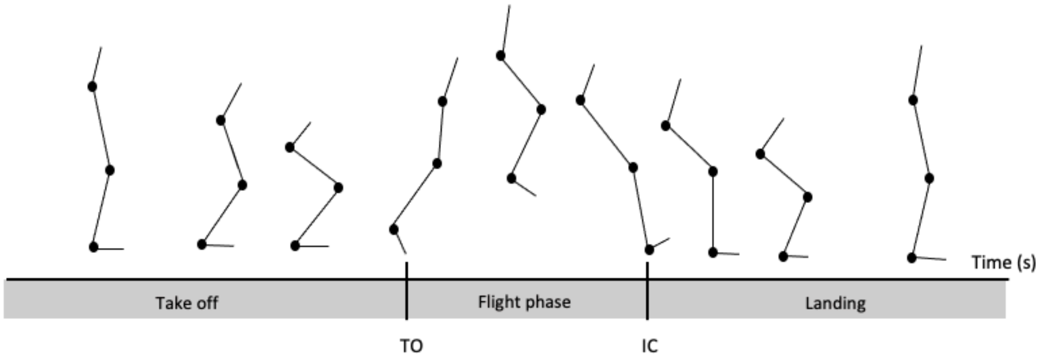

Figure 2.3 Schematic representation of a typical sequence of knee movement during SLHD. SLHD = single leg hop for distance, TO = toe-off, IC = initial contact.

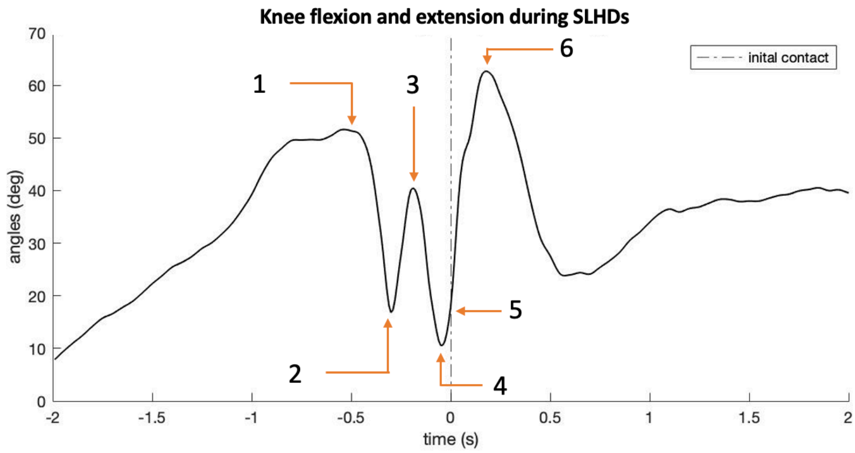

Figure 2.4 Knee kinematics in the sagittal plane during SLHDs. Numbers indicates moments of interests: 1) maximal knee flexion during take-off, 2) minimal knee flexion during take-off, 3) maximal knee flexion during flight phase, 4) minimal flexion just before IC, 5) knee flexion at IC, 6) maximal knee flexion during landing. Vertical line indicates IC. SLHDs = single leg hop for distances; IC = initial contact.

2.4.2 Muscle activation patterns: Raw sEMG data was pre-processed using a fourth-order, zero-lag band-pass Butterworth filter with high and lowpass cut-off frequencies of 20 and 500Hz respectively. A fourth order, zero-lag band-stop Butterworth filter with high- and lowpass cut-off frequencies of 48 and 52 Hz respectively, was used to eliminate 50 Hz interference. Afterwards, the filtered sEMG signals were smoothened by a moving average calculation over a sliding window of 500 samples. Then, the sEMG amplitudes were normalized to the peak amplitude obtained during the MVICs or MMTs for the specific muscle.

In contrast to the IMU signal, it was not possible to determine IC within the sEMG signal, since these signals were not synchronized. Therefore, an alternative reference point was sought, that is recognizable in the sEMG signal and can be related back to a specific moment in the jump. The reference point used in this study is based on the muscle activity patterns identified in previous research by Keizer et al. (31). Here, the muscle activation of the vastus medialis and vastus lateralis have activation peaks before take-off and after IC, with a minimum activity within these peaks. The flight phase was estimated by the point where the vastus medialis showed its lowest activity in between peaks. Each trial was visually inspected to verify the presence of this typical muscle activation pattern. In the absence of this recognizable pattern in the sEMG of the vastus medialis, the trial was excluded from the analyses. The data was reviewed two seconds before and after the estimated flight phase.

2.5 Statistical analyses

The analyses for this pilot study was conducted in a stepwise fashion. First, figures with knee kinematics and sEMG patterns of individual participants, including mean and standard deviations, are visually compared with means of the total population.
Second, differences in kinematic outcome parameters between successful and failed trials were assessed. Again, the data was visually inspected for normality. As the data were normally distributed, two-tailed paired t-tests were performed. Besides, complete sagittal-plane knee kinematics and muscle activation patterns were assessed using statistical-parameter mapping (SPM). This method assesses differences between data points in continued time series, rather than discrete values only. Two-tailed SPM paired t-tests were performed to compare the subject-averaged curves for both conditions (successful and failed trials). The level of statistical significance was set at $p \leq 0.05$ for all analyses.

Kinematic outcome parameters were implemented in IBM SPSS (version 27, SPSS Inc., Chicago, USA). SPM analyses were implemented in Matlab R2020B using open-access SPM1D scripts (vM.0.4.5, www.spm1D.org).

3. Results

Fourteen participants were included in this pilot study. Three participants were excluded from the analyses since kinematic data was not recorded. Study characteristics of the remaining 11 participants can be found in Table 2.1. Four participants reached their maximum number of attempts without executing ten correct SLHDs: one participant had recorded data of eight SLHDs and three participants had recorded data of nine SLHDs. Six participants performed at least five failed trials and were included in the second analysis.

Table 2.1 Subject characteristics (n=11)	
	Characteristics
Gender (male/female)	5 / 6
Age (years)	26 ± 4
Length (cm)	178 ± 7
Body weight (kg)	69 ± 10
Limb dominance (left/right)	10 / 1

Values are reported as mean ± SD

3.1 Intrasubject analyses

3.1.1Knee kinematics: For each participant, all recorded SLHDs were averaged to ensemble one average curve of knee kinematics. For one participant, this result is shown in Figure 2.5, panel A. Although there are large differences between the individuals, the pattern is representative of the other participants. The means of the individual persons were averaged to ensemble one average curve of the population, which is shown in Figure 2.5 panel B. Comparing the shaded area in panel A and B, it is noticeable that this area is much wider in panel B, especially at the beginning and end of the recording.

The parameters of interest, as described in the data analyses, are shown in Table 2.2 for all individuals and the mean of the total population. In each column, the maximum and minimum value is indicated with a superscript. It is noticeable that there are large differences between participants. The differences are especially large in minimal knee flexion during take-off and maximal knee flexion during flight phase.

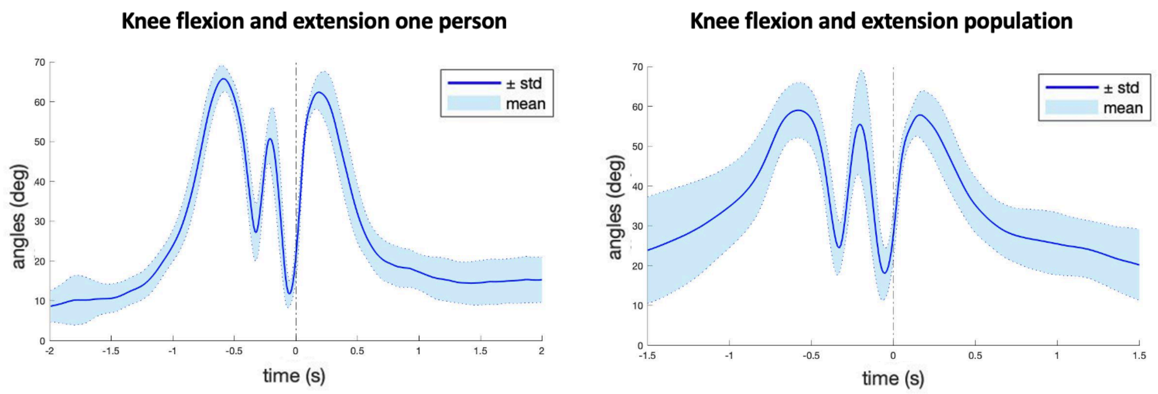

Figure 2.5 Knee flexion and extension angles. A) mean of ten jumps for one person and B) mean of total population. The solid line reflects the mean, with the shaded area reflecting the standard deviation. Vertical line indicates IC.

Table 2.2 Knee kinematics in degrees during successful trials

	Take-off		Flight-phase		IC	Landing	
	Max	**Min**	**Max**	**Min**		**Max**	**ROM**
1	54.5 ± 2.6	20.7 ± 3.0	45.7 ± 7.6	9.5 ± 1.4	18.9 ± 5.2	65.8 ± 6.6	56.4 ± 7.2
2	66.1 ± 2.7	29.9 ± 1.9	52.3 ± 6.2	10.7 ± 3.4	20.6 ± 5.8	63.1 ± 4.1	52.3 ± 6.3
3	67.3 ± 2.7	21.5 ± 1.0	44.8 ± 4.5	11.7 ± 2.2	36.7 ± 6.9[1]	54.6 ± 2.1	42.9 ± 3.6
4	67.6 ± 3.8	44.5 ± 1.0[1]	77.5 ± 3.6[1]	15.9 ± 1.2	28.8 ± 3.8	56.2 ± 7.2	40.3 ± 7.6
5	58.7 ± 2.1	32.6 ± 7.4	62.1 ± 7.0	26.2 ± 5.3	30.6 ± 8.7	58.9 ± 6.9	32.6 ± 8.4
6	67.8 ± 2.0[1]	13.7 ± 5.2[2]	73.5 ± 10.1	20.7 ± 2.3	30.8 ± 5.2	64.8 ± 7.5	44.1 ± 8.8
7	65.6 ± 4.9	36.2 ± 2.7	57.0 ± 4.1	22.9 ± 7.7	25.4 ± 7.7	51.5 ± 4.8[2]	38.6 ± 7.8
8	56.5 ± 7.5	32.3 ± 4.0	71.9 ± 4.7	28.1 ± 0.9[1]	33.7 ± 3.2	60.4 ± 7.4	31.5 ± 7.3[2]
9	48.8 ± 4.6[2]	20.3 ± 3.8	50.1 ± 4.8	5.5 ± 2.62[2]	17.9 ± 3.5[2]	52.6 ± 5.1	44.9 ± 7.9
10	63.6 ± 3.8	27.7 ± 1.9	58.5 ± 6.7	25.2 ± 3.5	31.2 ± 6.3	64.4 ± 8.3[1]	39.1 ± 9.7
11	55.2 ± 3.8	22.5 ± 3.9	44.0 ± 4.8[2]	12.6 ± 2.2	31.0 ± 4.6	62.0 ± 8.1	46.9± 11.2[1]
POP	59.9 ± 6.9	27.7 ± 8.6	57.6 ± 11.7	16.9 ± 7.0	27.1 ± 5.9	58.7 ± 4.8	41.8 ± 8.6

Rows 1 to 11 represent an individual participant; the bottom row represents the mean of the population. Columns represent moments of interests: maximal knee flexion during take-off, minimal knee flexion during take-off, maximal knee flexion during flight phase, minimal flexion just before IC, knee flexion during IC, maximal knee flexion during landing, range of motion during landing. Values are reported as mean ± standard deviation. [1] indicates maximal knee flexion and [2] indicates minimal knee flexion for specific moment of interest. IC = initial contact. POP = population

3.1.2 Muscle activation patterns:

Figure 2.6 shows the muscle activation patterns of six muscles in the lower extremity, during SLHDs. The left side shows the mean sEMG of ten SLHDs for one participant. As with the knee kinematics, there are large differences between the individuals, yet the pattern is representative of the other participants. The right side shows the mean sEMG for the complete population. It is noticeable that the shaded area for the total population is much wider than for one person.

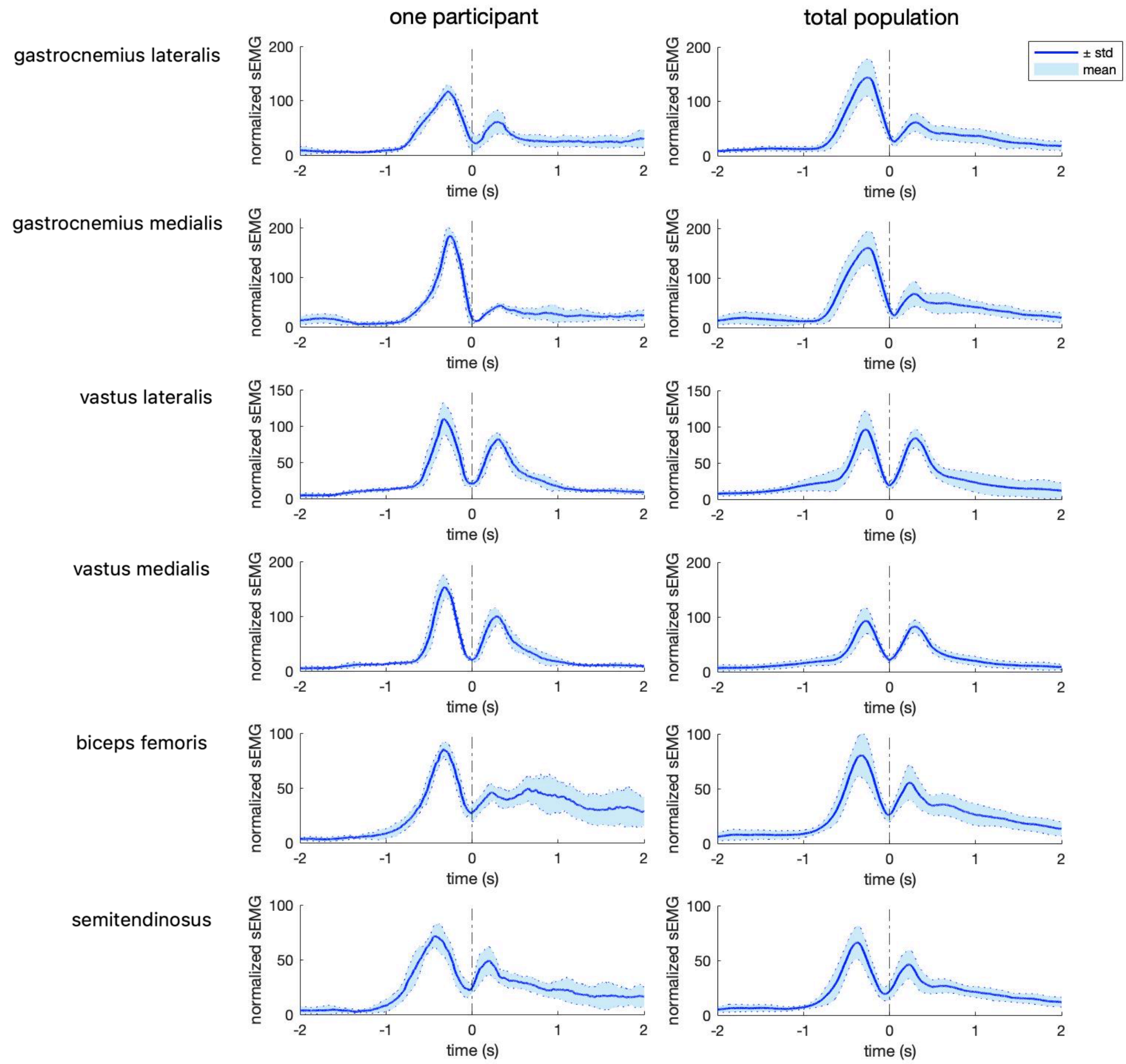

Figure 2.6 sEMG for gastrocnemius lateralis, gastrocnemius medialis, vastus lateralis, vastus medialis, biceps femoris and semitendinosus. Left: mean of ten jumps for one person and right: mean of all participants. The solid line reflects the mean sagittal-plane joint angle for all jumps, with the shaded area reflecting the standard deviation. Vertical line indicates minimal activation of vastus medialis

3.2 Failed jump trials

3.2.1 Knee kinematics

The parameters of interest are shown in Table 2.3 for successful and failed trials. From this table, it can be seen that failed trials resulted in a larger ROM during landing. Additionally, Figure 2.7 panel A shows the entire flexion/extension motion of the knee, for successful trials and for failed trials. It can be seen that knee kinematics of successful trials and failed trials are almost equal, since the means largely overlap. This is confirmed by the SPM analysis in Figure 2.7 panel B, which values remain between the threshold value. Thus, SPM analysis showed no significant differences in mean knee flexion/extension angles between successful and failed trials.

3.1.2 Muscle activation patterns

Figure 2.8 panel A and B shows the muscle activation patterns of three muscles, for successful and failed trials. One muscle of each muscle group is shown, results of the remaining muscles can be found in Appendix A. The most notable aspect of these graphs is the significant difference during peak activation in the gastrocnemius medialis. This shows that there is more muscle activation during failed trials compared to successful trials. Vastus medialis also shows a higher peak activation during failed trials, however this difference is not significant in SPM analysis. Furthermore, it is striking that during failed trials more muscle activation is present at the end of the recording with a wider standard deviation compared to successful trials, in which muscle activation remains a stable line.

Table 2.3 Knee kinematics in successful and failed trials of SLHDs.

		Successful trials	Failed trails	p-value
Take-off	**Max**	57.9 ± 7.7	57.8 ± 9.4	0.912
	Min	29.5 ± 5.6	26.8 ± 9.7	0.438
Flight phase	**Max**	56.1 ± 9.0	59.4 + 9.2	0.199
	Min	17.9 ± 8.6	26.4 + 12.7	0.228
IC		26.0 ± 5.8	28.0 ± 5.2	0.398
Landing	**Max**	57.4 ± 4.7	57.9 ± 4.3	0.570
	ROM	39.5 ± 9.8	51.5 ± 10.5	0.028 *

Rows represent moments of interests: maximal knee flexion during take-off, minimal knee flexion during take-off, maximal knee flexion during flight phase, minimal flexion just before IC, knee flexion during IC, maximal knee flexion during landing, range of motion during landing. * Indicates a significant difference

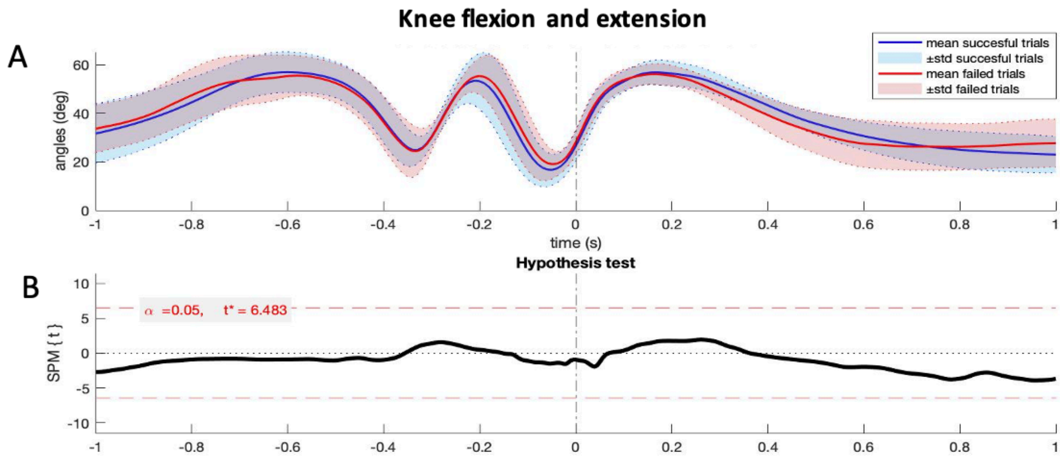

Figure 2.7 Knee flexion and extension angles and statistical parametric mapping outcomes. The solid line reflects the mean for successful (blue) and failed (red) SLHDs trials, with the shaded area reflecting the standard deviation. Vertical line indicates IC.

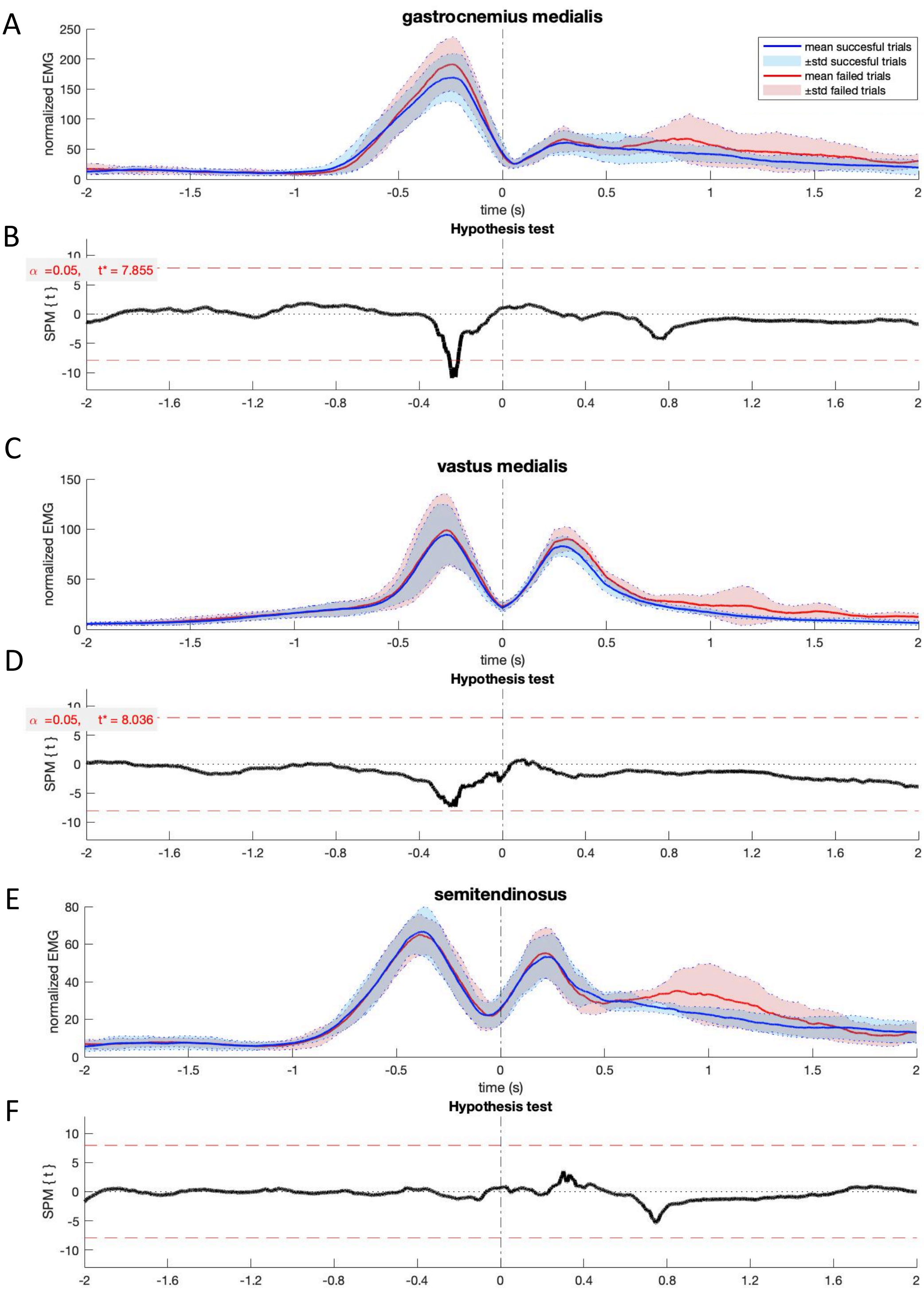

Figure 2.8 sEMG of the gastrocnemius medialis, vastus medialis, semitendinosus and statistical parametric mapping outcomes during successful and failed trials. The solid line reflects the mean sEMG for successful (blue) and failed (red) SLHDs trials, with the shaded area reflecting the standard deviation. Vertical line indicates minimal activation of vastus medialis.

4. Discussion

This pilot study showed that both knee kinematics and muscle activation patterns differ minimally within a participant over several jumps in a population without knee injuries. Over the population, however, the differences are large, leading to a wide spread in standard deviations. No differences were found in knee kinematics between successful and failed trials, except for range of motion. During failed trials of the SLHDs, however, participants showed a higher peak activation of the gastrocnemius medialis during take-off.

4.1 Intrasubject variation

All participants show the typical sequence of knee movements during a SLHD as outlined in Figure 2.4. The participants start in a vertical upright position. In all participants, the jump is initiated by (further) flexing the knee of the supporting leg, and thus lowering the center of gravity. During the subsequent jump movement, the knee must be fully extended to get the body into the flight phase. The vastus medialis and vastus lateralis play an important role here, as these are powerful extensors of the knee. This is reflected in a peak in the sEMG signal from both muscles. Although this study focuses on the knee, there are unmistakable more joints involved in organizing a jump. Especially the hip and ankle play an important role in making a controlled jump. During take-off, an extension movement of the hip joint takes place. From the muscles studied in this study, the semitendinosus and the biceps femoris are involved in this movement. This function may explain the sEMG activation during push-off, despite being the major flexors of the knee. The ankle joint will go into full plantar flexion during take-off. The m. gastrocnemius medialis and m. gastrocnemius lateralis are so called two joint muscles, and act as both a knee flexor and as ankle plantar flexor. Therefore, highest activity of the gastrocnemius medialis and gastrocnemius lateralis will correspond to take-off. When the involved muscles have generated enough force to overcome gravity, the body rises, and the flight phase starts. During the flight phase, the leg is flexed and extended forward again to maximize the jumping distance. This movement takes place in the air, without body weight and muscle activation is therefore virtually absent. After this action, the body will be prepared for IC and the landing phase. During landing, muscles of the lower extremity in particular must decelerate and stabilize the body’s center of mass.

Within a person, reproducible patterns were found for both knee kinematics and muscle activation patterns. However, when individuals are compared to each other, the differences are much larger. This is expressed in a larger standard deviation for the total population compared to the standard deviation of repetitions within one person. As can be seen in Figure 2.5, for the knee kinematics, the standard deviation is especially large in the pre-jump phase. A possible explanation for this might be that individual participants used different jumping strategies. For example, one person was still standing with a straight knee, while the other was already bending the knee more. This was not stated in the instructions, and participants were free to do what was comfortable for them. In the muscle activation patterns, the differences between the hamstrings is particularly large between individuals. An example of this is given in Figure 2.9 panel A and B. This Figure shows the sEMG signal of two different participants. Only one peak can be seen in the sEMG signal in panel A, during the take-off phase, while the sEMG in panel B contains two peaks, during take-off and landing. As noted previously, the hamstrings are involved in both knee extension and hip flexion. The amount of hip flexion during landing could be an explanation for this difference.

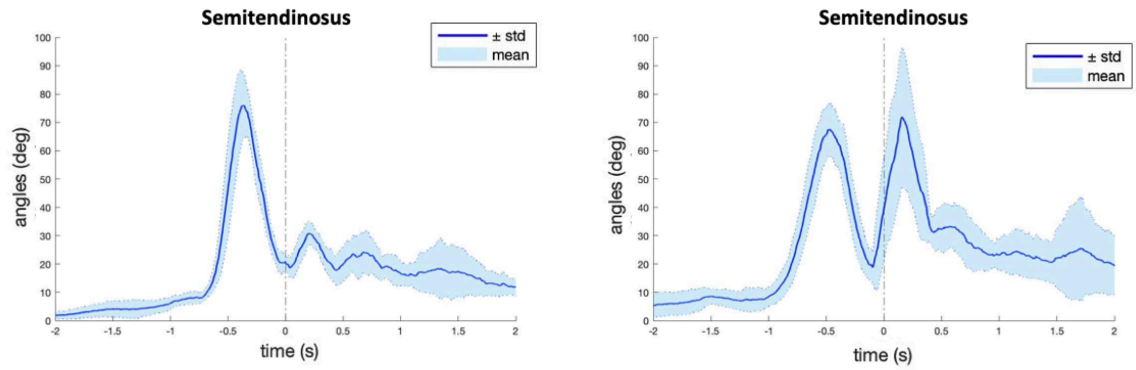

Figure 2.9. sEMG of the semitendinosus during successful trials for two different participants. The solid line reflects the mean sagittal-plane joint angle for all jumps, with the shaded area reflecting the standard deviation. Vertical line indicates minimal activation of vastus medialis.

Literature on evaluating SLHDs mainly focus on biomechanics. In addition, studies that measure sEMG often only describe parameters extracted from the sEMG around IC. Two studies were identified in which sEMG was measured, and muscle activation patterns of the entire jump movement were displayed. Keizer et al. showed average muscle activity patterns of the gastrocnemius lateralis, gastrocnemius medialis, vastus lateralis, vastus medialis, biceps femoris and semitendinosus during SLHDs of both legs in ACLr patients (31). The overall shape of the average muscle activation patterns for both the unaffected and effected leg of the ACLr patients during SLHDs seem similar to the muscle activation patterns found in this study. However, the results can only be compared qualitatively. Nyland et al. compared sEMG activity of the gluteus maximus, vastus medialis, medial hamstrings and gastrocnemius in patient after ACLr feeling very capable of performing sports activities (32). They observed normalized sEMG amplitudes of 0.97, 1.31, 0.77 and 1.32 during take-off and 1.14, 1.52, 1.05 and 1.00 during landing, in the unaffected leg of ACLr patients. When quantitatively comparing these findings to the average normalized sEMG amplitudes measured in the current study the results are within the same range.

In the present study MVICs or MMTs were used, depending on the muscle. The gastrocnemius laterals and medialis were the only muscles where MMTs were performed. During SLHD's normalized sEMG values exceeded 100%. It could be argued that MMTs are less accurate than MCIVs, because MMTs are generated manually. When not enough counterforce can be given, the maximum muscle activity is underestimated. Underestimation of the maximum sEMG subsequently leads to higher values in the normalized sEMG. When comparing these results to the results of Keizer et al. and Nyland et al., corresponding results are observed. All three studies show that the gastrocnemius muscle is most active during take-off, whereby values for the normalized sEMG signal exceeds 100%. Different techniques, however, were used to obtain the maximum sEMG values. Nyland at al. used MVICs in all muscles and Keizer et al. used the mean muscle activation from 1 second before IC to 1.5 seconds after IC to scale sEMG signals in all muscles. MMTs thus seem to have no influence relative to the normalization.

4.2 Failed jumps

During landing, especially muscles of the lower extremity must decelerate and stabilize the body's center of mass. When a participant is unable to reduce the body's velocity to zero, the landing will not be successful. During the execution of the protocol – in which ten successful jump trials had to be performed – there were inevitably also trials that were marked as failed. A trial was marked as failed when someone was unable to maintain balance for at least 2 seconds and/or was unable to place the other leg next to the jumping leg in a controlled manner. In most research, however, these failed trials are removed or discarded, and only the data of successful trials are analyzed. This while muscle activation patterns and kinematics during tasks in failed trials might be important for understanding the mechanisms and risk factors of non-contact sports injuries.

Interestingly, there was a significant difference in muscle activation of the gastrocnemius medialis according to SPM analysis. In all participants the gastrocnemius medialis showed a higher amplitude of normalized sEMG during failed trials compared to successful trials (Figure 2.8). As mentioned before, peak activation in sEMG occurs during take-off when the ankle goes into plantar flexion. These results are probably related to the fact that failed trials mainly occur when a participant challenges him- or herself and tries to break his maximum jumping distance record. Assuming that the force supplied by the muscles determines the distance that would be reached, the trials with the highest peak values thus exceed the trials that jumped the greatest distance. However, the distance at which a person landed during a failed trial has not been measured, so this could not be verified afterwards. Furthermore, differences in muscle activation were noted at the end of the recordings. Although not significant, failed trials show more muscle activation with a wider standard deviation compared to successful trials, in which muscle activation remains a stable line. This result can be explained by the inability to stand stable during de failed trials. Participants keep moving, causing muscle activation. Besides, the variety of failed jumps (for example: an extra jump or a slow fall to the side) causes a large standard deviation.

Only two studies were identified looking at the comparison of successful and failed trials. Wikstrom et al. collected data during a single leg hop maneuver, with a fixed distance of 70 cm (33). During the jump participants had to reach a jumping height equal to half their maximum jumping height. They defined their criteria for a failed trial as "loss of balance forcing stepping off the force plate to regain balance" and focused on sEMG variables. The authors included muscle activation and average sEMG amplitudes of the vastus medialis, semimembranosus, gastrocnemius lateralis, and tibialis anterior, 200 ms before and after IC. So, the authors focused on a short time interval around IC, and concluded that successful jump landing trials had earlier activation times and higher sEMG amplitudes before and after IC. These authors however, did not describe muscle activation during take-off, where in this study a significant difference was found in the gastrocnemius medialis. Conversely, in our measurement setup it was not possible to investigate the sEMG activation around IC, since IC in the sEMG cannot be determined. It is therefore not possible to conclude whether muscle activation patterns correspond to the results in our study.

Hirohata et al. collected data during a single-leg lateral drop jump-landing, whereby participants jump sideways from a step, make a landing on the same leg and maintain balance (34) . They defined their criteria for a failed trail as "foot moved or slipped after landing", "the sole of the opposite foot touched the floor or force plate" or "the hands pulled away from the axillae" and analyzed the correlation between ground reaction force and body movements in the frontal plane. Outcome measures cannot be compared therefore, since the research by Hirohata et al. focused on body movements in a different plane than in the study presented here. What is interesting, however, is that the authors found a significant negative correlation between the number of failed jump trials and the time from initial contact to peak vertical ground reaction force during successful trials. From this, they concluded that athletes who frequently failed during single-leg lateral drop jump-landing had poor skills in absorbing jump-landing impact, which is related to various sports injuries. This raises the question whether the number of failed trials say something about the movement control of the participant, and perhaps also about failing to achieve RTS and the risk of re-injury. This is interesting, since the number of failed trials is not considered in the current RTS-decision making. In follow-up research it might be interesting to see whether participants with higher number of failures show a different movement pattern than participants with a lower number of failures.

SECTION II: CLINICAL STUDY

1. Introduction

There is a growing body of literature showing differences between injured and injured limbs in ACLr patients, as well as differences when compared to healthy controls (30, 35-39). In recent years, the use of objective equipment to study the kinematics of SLHDs in ACLr patients in a clinical setting has become more popular (29). Although mechanical function of the knee is largely restored following ACLr, the collective evidence from these studies demonstrates that athletes recovering from ACLr have measurable asymmetries in kinematics during hop tests (38). In addition, differences in muscle activation patterns have been demonstrated (32, 40). It is supposed that the asymmetries in kinematics and muscle activation patterns are related to an increase in risk for re-ruptures. Therefore, the first research goal of this study was to evaluate differences in jumping distance, knee kinematics and muscle activation patterns between the reconstructed leg of ACLr patients and controls without knee injuries. For controls without knee injurie the dominant limb was used as previous research showed no clinically relevant differences between dominant and non-dominant limbs (41). Based on the literature it is hypothesized that ACLr patients would demonstrate stiffer landing patterns compared to the controls without knee injury.

Recommendations for the RTS decision state that a test battery should consist of multiple tests that use reactive elements, and decision-making steps athletes use in their real sports situations (25). In this, neurocognitive functions play an important role. This refers to the mental action or process of acquiring knowledge and understanding through thought, experience, and the senses. Neurocognitive functions are important in tasks that demand concentration, adaptation, and control to override internal or external stimuli. Core neurocognitive functions control complex, goal-directed thought, and behavior, and involve multiple domains, such as inhibitory control, attention, working memory, and cognitive flexibility. Neurocognitive load is not assessed during current SLHDs. As a result, SLHDs might not be specific enough to determine whether an athlete can safely return to his/her sport. In this study, two different neurocognitive SLHDs are performed. Both neurocognitive SLHDs assess different aspects of neurocognitive function. In this way, sport-specific tasks may be better represented, bridging the gap between standard SLHDs and the sports environment.

Solely measuring the jumping distance, as is done in clinical practice, is probably not sufficient to evaluate the effects and understand underlying mechanisms. In addition, movement patterns and muscle activation patterns should be evaluated objectively. Therefore, the second research goal was to evaluate the influence of neurocognitive load on jumping distance, knee kinematics and muscle activation patterns during a SLHDs, in both the reconstructed leg of ACLr patients and the dominant leg of controls without knee injuries. It was hypothesized that, when neurocognitive demands increase, some ACLr patient may not be able to maintain motor performance. These patients may be at risk for ACL (re-) injury.

2. Methods

This study is a two-arm cross-sectional patient control study, consisting of ten patients who had undergone ACLr and ten participants without knee injuries. The study was conducted at Orthopedisch Centrum Oost Nederland (OCON) in Hengelo. Patient inclusion took place between September and

November 2021. The study design, procedure and protocol were approved by the Medical Research Ethics Committees United (MEC-U), and all participants provided written informed consent prior to study participation.

2.1 Participants

Participants were eligible for participation if they were aged between 18 and 30 years. Additional to this, patients in the ACLr group had a rupture of their ACL and underwent an isolated ACLr at OCON. During their follow-up appointments at 9- or 12-months post-surgery, the patients were asked if they wanted to participate in the study. Patients who had a posterior cruciate ligament injury, who underwent revision ACLr, who had contralateral ACLr injuries, or who had not participated in a rehabilitation program led by a physiotherapist were excluded from participation. Exclusion criteria for the control group included lower limb injuries in the last six months resulting in inability to exercise for more than two weeks or pathologies of the lower extremities that needed surgical treatment within the last year. Table 3.1 gives an overview of the in- and exclusion criteria.

Table 3.1 Participant in- and exclusion criteria

	ACLr-group	**Control group**
Inclusion criteria	· Isolated ACL reconstruction · Able to perform SLHD on both legs · Age between 18 and 35 years · Informed consent	· Age between 18 and 35 years · Informed consent
Exclusion criteria	· Posterior cruciate ligament injury · ACL revision · Contralateral ACL rupture/reconstruction · Did not participate in a rehabilitation program · Colorblindness	· Surgical treatment of the lower extremities in the last year. · Injury of lower extremities that lead to inability to exercise for more than 2 weeks · Colorblindness

2.2 Instrumentation and data acquisition

The set-up for collection of knee kinematics and muscle activation patterns has been described previously in *Section I – Instrumentation and data acquisition*. In the current protocol, IMU's sensors were placed in a similar manner. Minor changes in location of the sEMG sensors were made since muscle activation patterns were measured bilaterally in this study. These adjustments will be briefly explained below.

<u>2.2.1 Muscle activation patterns:</u> Simultaneous sEMG activities of the gastrocnemius medialis, vastus medialis, biceps femoris and semitendinosus of both legs were measured. A reference electrode was attached to the lateral malleolus of the left leg. A schematic representation of the participants' leg with sEMG electrodes and IMUs can be found in Figure 3.1.

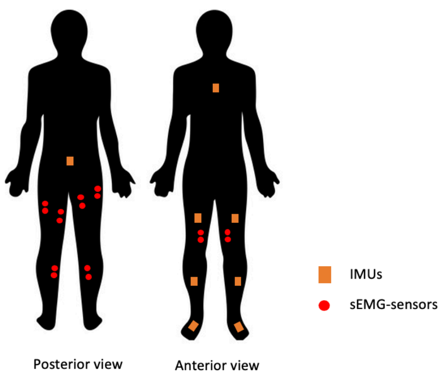

Figure 3.1 Schematic representation of the participants' leg with the attached sEMG sensors in red and IMUs in orange

2.3 Testing procedure

All tests for all participants were done in a single session. For ACLr patients, the measurements were combined with a visit to the outpatient clinic. Controls without knee injuries came to the hospital specifically for the measurements. The flowchart in Figure 3.2 describes the different steps which were completed. It is indicated which steps are related to standard care and which steps are additional for the research.

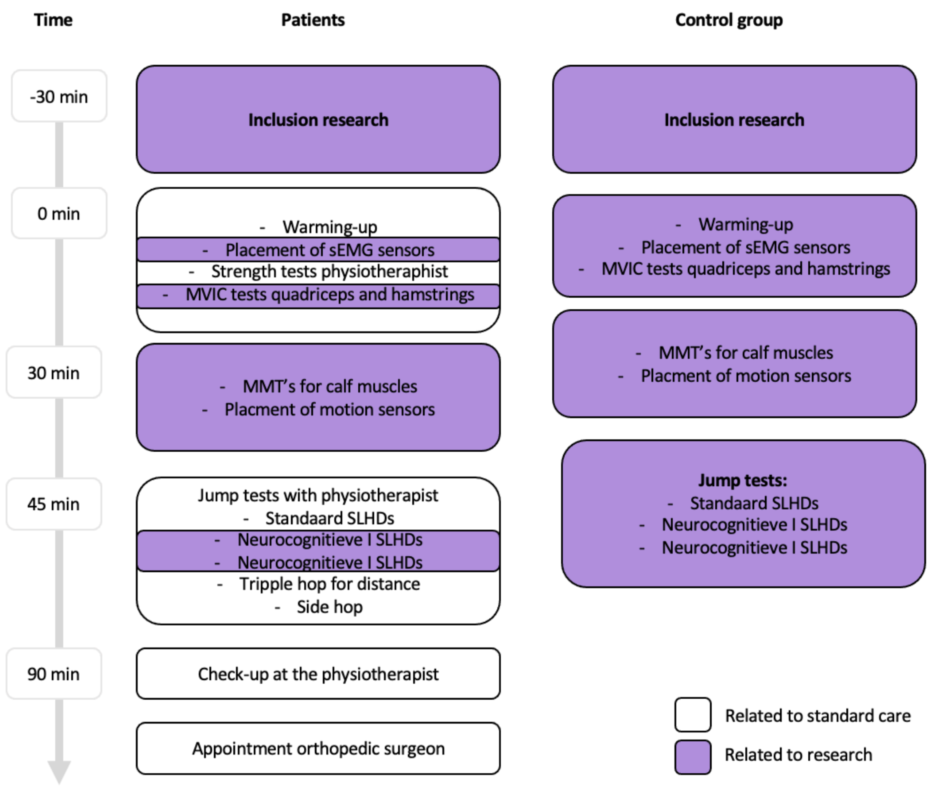

Figure 3.2 Flowchart of the measurement protocol. MVIC: maximal voluntary isometric contractions, MMT's: manual muscle tests.

Prior to testing, participants performed a warming-up consisting of five minutes of cycling on a home trainer on their preferred speed.

The warming-up was followed by three repetitions of maximal voluntary isometric contractions (MVICs) or manual muscle tests (MMTs), depending on the muscle, to obtain the maximum sEMG signal. MVICs were performed to retrieve the maximum sEMG signal of the vastus medialis, bicep femoris and semitendinosus, MMTs were performed to retrieve the maximum sEMG signal of the gastrocnemius lateralis. Execution of the MMTs and MVIC is described in *Section I – testing procedure.*

Next, standard SLHDs were performed. The researcher introduced these tests as described in *Section I – testing procedure*. In addition to the standard SLHDs, two neurocognitive SLHDs were designed, based on the methods outlined in Milikan et al. (26). The neurocognitive load was added using a Fitlight system. This system functioned as visual stimuli to execute the hop instead of being able to jump when the participant wanted to. The neurocognitive SLHDs had varying levels of difficulty. In the first step, a FitLight was added which gave a visual stimulus to which the participant had to react. In the second step, the Fitlight showed different colors with multiple no-hop stimuli and only one hop stimulus. A schematic representation of the measurement setup is shown in Figure 3.3. As with the standard hop tests, the participant had to maintain balance for at least 2 seconds after landing and place the other leg on the ground in a controlled manner for a successful trial. Detailed execution of the standard and neurocognitive SLHDs is described in Table 3.2.

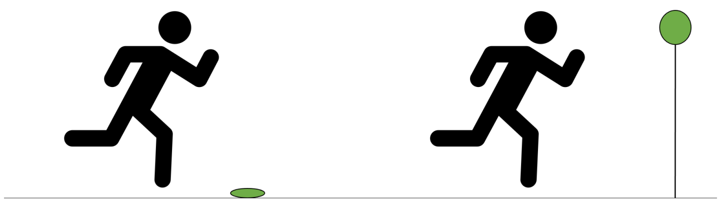

Figure 3.3 Depiction of the neurocognitive SLHD test, including two Fitlights.

Table 3.2 Description of the standard and neurocognitive SLHDs

Standard SLHDs	The participant stands behind the line on the dominant leg, jumped as far as possible and landed om the same leg. After maintaining balance for at least 2 seconds the other leg is placed next to the leg.
First neurocognitive SLHD	A FitLight was placed at eye level in front of the participant. The participant stood on one leg and waited for the FitLight to flash. Here, the FitLight always flashed green. When the FitLight flashed, the participant jumped as fast as possible and as far as possible.
Second neurocognitive SLHD	A FitLight was placed at eye level in front of the participant. The participant stood on one leg and waited for the FitLight to flash the correct color**.** The FitLight flashed one of six colors (red, light blue, dark blue, yellow, green, or purple) at random. Each trial, a random color was selected as the “hop” color, while the remaining five colors were assigned as “do not hop”. When the “hop” color flashed, the participant jumped as fast as possible and as far as possible. Additionally, a jump during a “do not hop”-color, or no jump during the “hop”-color was noted as a failed trial.

All three hop tests were performed with both legs. Controls started with their dominant leg (defined as the preferred leg to kick a ball), ACLr patients started with their non-operated leg. For each SLHDs, three successful SLHD-tests were collected. A maximum number of five attempts is allowed, to avoid learning effect and fatigue. This resulted in a maximum of fifteen attempts per leg.

2.4 Data analyses

Data analyses were performed using MATLAB R2020B (The MathWorks, Inc., MA, USA). Although both legs were measured, this analysis uses the operated leg of the ACLr patient and the dominant leg of the participant in the control group. Only successful trials were analyzed.

<u>2.2.1 Knee kinematics:</u> The parameters of interest were 1) maximal knee flexion during take-off, 2) minimal knee flexion during take-off, 3) maximal knee flexion during flight phase, 4) minimal flexion just before IC, 5) knee flexion during IC, 6) maximal knee flexion during landing. In addition, the range of motion during the landing is determined, defined as the difference between minimal flexion just before IC and maximum flexion during the landing (moment 6 – moment 4). These knee angles are determined with the algorithm developed in the pilot study (Section I – Data analyses, knee kinematics).

<u>2.2.1 Muscle activation patterns:</u> Muscle activation patterns were determined using the algorithm developed in the pilot study (Section I – Data analyses, muscle activation patterns).

2.5 Statistical analyses

The analysis for this pilot study was conducted in a stepwise fashion. First, the differences in jumping distance and kinematic outcome parameters between the reconstructed leg of the ACLr group and the dominant leg of the control group were assessed. Therefore, the data was visually inspected for normality. As the data were normally distributed, two-tailed independent t-tests were performed. Besides, complete sagittal-plane knee kinematics and muscle activation patterns were assessed using statistical-parameter mapping (SPM). Two-tailed SPM independent t-tests were performed to investigate differences between the reconstructed leg of the ACLr group and the dominant leg of the control group.

Second, differences in in jumping distance and kinematic outcome parameters between standard SLHDs and both neurocognitive SLHDs were assessed. Again, the data was visually inspected for normality. As the data were normally distributed, two-tailed paired t-tests were performed. Besides, complete sagittal-plane knee kinematics and muscle activation patterns were assessed using SPM. Two-tailed SPM paired t-tests were performed to compare the subject-averaged curves for both conditions (standard versus the first neurocognitive SLHDs and standard versus the second neurocognitive SLHDs).

Jumping distance and kinematic outcome parameters were implemented in IBM SPSS (version 27, SPSS Inc., Chicago, USA). SPM analyses were implemented in Matlab R2020B using open-access SPM1D scripts (vM.0.4.5, www.spm1D.org). The level of statistical significance was set at $p \leq 0.05$ for all analyses.

3. Results

Ten participants were included in the ACLr group and ten participants were included in the control group. Two participants from the ACLr group were excluded, either due to pain or not enough time to complete the protocol. Study characteristics can be found in Table 3.3.

Table 3.3 Subject characteristics

	Control group (n=10)	ACLr group (n=8)
Gender (male/female)	7 / 3	6 / 2
Age (years)	23 ± 2	24 ± 5
Length (cm)	184 ± 10	181 ± 13
Body weight (kg)	80 ± 15	76 ± 9
Limb dominance (left/right)	2 / 8	1 / 7
Reconstructed leg (left/right)	-	4 / 4
Time after surgery (months)	-	13 ± 2

Values are reported as mean ± SD

3.1 Difference between ACLr patients and controls

3.1.1. Jumping distance:

Controls jumped on average 134 ± 31 cm, whilst ALCr patients jumped on average 144 ± 27 cm. This difference is not statistically significant (p = 0.0486).

3.1.2. Knee kinematics:

The mean knee angles for ACLr patients and controls during SLHDS were highly similar during the entire jump (Figure 3.4). The critical threshold was not exceeded. From the chart, it can be seen that the spread in the ACLr group appears to be greater than in the control group. Parameters of interest are shown in Table 3.4, no differences are shown here either.

3.1.3. Muscle activation patterns:

Figure 3.5 shows the sEMG data of all muscles and SPM outcomes for the biceps femoris. The mean sEMG patterns were highly similar for the entire SLHD. The critical threshold was not exceeded.

Table 3.4 Knee kinematics during standard SLHDs for the dominant leg in controls and reconstructed leg in ACLr patients

		Control	ACLr	p-value
Take off	Max	56.2 ± 8.2	49.7 ± 2.7	0.077
	Min	23.9 ± 6.6	22.4 ± 5.9	0.691
Flight phase	Max	56.5 ± 8.5	59.9 ± 11.3	0.484
	Min	16.5 ± 6.3	13.5 ± 6.9	0.374
IC		28.2 ± 7.4	27.2 ± 5.1	0.751
Landing	Max	56.6 ± 5.1	53.4 ± 6.9	0.280
	ROM	40.1 ± 8.4	39.8 ± 7.0	0.938

Rows represent moments of interests: maximal knee flexion during take-off, minimal knee flexion during take-off, maximal knee flexion during flight phase, minimal flexion just before IC, knee flexion during IC, maximal knee flexion during landing, range of motion during landing. * Indicates a significant difference.

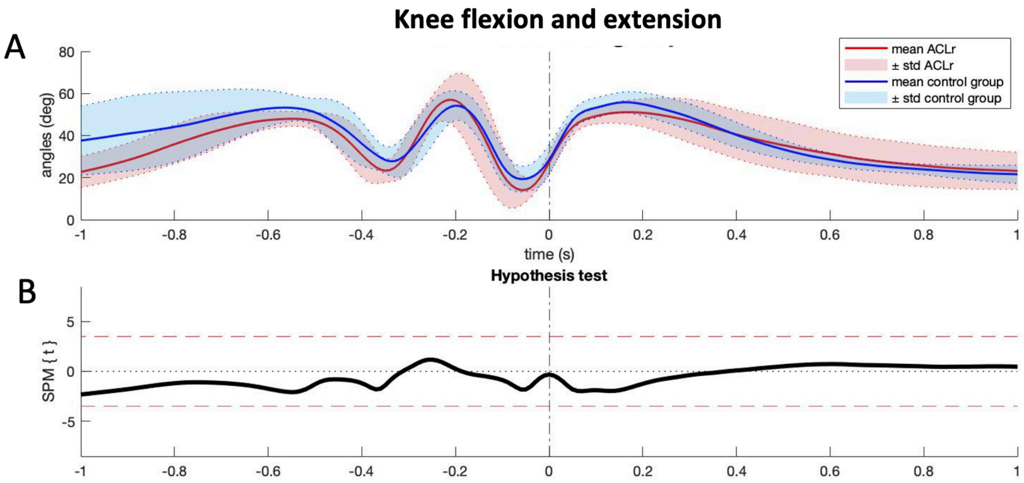

Figure 3.4 Kinematics and statistical parametric mapping outcomes for knee flexion and extension. The solid line reflects the mean for the control group (blue) and ACLr patients (red), with the shaded area reflecting the standard deviation.

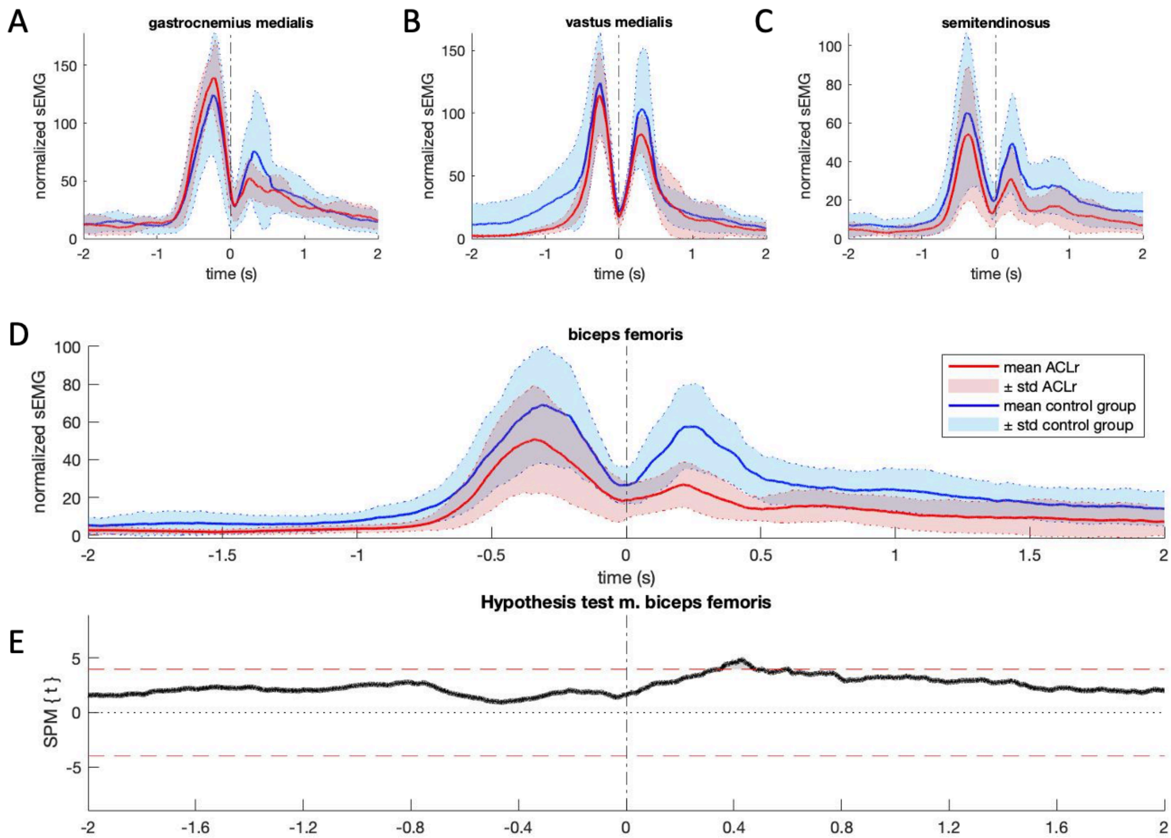

Figure 3.5 Normalized sEMG values for the A) gastrocnemius, B) vastus medialis, C) semitendinosus and D) biceps femoris. The solid line reflects the mean sEMG for the control group (blue) and the VKB-patients (red), with the shaded area reflecting the standard deviation E) statistical parametric mapping outcomes for sEMG of biceps femoris. Red dashed line indicates the critical threshold.

3.2 Influence of neurocognitive load

3.2.1. Jumping distance

As can be seen in Table 3.5, controls on average jumped 134 ± 29 cm during the standard SLHDs. For the neurocognitive hop tests participants jumped 124 ± 28 and 125 ± 28 cm respectively. ACLr patients on average jumped 144 ± 25 cm during the standard SLHD. For the neurocognitive hop tests, ACLr patients jumped 143 ± 25 and 139 ± 23 cm respectively. In the control group the differences were statistically significant for both neurocognitive SLHDs, however, in the ACLr group the differences were not statistically significant.

Table 3.5 Jumping distance for standard and neurocognitive SLHDs for the dominant leg in controls and reconstructed leg in ACLr patients

	Standard	Neuro-I	p-value [1]	Neuro-II	p-value [2]
Controls	134 ± 31 cm	124 ± 30 cm	0.001*	127 ± 30 cm	0.035*
ACLr patients	144 ± 27 cm	143 ± 27 cm	0.476	139 ± 24 cm	0.131

Values are reported as mean ± SD. [1] differences between standard SLHDs and first neurocognitive SLHDs. [2] differences between standard SLHD and second neurocognitive SLHDs.

3.2.2. Knee kinematics:

For the control group, the mean knee angles were similar for the standard and the first neurocognitive SLHDs (Figure 3.6A) and for the standard and second neurocognitive SLHDs (Figure 3.6C). The critical threshold was not exceeded (Figure 3.6B and 3.6D). At the time of minimal knee flexion during take-off, the graph does move towards this threshold for both the first and second neurocognitive SLHDs. This is not reflected in Table 3.6. Here, a difference is seen between the standard and first neurocognitive SLHDs during maximal knee flexion during the flight phase. In addition, a difference is seen between the standard and second neurocognitive SLHDs during maximal knee flexion during take-off and minimal knee flexion just before IC.

For the ACLr group, the mean knee angles were highly similar for the standard and first neurocognitive SLHDs (Figure 3.7A) and for the standard and second neurocognitive SLHDs (Figure 3.7C). However, in both analyses, de critical threshold was exceeded around - 0.2 seconds. This moment corresponds to the flight phase of the jump. This means that the knee is more flexed during flight phases of the neurocognitive SLHDs compared to the standard SLHDs. Similar results can be seen in Table 3.6. For the ACLr group, a significant difference was found during maximal knee flexion during flight phase.

3.2.2 Muscle activation patterns:

Figure 3.8A to 3.8D shows the mean muscle activation patterns for standard and both neurocognitive SLHDs for the control group. Figure 3.5E shows the SPM outcomes for the gastrocnemius medialis, SPM analyses of the other muscles can be found in Appendix B. As can be seen in this Figure, the mean sEMG patterns are highly similar. This is confirmed by the SPM analysis, where the critical threshold was not exceeded. A similar result can be seen in Figure 3.9A to 3.9E for the ACLr patients. Again, the critical threshold was not exceeded, and no differences are observed. Not significantly different but striking is the higher sEMG activity of the semitendinosus and biceps femoris the second neurocognitive SLHDs, compared to the standard and first neurocognitive SLHDs.

Table 3.6 Knee kinematics during standard and neurocognitive SLHDs for the dominant leg in controls and reconstructed leg in ACLr patients

		Standard	Neuro-I	p-value [1]	Neuro-II	p-value [2]
Control group						
Take off	Max	56.3 ± 8.2	52.3 ± 7.3	0.120	51.0 ± 5.3	0.026*
	Min	23,9 ± 8.9	20.6 ± 6.5	0.317	18.6 ± 5.5	0.065
Flight phase	Max	56.5 ± 8.0	64.7 ± 14.3	0.017*	62.9 ± 18.0	0.182
	Min	16.5 ± 6.0	18.8 ± 5.7	0.264	19.8 ± 5.9	0.032*
IC		28.2 ± 7.0	31.3 ± 6.9	0.240	31.5 ± 5.2	0.167
Landing	Max	56.6 ± 4.8	57.7 ± 4.7	0.294	56.3 ± 3.1	0.835
	ROM	40.1.5 ± 7.9	38.9 ± 4.7	0.597	36.5 ± 4.7	0.117
ACLr patients						
Take off	Max	49.7 ± 2.5	49.1 ± 3.5	0.479	48.1 ± 3.8	0.135
	Min	22.4 ± 5.5	17.2 ± 6.7	0.073	19.5 ± 7.2	0.139
Flight phase	Max	59.9 ± 10.6	69.8 ± 12.1	< 0.001*	64.7 ± 12.1	0.130
	Min	13.5 ± 6.5	13.5 ± 6.2	0.918	13.5 ± 4.6	0.988
IC		27.2 ± 4.8	25.0 ± 4.0	0.215	25.2 ± 5.1	0.380
Landing	Max	53.4 ± 6.5	53.3 ± 5.4	0.960	51.1 ± 4.5	0.253
	ROM	39.8 ± 6.5	39.8 ± 4.4	0.988	37.6 ± 3.1	0.340

Rows represent moments of interests: maximal knee flexion during take-off, minimal knee flexion during take-off, maximal knee flexion during flight phase, minimal flexion just before IC, knee flexion during IC, maximal knee flexion during landing, range of motion during landing. * Indicates a significant difference
[1] differences between standard SLHDs and first neurocognitive SLHDs. [2] differences between standard SLHD and second neurocognitive SLHDs.

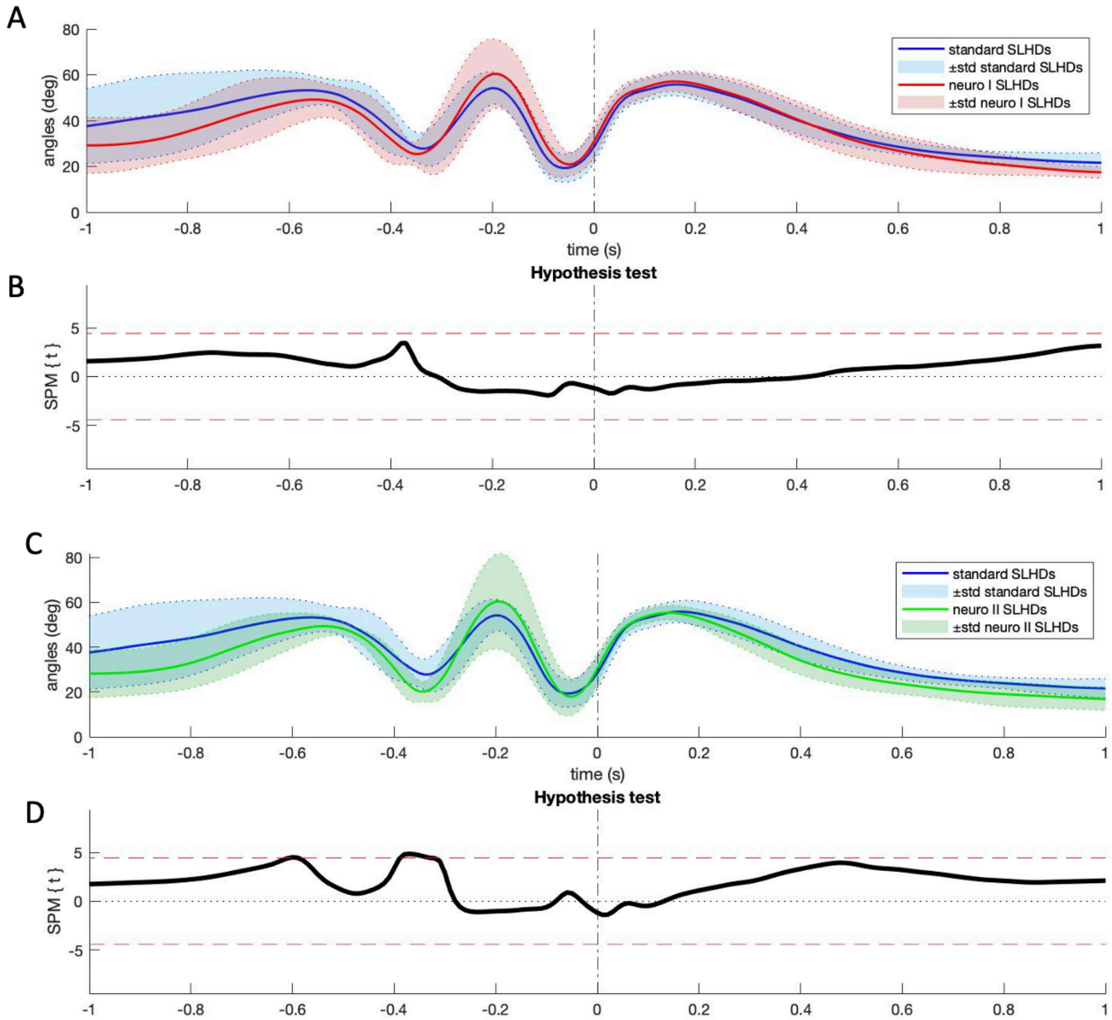

Figure 3.6 Kinematics and statistical parametric mapping outcomes of the knee flexion and extension for A) standard SLHDs (blue) and the first neurocognitive SLHDS (red) and B) for standard SLHDs (blue) and the second neurocognitive SLHDs (green) in the control group. The solid line reflects the mean sagittal-plane joint angle for all jumps, the shaded area reflects the standard deviation.

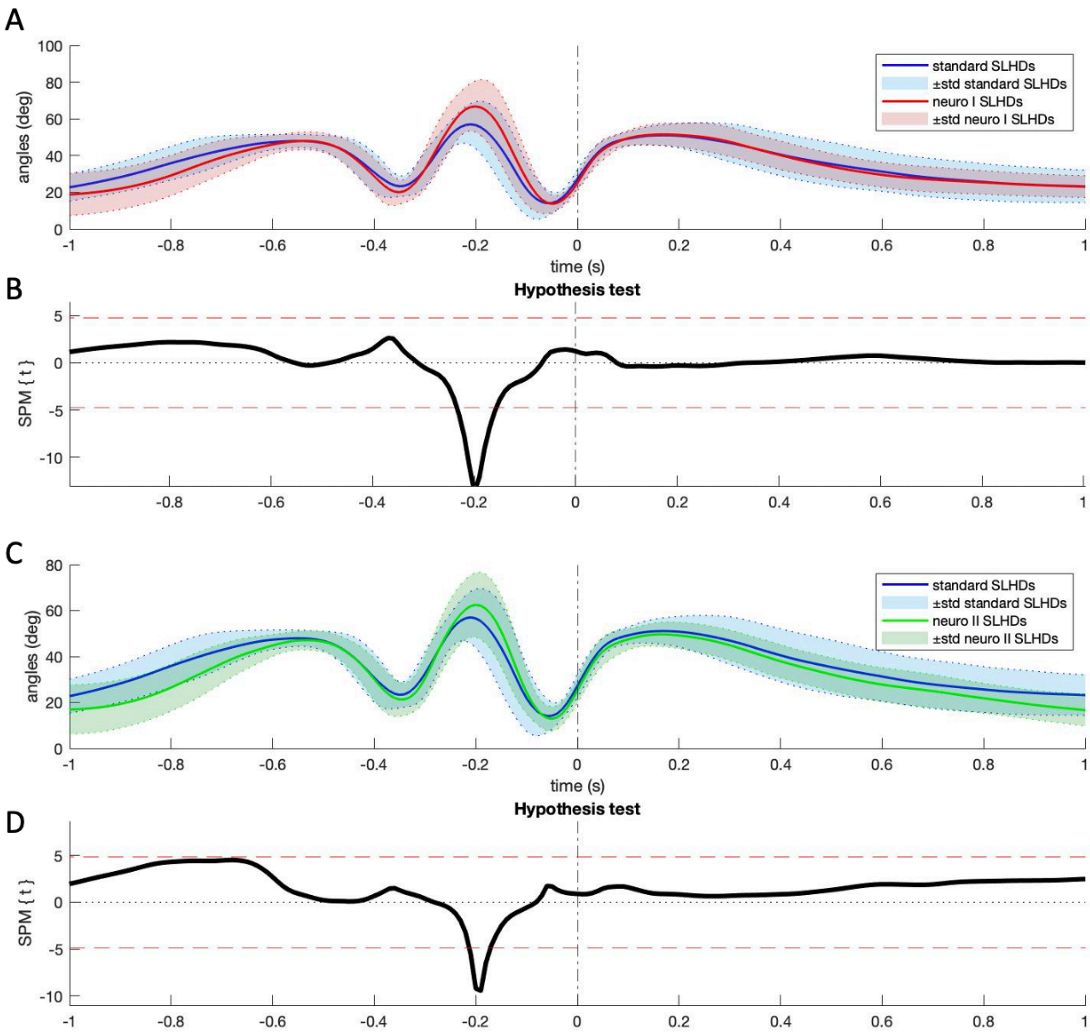

Figure 3.7 Kinematics and statistical parametric mapping outcomes of the knee flexion and extension for A) standard SLHDs (blue) and the first neurocognitive SLHDS (red) and B) for standard SLHDs (blue) and the second neurocognitive SLHDs (green) in the ACLr patients. The solid line reflects the mean sagittal-plane joint angle for all jumps, the shaded area reflects the standard deviation.

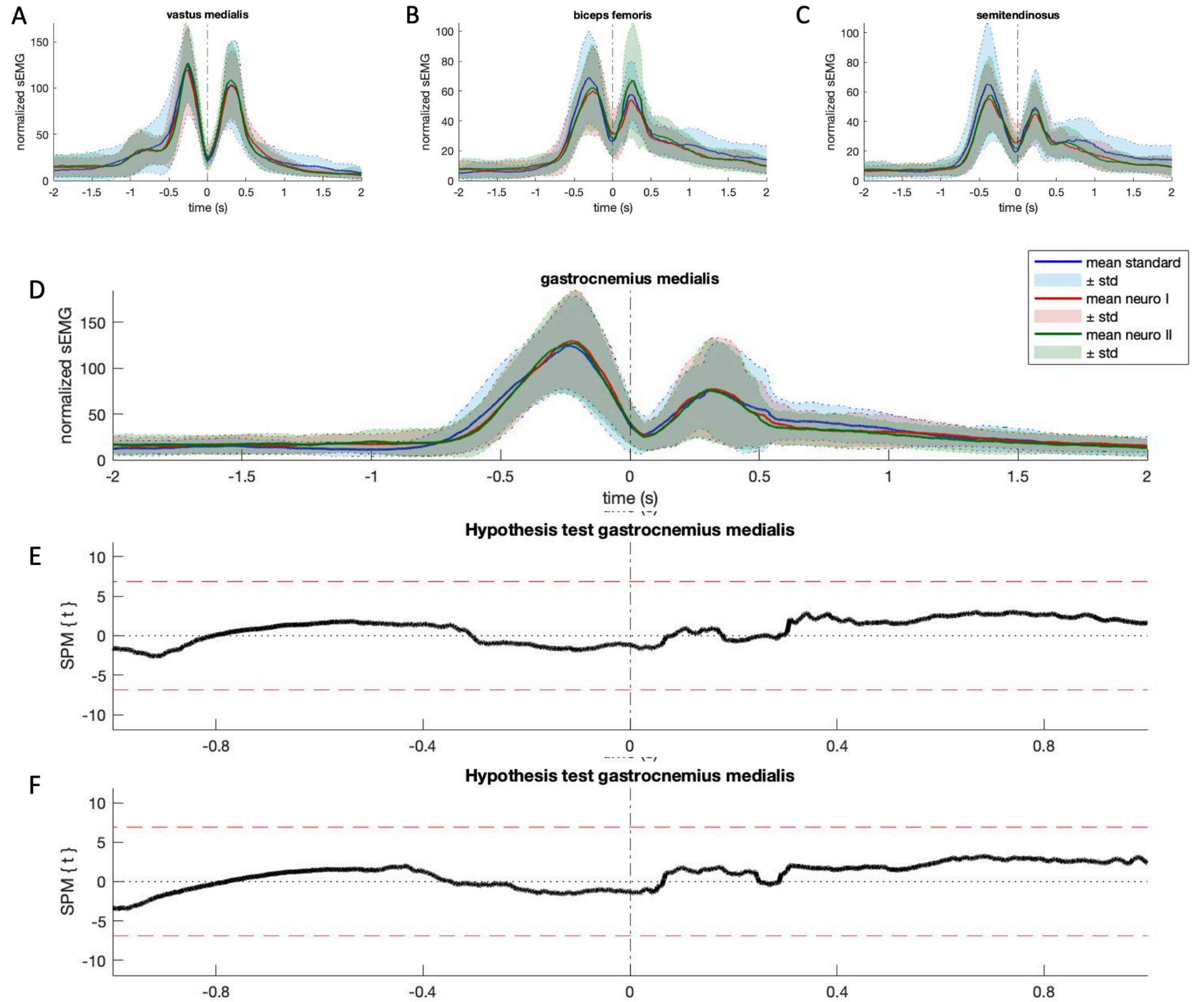

Figure 3.8 Normalized sEMG values for A) vastus medialis B) biceps femoris, C) semitendinosus and D) gastrocnemius medialis during standard SLHDs (blue), first neurocognitive SLHDs (red) and second neurocognitive SLHDs (green) for the control group. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. E) statistical parametric mapping outcomes for sEMG of the gastrocnemius medialis for standard SLHD and first neurocognitive SLHD F) statistical parametric mapping outcomes for sEMG of the gastrocnemius medialis for standard SLHD and second neurocognitive SLHD.

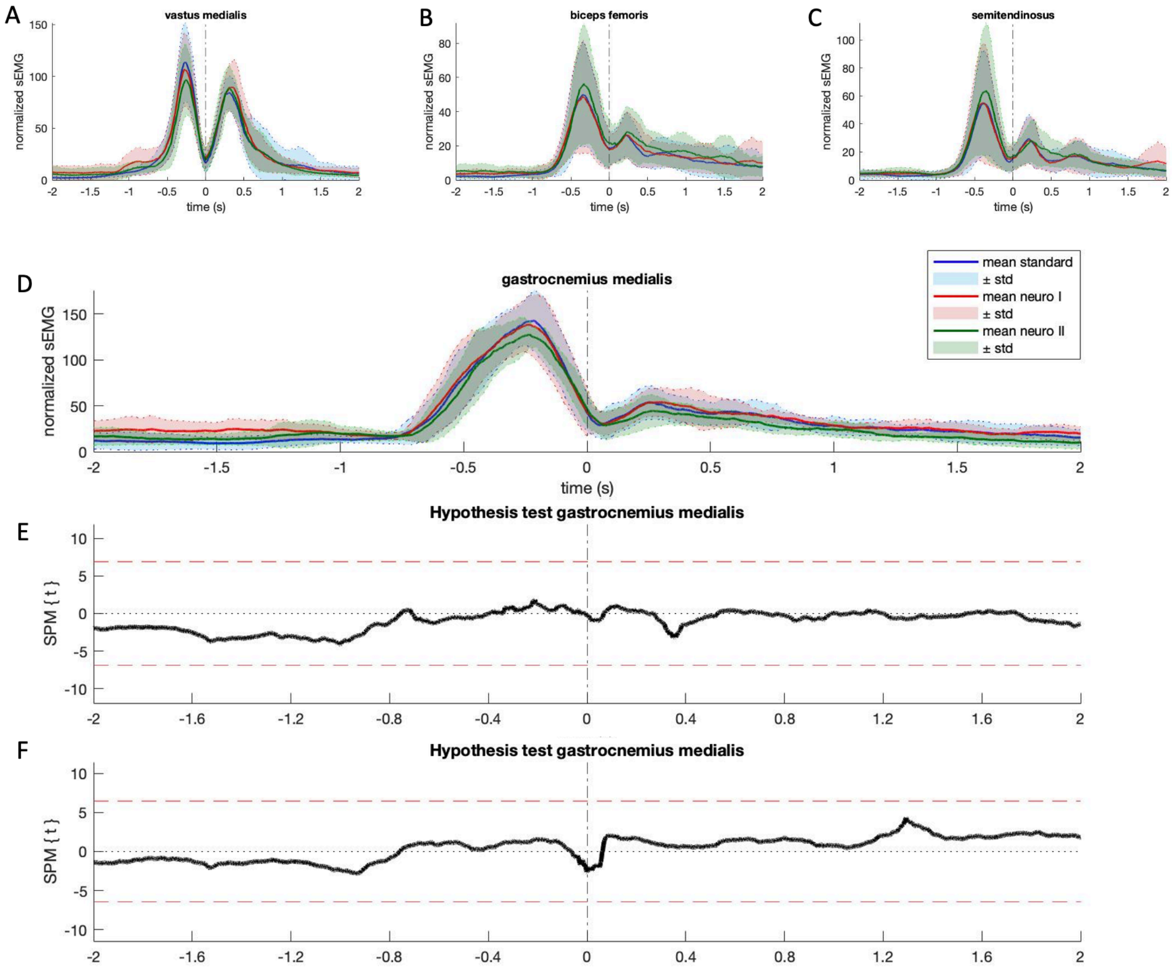

Figure 3.9 Normalized sEMG values for A) vastus medialis B) biceps femoris, C) semitendinosus and D) gastrocnemius medialis during standard SLHDs (blue), first neurocognitive SLHDs (red) and second neurocognitive SLHDs (green) for ACLr patients. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. E) statistical parametric mapping outcomes for sEMG of the gastrocnemius medialis for standard SLHD and first neurocognitive SLHD F) statistical parametric mapping outcomes for sEMG of the gastrocnemius medialis for standard SLHD and second neurocognitive SLHD.

4. Discussion

The purpose of the clinical study was twofold. First, we sought to demonstrate a difference in knee kinematics and muscle activation patterns during SLHDs between the reconstructed leg of the ACLr group and the dominant leg of the control group. The results of this study showed that the differences were not statistically significant. The second purpose of the clinical study was to measure the influence of neurocognitive load during SLHDs on jumping distance, knee kinematics and muscle activation patterns. Although muscle activation patterns were not statistically significant, statistical differences in jumping distance and knee kinematics did arise. Both neurocognitive loads resulted in larger knee flexion angles during the flight phase for the reconstructed leg of the ACLr group as well the dominant leg of the control group. These differences were more pronounced for the ACLr group than for the control group.

4.1 Difference between the reconstructed leg of the ACLr population and the dominant leg of the control population

Many studies have been performed to analyze biomechanical landing patterns (30, 35, 42-47). For knee kinematics, decreased flexion angles were found during the landing of a single leg hop for distance and the drop vertical jump for the ACLr knee compared to the contralateral knee at initial contact and maximal flexion (30, 48-50). These stiff landing patterns are associated with an increased risk for a re-rupture since more forces are generated on the ACL (29). These differences, however, were not found in this study. This is probably due to the large differences between the individuals. In the pilot study it was already shown that there are large individual differences between individuals. Looking at Figure 3.4, this intra-subject variability seems even larger in ACLr patient, resulting in a wider standard deviation. This makes it difficult to demonstrate statistically significant differences, especially in this small population.

In addition, no differences were found in the jump distance between the reconstructed leg of the ACLr patients and the dominant leg of the control group. However, by comparing the jumping distances to normative data of large samples of healthy athletes several things stand out (41). Comparing the differences to standard error of measurements (SEM) of healthy athletes for the SLHDs, the difference exceeds the SEM by far. This may indicate that the differences are clinically relevant, although they are not statistically significant. Contrary to expectations, this would indicate that patients after ACLr perform significantly better on the SLHDs compared to healthy controls. This raises the question of whether the individuals in the control group were physically active enough. According to normative data from Myers et al, a woman should jump about 149 cm and a man 192 cm (41). Both distances are well beyond the 144 cm found in this study.

In conclusion, potential reasons for not reaching statistically differences in the current study could be related to 1) sample size 2) large intrasubject variation and 3) the sport activity level of the participants in the control group.

4.2 Neurocognitive hop tasks

Currently, RTS protocols are primarily based on functional tests, for examples SLHDs. These jump landing tasks can be defined as standardized movements in a predictable environment. When returning to the field after rehabilitation, however, the requirements are vastly different. Here, athletes are exposed to multiple stimuli and have to make decisions in an unpredictable and changing environment. Interpretation and the subsequent (subconscious) decisions must be made quickly and be re-evaluated. The neurocognitive SLHDs performed in this study attempt to mimic this rapidly changing sports environment. Instead of being able to jump when the participant wants to, as is done during standard SLHDs, the participant had to react to a Fitlight.

In controls without knee injury, jumping distance was statistically different between standard and both neurocognitive SLHDs, indicating that the neurocognitive SLHDs were more challenging. The significant difference between the standard SLHDs and first neurocognitive SLHDs contrasts with earlier finding of Simon et al., who did not find significant differences in similar jumps with similar neurocognitive load (27). The authors did find significant differences in triple leg hop for distances with a comparable neurocognitive load as the second neurocognitive load in this study. No significant differences were found in the ACLr patients. These may be partly explained by the fact that ACLr patients will practice jump-tasks within their rehabilitation program. Besides, the test incorporated only one stimulus directly in front of the participant. The sports field contains many more stimuli where an athlete must respond to. Both neurocognitive SLHDs are therefore still a simplified representation of a true sport environment. This may not have been challenging enough to decrease performance of a frequently practiced task. For example, we did not test the effect of peripheral vision. Expanding the complexity of the measurement set-up and movements might therefore be necessary for a better representation of the sport environment, to further bridge the gap between standard SLHDs and the sports environment.

Differences in knee kinematics were demonstrated in both groups. The most noticeable difference was the difference found in the knee flexion angle during the flight phase, where the addition of a neurocognitive load yielded larger knee flexion angles for both the reconstructed leg of the ACLr group and the dominant leg of the control group. It is unknown what causes these differences. One explanation might be that less height is created during take-off by performing is quickly. This could be compensated by bending the knee more. Analysis of the body's center of gravity could provide more insight into this Although not officially tested, the differences in the ACLr patients appear to be greater than the differences that occur in the control group. This could be an indication that ACLr patients respond differently to the neurocognitive load than controls. However, as indicated, this difference was found in the minimal knee flexion angle during the flight phase. Much is known about changes in knee kinematics that increase the risk of injury, for example a stiffer landing pattern. However, these previous studies have not described anything about knee flexion of the knee during the flight phase. The clinical relevance will therefore have to be further investigated.

All participants performed the jumps in the same order. That is, first the standard SLHDs, then first neurocognitive SLHD, and finally the second neurocognitive SLHD. Ideally, the order of the conditions was randomized to decrease a possible learning effect. It was, however, a conscious choice to apply this fixed order, especially for the ACLr group. Each neurocognitive SLHDs was designed to become more difficult and challenge the participant with increasing neurocognitive demand. In this way it could be checked whether the jumps still felt good to the patient. If any doubt arose about the ability to perform the next step, the protocol was stopped.

This clinical study is the first step towards the analysis of a true effect of neurocognitive load during SLHDs. The study is currently running, and this chapter describes the preliminary results of the analysis. So far, only 18 participants were included in the study, eight ACLr patients and ten participants without knee injury. It is intended to perform the analysis and include a total of 30 participants in both subgroups, resulting in 60 participants in total. Statements on whether differences exist between the operated leg of the ACLr patients and dominant leg of the control group are for now omitted and require a larger study population. The same applies to the influence of neurocognitive load on the SLHD on jumping distance, knee kinematics and muscle activation patterns. Continuation of the current study will deliver more data measured from individual participants, causing reliable between and within subject comparisons.

GENERAL DISCUSSION

The goal of this graduation internship was to introduce a research line on the role of neurocognitive load on knee kinematics and muscle activation patterns during SLHDs after ACLr. The two parts of this thesis approached different components concerning the implementation of this research project. The first part (section I) was a pilot study analyzing the knee kinematics and muscle activation patterns of participants without knee injury during SLHDs. During this pilot study, the intrasubject variation in both knee kinematics and muscle activation patterns was assessed. Besides, knee kinematics and muscle activation patterns during successful and failed trials of the SLHDs were assessed. The second part (section II) was a clinical study analyzing the difference in jumping distance, knee kinematics, and muscle activation patterns between the operated leg of ACLr patients and the dominant leg of controls. In addition, the effects of neurocognitive load on these parameters were analyzed. The connection between those different parts is described in this discussion, together with the limitations and future perspectives. This chapter ends with a substantiated recommendation for the continuation of our line of inquiry.

A wide range of clinical tests has been described for RTS decision (51, 52). In clinical practice, the SLHD is widely used. Usually the jumping distance is considered, whereby the limb symmetry index (LSI) is used to objectify the RTS decision. This index assesses the performance of the affected leg using the performance of the unaffected leg as a reference. An LSI of > 90% is suggested to represent a successful rehabilitation and safe RTS (53). However, the outcome of the LSI is heavily debated, partly because functional status of the contralateral lower limb is also reduced after unilateral ACL injury (54, 55). This can lead to an overestimation of the LSI. Besides, the same jumping distance can be achieved with different movement strategies. While a patient may be able to perform a good result on the SLHDs based on jumping distance, it cannot be assumed that this is based on a good movement pattern. On the contrary, altered movement patterns in the injured leg compared to the uninjured leg have been demonstrated in patients with LSI scores >90% (29). Reliance on jumping distance or LSI results alone can therefore be questioned. Therefore, this study investigated knee kinematics and muscle activation patterns, in addition to jumping distance. To do so, it was important to determine the parameters of interest. However, current literature reports a wide range of parameters which have been analyzed. There is still no agreement in the clinic or in research on which kinematic variables are of interest and thus should be documented. Because of this discrepancy, the combination of variables with the highest clinical relevance is still unknown.

Knee kinematics

Commonly 3D optical motion systems are used knee kinematics analysis (56). Frequently analyzed kinematic parameters in these studies include the peak knee flexion and ROM of the knee. Besides, rotations of the knee and the dynamic valgus angle were described as interesting parameters (30, 35-39). However, in the present study, data on knee kinematics were obtained using IMUs. The use of these IMUs in the medical setting is innovative, and it offers some potential benefits. IMU sensors are more accessible than an optical system: there is no need for a specially equipped room and their use is relatively simple, making them easy to apply in daily practice. This raises the question whether parameters validated in 3D analysis can also be applied in IMU analysis. A study by Cuesta-Vargas et al. found this to be true after reviewing studies comparing inertial sensors with any kind of golden standard to measure human motion analysis (57). They concluded that inertial sensors could offer an accurate and reliable method to study human movement. However, the degree of accuracy and reliability depends on the analyzed parameters and tasks. Moreover, Zang et al. performed a validation study of the Xsens motion trackers to measure lower-limb joint angles during gait compared to an optical system (58). Likewise, they concluded that especially knee flexion and extension angles measured with Xsens corresponded to the angles measured with the optical system. In contrast, the adduction/abduction and internal/external rotation showed considerably larger errors. Therefore, this study was limited to sagittal plane kinematics of the knee.

Muscle activation patterns

According to sEMG analysis, one of the parameters which is particularly of interest is the timing of onset of muscle activation. It is thought that early activation of muscles increases the stiffness of the joints. This grants the muscles time to generate forces to provide correct lower extremity alignment during landing (59). A study by Gokeler et al. provided supporting evidence by observing nine patients during a hop task, six months after ACLr (30). The authors concluded that sEMG onset times of various leg muscles were significantly earlier in the involved limbs compared to the uninvolved leg. This is consistent with findings of Coats-Thomas et al., which indicated that patients increase the pre-tension of the limb muscles before the landing of various different jumps (60). However, other studies did not find differences in the sEMG activity of the hamstrings when comparing ACLr patients to uninjured participants during SLHDs (61). Possible explanations for the deviating conclusions include different timing between surgery and the jumping task, varying sEMG analysis approaches and differences in gender, age, and level of sports of the participants.

All above-mentioned studies used a force plate to determine IC. Onset time of muscle activation is subsequently determined relative to this point. The measurement set-up of the presented study, however, did not contain a force plate. This made it impossible to determine IC in the sEMG signal. Nevertheless, the best possible effort has been made to define a reference point in the sEMG signal which can be related to a moment in the jump. The activation pattern of the vastus medialis contains two distinct peaks: one during take-off and one during landing. The minimum between these peaks is used as reference point and corresponds to the flight phase. Since this is a very rough estimation, it was decided to analyze the entire activation pattern of the muscles. These sEMG patterns broadly resemble those found in other studies, and we therefore assume that the measurements are representative (31).

After determining the parameters for knee kinematics and muscle activation patterns, differences were sought between the different groups (ACL and control) and the different conditions (standard versus both neurocognitive SLHDs). However, an important remark should be made here: these differences do not have to be disadvantageous. Movement variability has a functional role in neuromuscular adaptations. This role includes facilitating adaptations of the individual motor system to processes such as injuries. Sinklaer et al. investigated muscle activity during gait in patients who suffered from ACL deficiency (62). They found that ACL patients demonstrated an earlier recruitment and a tendency to prolonged activity in muscles around the deficient knee as compared with a control group. To assess clinical relevance, they made a comparison between a patient group who had a functionally good/excellent recovery and a group who had a poor functionally recovery. Significant differences between the two groups were noted in sEMG onset and burst duration of the gastrocnemius. Interestingly, the sEMG pattern of the poor ACL-group matched the healthy population, whereas the good/excellent ALC-group adapted their muscle activity and recruited the gastrocnemius earlier and in two bursts. Although this study focused on patients with ACL-deficiency patients while walking, comparable findings were observed by Keizer et al. in patients after ACLr during SLHDs (31). They also observed significant differences in gastrocnemius activity during SLHDs for patients who manage to return to their preinjury sports type and level and those who did not. They concluded that patients who returned to their preinjury sport used increased gastrocnemius muscle activity to limit anterior tibial translation during landing, whereas patients who did not return to their preinjury sport fail to do so and limit their knee flexion moment to reduce anterior tibial translation during landing. These results suggest that muscle activation patterns are adjusted in both ACL deficiency patients and ACLr patients, and that differences in these adjustments determine their level of RTS. The difference between returning or not returning to pre-injury sport level may thus, amongst other things, be caused by the ability to adapt knee kinematics and muscle activation patterns to a new situation. These findings reinforce the idea that modified muscle activation patterns have clinical relevance. Taking this into account, rehabilitation programs should perhaps focus on adjusting muscle activation patterns as best as possible and not aiming to return muscle activation to normal. However, more knowledge is needed to determine which adjustments are beneficial.

Methodological considerations

In this thesis, algorithms provided by the manufacturer were used for the analysis of the knee kinematics. The exact content of the algorithms is unknown, and no adjustments could be made. The moment of initial contact was the determined by the largest peak in the vertical acceleration signal. This method has been used in previous research within OCON, however, it is unclear how accurately IC contact is determined in this way. The way of landing differed from person to person: some patients landed at on their full foot and some patients landed on their forefoot. These differences may have affected the acceleration signal and thus determination of IC. Since the flexion-extension curve is steep here, a small deviation on the time axis can lead to large differences in the detected knee flexion angle.

During analysis, two different statistical analyses were performed. The first analysis examined some discrete values within time-continuous curves through discrete statistical test. However, this discrete analysis ignores most of the data in the time-continuous curves. Instead of discrete analyses, it has become more common in human biomechanics research to use time-continuous analyses such as SPM. In this thesis, this was applied on the originally sampled time series of the knee kinematics and muscle activation patterns. Compared to traditional statistics, this analytical approach has the advantage of considering the entire time-varying structure of kinematic and muscle activation data, identifying time intervals in which compromised patterns are evident. An essential consideration in applying this continuous analysis is the definition for aligning the curves. In gait analysis, it is common practice to align time-continuous curves based on a single event, for example foot contact or toe-off. Since walking is a repeatable event, one event is enough to segment the steps. The result is a normalized graph from 0 to 100% showing the knee angles from toe-off till toe-off. During the SLHDs, it was not possible to determine the start and end of the jump, and thus not possible to normalize for time.

To facilitate between-subject comparisons and clinical interpretation, it is recommended to express time as a percentage of the three different phases. As indicated in Figure 2.3, phase transitions are marked by the toe-off and IC. In addition to these points, the moments of maximal knee flexion could be used for data alignment. More specifically, during take-off, the time from the first maximal knee flexion to the toe-off event should represented 50% of the take-off phase, with the remaining 50% spanning the time prior to maximal knee flexion. Similarly, the time from the touch-down to the maximal knee flexion event represented 50% of the landing phase, with the remaining 50% spanning the time following maximal knee flexion. Finally, the time from the take-off to the touch-down event represented 100% of the flight phase, with maximal knee flexion at 50%. According to such landmark registration, the designated moments of interests (maximal knee flexion during take-off, knee flexion during take-off, maximal knee flexion during flight phase, knee flexion at IC, maximal knee flexion during landing) occurred at the same relative time point for each subject. This allowed better comparison of the continuous data series.

Limitations and recommendations

There are some limitations that should be acknowledged. Firstly, no synchronization could be made between the IMUs and sEMG. This made it difficult to compare muscle activation and knee movements at a detailed level. To tackle this problem, it could be tried to start and end the experiments with a specific movement, such as dorsal flexing of the feet. However, it would be even more precise when the measured sEMG and kinematics are automatically synchronized. It should therefore be considered to acquire software for this. When both systems are synchronized, the recorded kinematics can be used to support the interpretation of the sEMG data and vice versa. Secondly, to determine the moment of IC even more accurately, it can be considered to add a force plate, which is synchronized with both the IMUs and sEMG. This addition will provide a more comprehensive representation, and this makes it possible to compare the results with those of previous studies.

Besides, analysis of the kinematics is limited to the knee joint, unmistakable one of the most important joints during a SLHDs. This is, however, a simplified representation of the complex task being performed. This is already apparent from the fact that muscle activation patterns cannot fully be explained by looking at the flexion and extension of the knee. The gastrocnemius, biceps femoris and semitendinosus are bi-articular muscle groups. Muscle activation can therefore result in movement in different joints. For a more complete understanding of the jump mechanism, the analysis should be extended to other joints in de chain, such as the ankle and the hip.

Finally, it is interesting to perform sub analysis when more participants are included. It would be interesting to distinguish between a patient group who have a good recovery and a group who have a poor recovery. It can be investigated whether these patients can already be identified based on the measurement outcomes.

Future perspectives

The main aim of the research line is to evaluate the effect of neurocognitive load in ACLr patients and controls without knee injury in terms of jumping distance and strategy. With these insights, future rehabilitation can be better adapted to the needs of an individual patients. However, in this study, only neurocognitive testing has been proposed as an addition to the current RTS decision. This is only a small element in the RTS decision.

Many more factors have been identified that contribute to RTS after ACLr (63, 64). First, it is demonstrated that a range of contextual factors affect RTS after ACLr, including age, sex and participation level. For example, a swimmer with a ACLr has a different risk than a basketball player (different sports), and a recreational football player may have a different risk than a competitive player (different competitive levels). While these factors should certainly be included in the RTS-advice, it is more interesting to look at components with a potentially modifiable nature. One of these components are psychological factors. Negative emotions, such as anxiety and fear, can have a negative effect on recovery after ACLr. All these components need to be included in the development of an RTS assessment model for ACLr patients (65). In this model, the weighting of individual components will likely vary from person to person.

Conclusion

The hop tests presented in this thesis are a first step to clinically incorporate a neurocognitive component to functional testing. Overall, this study established that adding a neurocognitive component to standard hop tests influences the jump strategy, according to knee kinematics. Specifically, there were differences in maximal knee flexion during the flight phase in ACLr patients. The analytical approach presented provides a sound template for further expansion of the research line. With future refinement, it could guide clinical decision-making by emphasizing deficiencies throughout the duration of a challenging neurocognitive task. This may improve an objective, personalized and more complete return to sport advise, which will contribute to minimizing the currently high incidence of re-ruptures of an ACL and while increasing the RTS ratio.

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Appendices

Appendix A

In this appendix the muscle activation patterns of the other three muscles (gastrocnemius lateralis, vastus lateralis and semitendinosus) are included, for successful and failed trials.

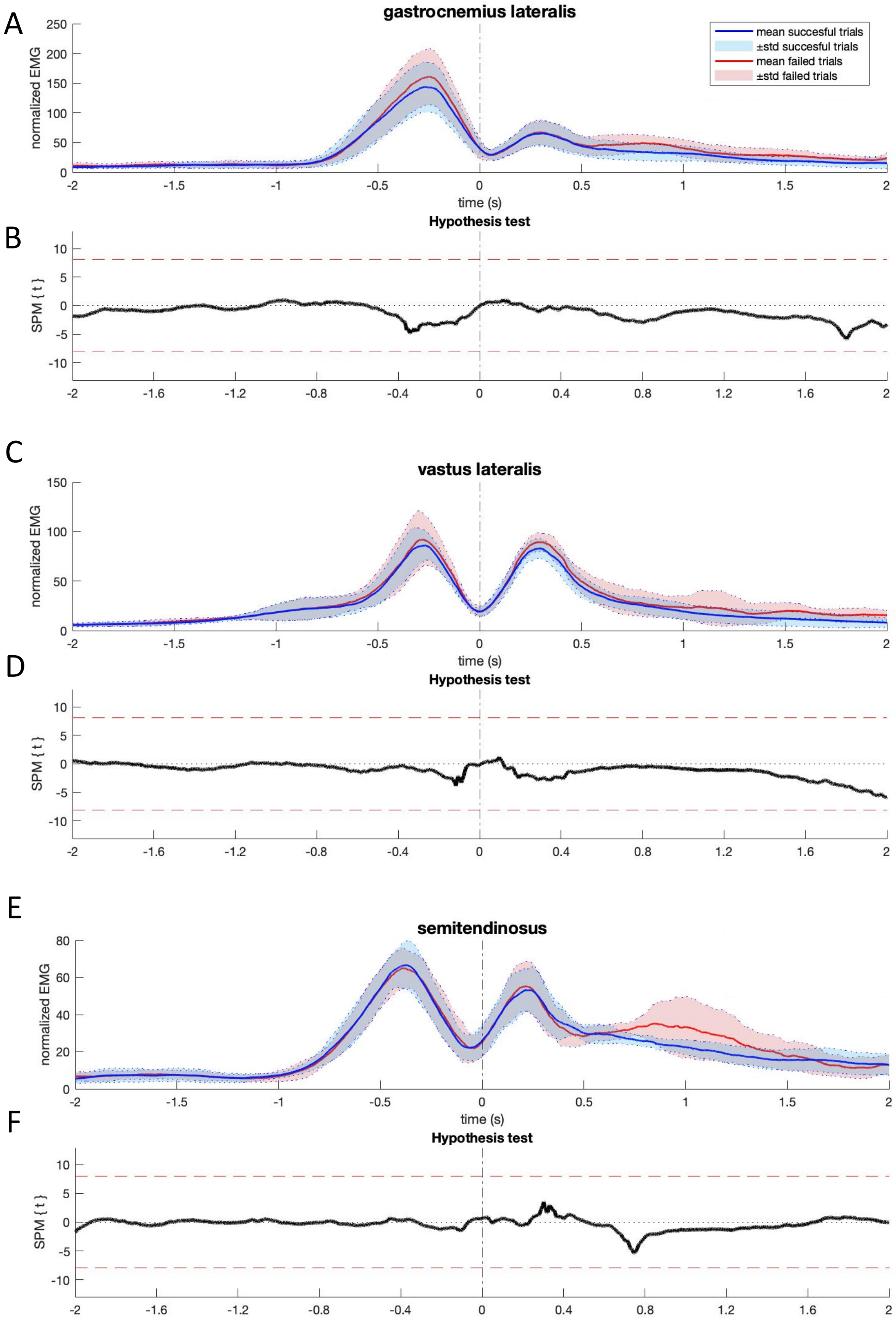

Figure A1:. normalized sEMG values for the gastrocnemius lateralis (A), vastus lateralis (C) and semitendinosus (E). The solid line reflects the mean sEMG for the control group (blue) and the VKB-patients (red), with the shaded area reflecting the standard deviation. Statistical parameter mapping outcomes for gastrocnemius lateralis (B), vastus lateralis (D) and semitendinosus (F). Red dashed line indicates the critical threshold.

Appendix B

In this appendix the statistical parameter mapping of the other three muscles (vastus medialis, biceps femoris and semitendinosus) are included, for standard and both neurocognitive SLHDs. The results of the control group are shown first (Figure A2-A4), followed by the results of the ACLr group (Figure A5-7).

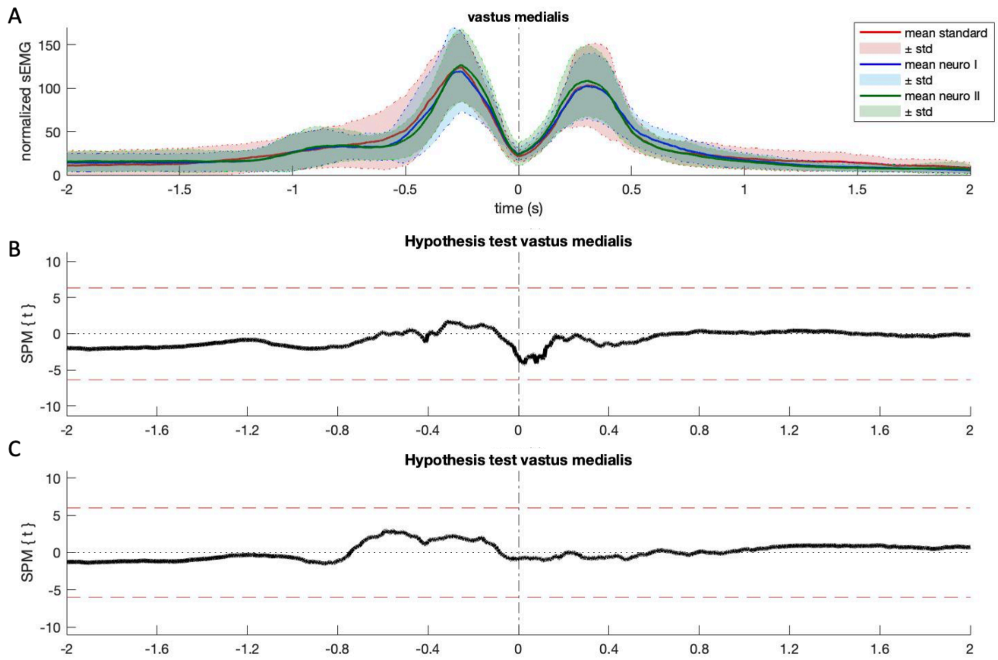

Figure A2 A) Normalized sEMG values for the vastus medialis during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the control group. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.

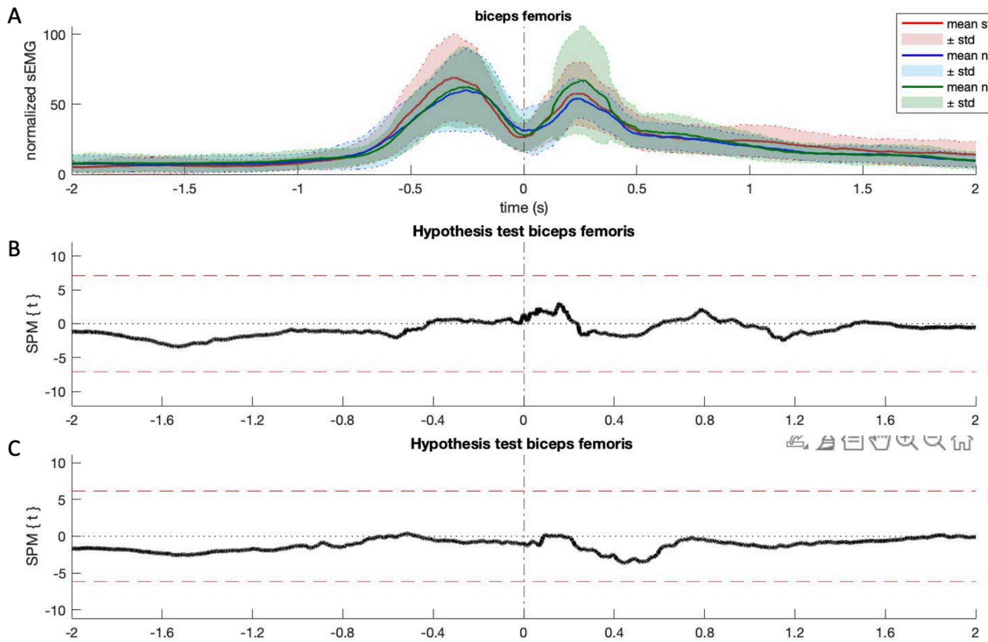

Figure A3 A) Normalized sEMG values for the bicep femoris during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the control group. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.

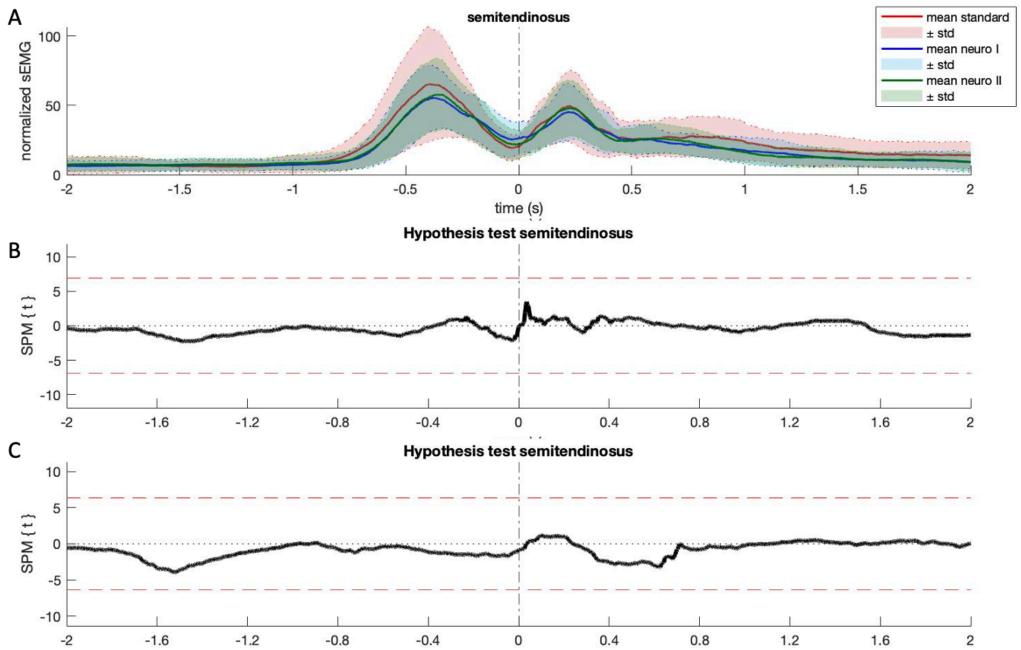

Figure A4 A) Normalized sEMG values for the semitendinosus during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the control group. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.

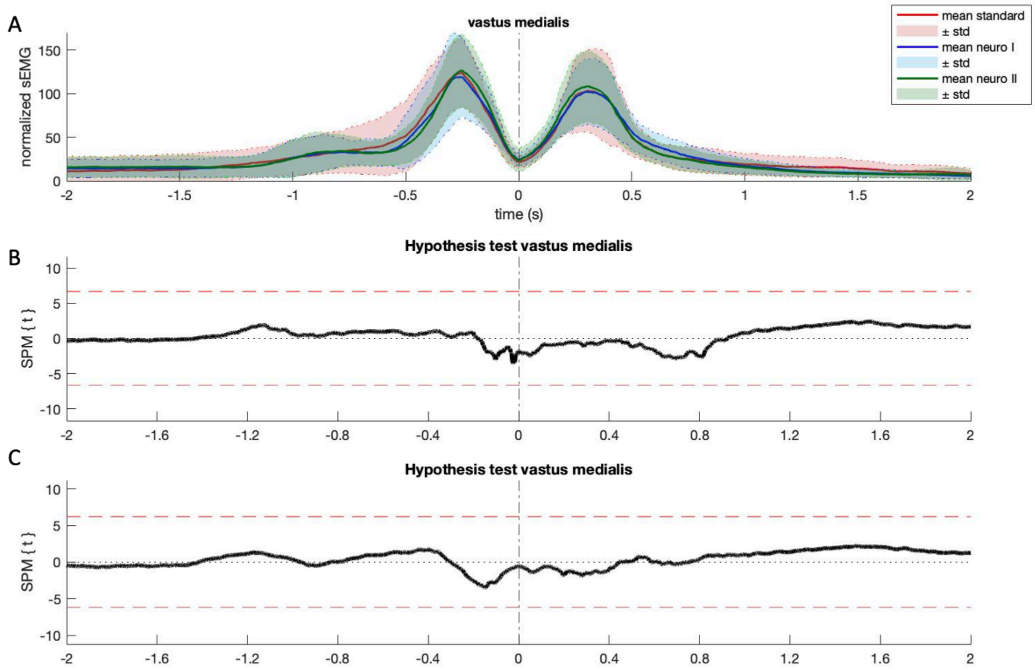

Figure A5 A) Normalized sEMG values for the vastus medialis during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the ACLr patients. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.

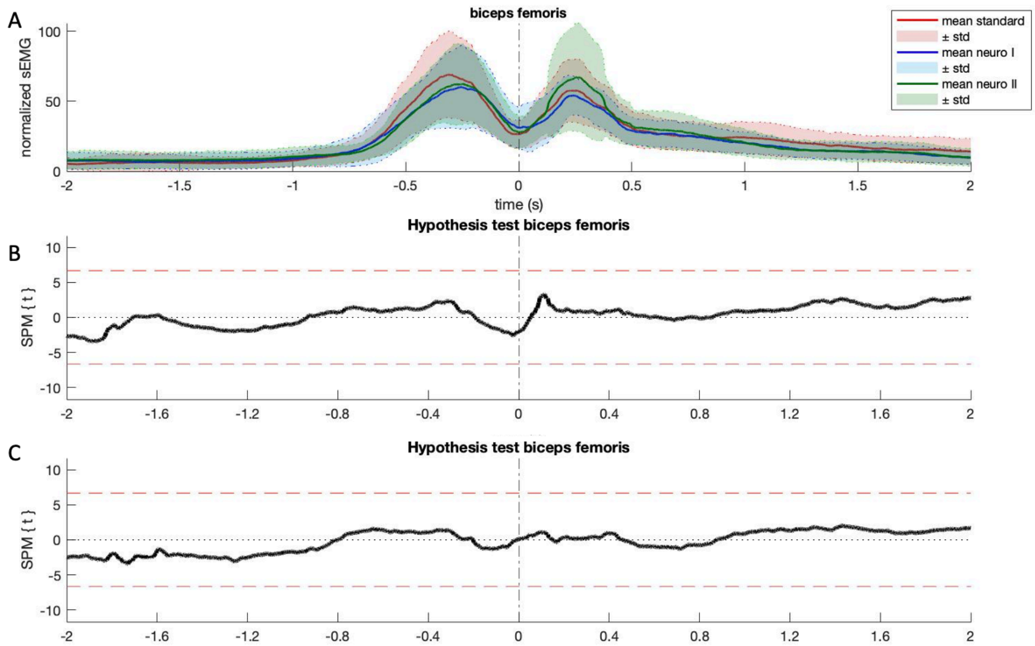

Figure A6 A) Normalized sEMG values for the biceps femoris during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the ACLr patients. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.

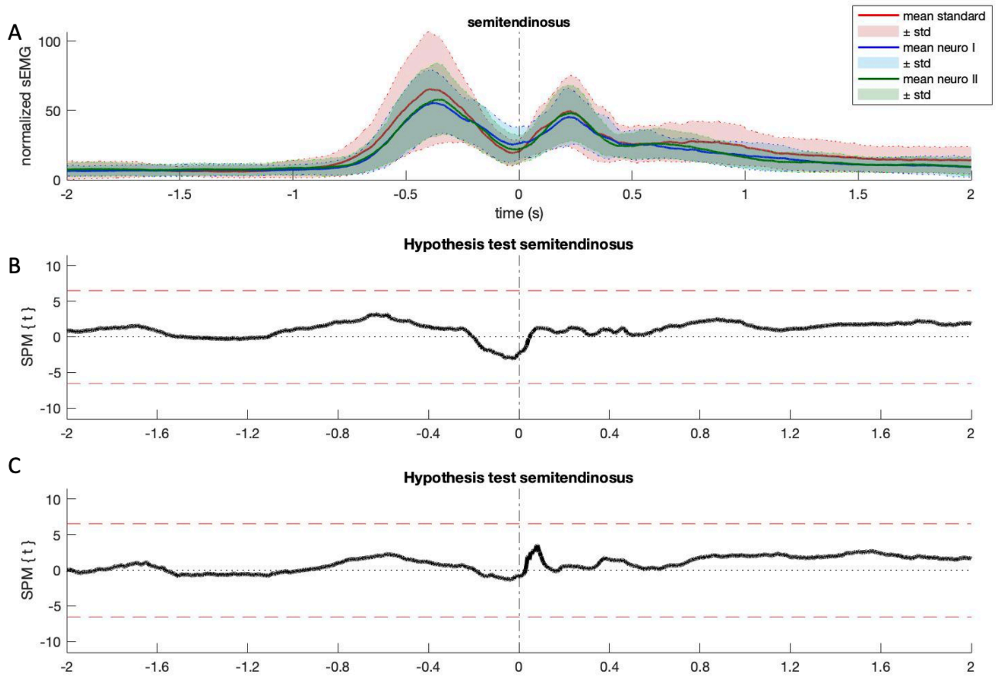

Figure A7 A) Normalized sEMG values for the semitendinosus during standard SLHDs (red), the first neurocognitive SLHDs (blue) and the second neurocognitive SLHDS (green) in the ACLr patients. The solid lines reflect the mean sEMG, the shaded areas reflect the standard deviation. B) statistical parametric mapping outcomes for sEMG for standard SLHD and the first neurocognitive SLHDs C) statistical parametric mapping outcomes for sEMG for standard SLHD and the second neurocognitive SLHDs.