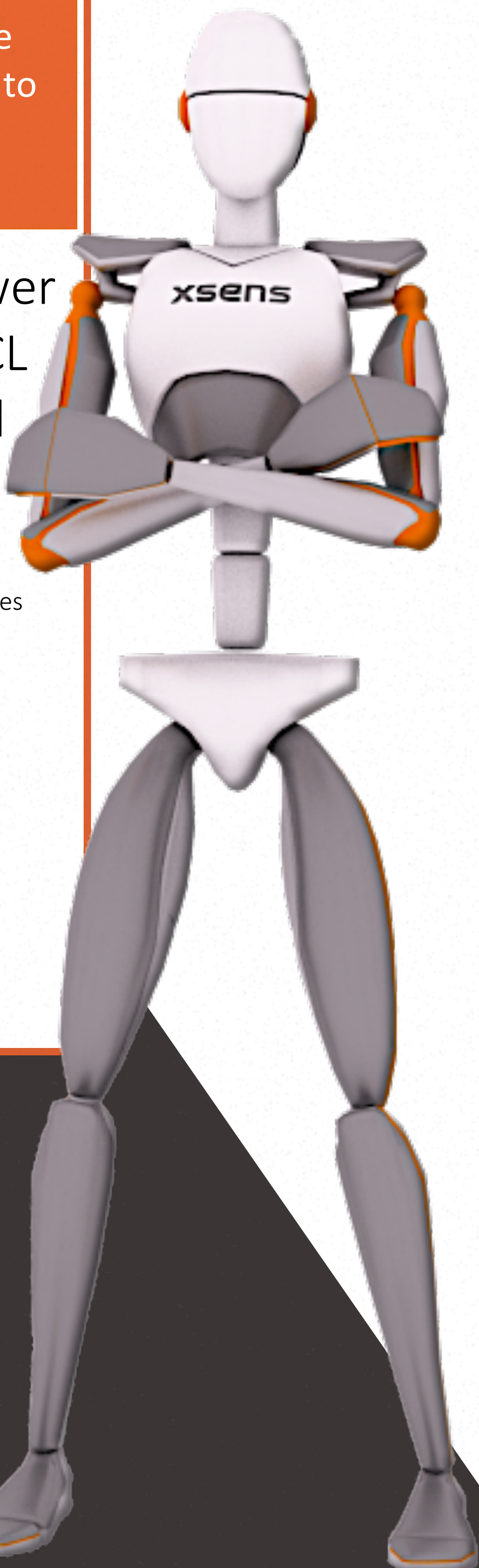
June 2019

Does the analysis of the lower extremity kinematic symmetry add value to the ACL reconstruction - return to sport tests?

Kinematics of the lower extremities after ACL reconstruction and returning to sport

Human Movement Technology
The Hague University of Applied Sciences

Thesis



Demi Loof - 13007378

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Thesis

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Demi Loof, 13007378
The Hague, June 2019
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Human Movement Technology
The Hague University of Applied Sciences
First assessor: A.H. Lagerberg, MSc
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B&B Healthcare, The Hague
External supervisor: J. van Tol, MSc

Preface

Before you lies the thesis *'Kinematics of the lower extremities after ACL reconstruction and returning to sport'*. It has been written to fulfill the graduation requirements of the bachelor study Human Kinetic Technology at The Hague University of Applied Sciences (THUAS). I was engaged in researching and writing this thesis from January till June 2019.

This research was formed while talking to Jordy van Tol from B&B Healthcare. Together we formulated the research question "*Does the analysis of the lower extremity kinematic symmetry add value to the ACL reconstruction – return to sport tests?'*. During my research, both my supervisors Aad Lagerberg and Daniël van Leeuwen. were always available and willing to answer all of my questions.

I would like to thank the following people: both my supervisors, Aad Lagerberg and Daniël van Leeuwen, for their outstanding guidance and support during this process; Jordy van Tol for giving me the opportunity to perform this thesis; all 53 subjects who participated in this study, without whose cooperation I would not have been able to conduct this thesis; Sophie Boelen, Hilke van Meurs and Romy Heesakkers for helping me during the testing days, which made those long days and nights a lot less stressful; Vera van Diepenhorst who made a promotion video of this research project, which is shared at LinkedIn and Facebook, and got over 4000 views; Kari Little for helping me write this thesis in correct English by doing a final grammar and spelling check; and all the other educators of Human Kinetic Technology who also helped me with answering my questions.

I hope you enjoy your reading.

Demi Loof

The Hague, June 29th 2019

Abstract English

A rupture of the anterior cruciate ligament (ACL) is one of the most common sports injuries worldwide, and also one of the most devastating injuries of the knee. An ACL injury happens mostly to young athletes (aged 14-40) who participate in landing, cutting and pivoting sports with fast decelerations, while around 70% of all ACL injuries result from a 'non-contact' mechanism.

Rehabilitation after an ACL rupture is prolonged and intensive and is needed to restore the knee function, strength and stability as it was prior to the injury. It is decided during the rehabilitation process in phase 5 if the athlete can return to sport. A triple hop test and a triple crossover hop test are used to assess an athlete's readiness. A limb symmetry index (LSI) greater than 90% indicates an athlete's readiness. Despite the fact that athletes can pass these hop tests, the incidence of a subsequent ACL rupture is 6 times as high as an initial rupture. This is partly due to the fact that an ACL injury results in joint specific, bilateral changes of the lower extremity kinematics, while the non-injured leg is also affected due to the long period of inactivity after reconstruction and therefore not the best comparison to use for the LSI. The bilateral changes of the lower extremity kinematics increase the risk for an ACL injury and therefore, should be looked at during the return to sport phase.

The main purpose of this thesis was to find out if the analysis of the lower extremity kinematic symmetry added any value to the ACL reconstruction – return to sport tests. Two criteria were used to do this: an LSI criterion based on the lower extremity kinematics, and a normative data criterion, also based on the lower extremity kinematics. Before both analyses were conducted on athletes with an ACL reconstruction, these criteria needed to be created with help from a healthy peers database. 40 Healthy subjects participated and were divided into 4 groups based on age and gender. The Xsens MVN Awinda was used to obtain the kinematic joint angles of the knee and hip at initial contact and 40ms after initial contact during the landing phase of the triple hop test and the triple crossover hop test.

Data from this study revealed the fact that healthy athletes also show significant differences in the side-to-side hip and knee kinematics during both hop tests. These differences are used to find LSI criteria for each joint motion separately. The exact kinematic data was used to create a normative data criterion for each joint motion separately. Both criteria were used to see how an individual athlete with an ACL reconstruction performed compared to his/her peers. Results showed that the majority of athletes with an ACL reconstruction did pass the hop tests based on their kinematics.

The findings of this study highlight the need for additional assessment of the side-to-side kinematics. While the control groups (based on gender and age) existed of 10 subjects each, more research with a greater amount of controls is needed to create more reliable criteria for kinematic LSI and normative kinematic data.

Abstract Dutch

Een scheuring van de voorste kruisband (vkb) is een van de meest voorkomende sportblessures wereldwijd. Een vkb-scheuring komt daarnaast het meeste voor bij jonge sporters (leeftijd 14-40) die sporten beoefenen waarin veel gesprongen, zijwaarts geschoven, gepivoteerd, van richting veranderd en veel afgeremd wordt na een sprint. Dit zijn voornamelijk teamsporten, zoals: basketbal, handbal, voetbal, volleybal en hockey. 70% van alle vkb-scheuringen komt voort uit een 'non-contact' mechanisme, waarin er geen contact is met een medespeler.

Het revalidatieproces na een vkb-scheuring duurt lang en is erg intensief. Dit is echter nodig om de volledige kracht, stabiliteit en functie van de knie terug te krijgen zoals deze waren voor de blessure. In het revalidatieproces wordt het terugkeren in de sport fase 5 genoemd, 'return to sport'. In deze fase zal bepaald worden of een sporter genoeg gerevalideerd heeft om terug te keren in de sport. Hierbij wordt gebruik gemaakt van de 'triple hop test' en de 'triple crossover hop test', beide op één been. Bij deze testen laat een limb symmetry index (LSI) groter dan 90% zien dat een sporter er klaar voor is. De limb symmetry index geeft het verschil in gesprongen afstand op het geopereerde en niet-geopereerde been aan.

Ondanks het feit dat sporters deze hop testen halen op basis van die LSI-waarde, blijft de kans op een tweede vkb scheuring 6 keer zo groot als de kans op een eerste scheuring. Dit komt door het verschil in kinematica van de onderste extremiteiten, waarmee niet alleen de kinematica van het gereconstrueerde been bedoeld wordt. Het niet-geopereerde been kan namelijk ook aangedaan zijn door de lange periode van inactiviteit na de reconstructie. Deze kinematische verschillen zorgen voor een verhoogde kans op een tweede vkb-scheuring en daarom is het belangrijk dat dit onderzocht wordt.

Het hoofddoel van deze scriptie was dan ook: onderzoeken of het analyseren van de kinematica van de onderste extremiteiten extra waarde gaf aan de al bestaande 'return to sport' testen in de vkb-revalidatie. Twee criteria zijn opgesteld om deze analyse mogelijk te maken, namelijk: een LSI-criterium en een normatieve data criterium voor de kinematica van de onderste extremiteiten. Hiervoor zijn eerst 40 gezonde sporters (zonder blessures) gemeten om als controlegroep te functioneren bij het bepalen van deze LSI en normatieve data criteria. The Xsens MVN Awinda is gebruikt om de heup- en kniekinematica te verkrijgen op initial contact (het eerste moment dat de voet de grond raakt) en 40ms na initial contact tijdens de triple hop test en de triple crossover hop test.

De resultaten van dit onderzoek laten zien dat ook de sporters zonder blessures significante verschillen vertonen in de kinematica van beide benen. Deze verschillen zijn gebruikt om een LSI-criterium op te stellen voor heup- en kniebewegingen apart. De exacte heup- en kniehoeken zijn gebruikt om een criterium op te stellen gebaseerd op normatieve waarden. Beide criteria zijn gebruikt om te kijken hoe een sporter met een vkb-reconstructie presteert t.o.v. zijn/haar controlegroep. Resultaten tonen aan dat sporters met een vkb-reconstructie het overgrote deel van de opgestelde kinematica criteria behalen nadat zij de criteria voor afstand al behaald hadden.

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List of abbreviations

ACL	= Anterior cruciate ligament
ACL-R	= Anterior cruciate ligament reconstruction
HD	= High definition
Hz	= Hertz
IC	= Initial contact
LESS	= Landing Error Scoring System
LSI	= Limb symmetry index
MTw	= Motion tracker wireless
N, *n*	= Capitalised *N* for the total sample size, lowercase *n* for the size of a particular group
SD	= Standard deviation
SEM	= Standard error of measurement
THUAS	= The Hague University of Applied Sciences
TLH	= Triple single-leg hop for distance
TLCH	= Triple single-leg crossover hop for distance

1. Introduction

A rupture of the anterior cruciate ligament (ACL) is one of the most common sports injuries worldwide[1,2], and also one of the most devastating knee injury[3]. Not only is the recovery time long, the majority of people who suffer an ACL injury have many long-term knee symptoms that affect their quality of life[4,5]. These patients maintain good, but definitely not normal knee function while over 60% of the patients will develop knee osteoarthritis over the years[4-6]. The incidence rate for ACL ruptures in the Netherlands is not known, but the estimate is 6000 per year[7]. The ACL runs diagonally across the centre of the knee and mainly provides rotational stability to the knee joint and prevents the tibia from sliding out in front of the femur (anterior instability)[8]. An ACL injury happens mostly to young athletes (aged 14 - 40 years) who participate in landing, cutting and pivoting sports with fast decelerations[7,9-11], while around 70% of the ACL injuries result from a 'non-contact' mechanism[12]. Non-contact is defined by Marshall et al. as "Forces applied to the knee at the time of injury resulted from the athlete's own movements that did not involve contact with another athlete or objects" [13].

Rehabilitation after an ACL rupture is prolonged and intensive, and is needed to restore the knee function, strength and stability as it was prior to the injury[14]. Most of the time, an ACL reconstruction is seen as a golden standard of treatment to gain full recovery, while rehab alone might not be enough to prevent instability[15]. This is especially true for young athletes who want to return to sport at the high levels they were previously capable of. However, even with the ACL reconstruction, there is no certainty that someone can return to sports safely and without any risks of a future subsequent ACL injury[16]. Female athletes have the highest incidence of a subsequent ACL injury to the contralateral knee. Athletes between 14-19 years old have the highest ACL injury rate to either knee, which is also associated with higher levels of activity[17,18]. Estimates of the likelihood that an athlete will incur a subsequent ACL injury range between 3%[19] and 12%[20] to 30%[21]. Due to the high subsequent injury rate, it is important to make sure an athlete is fully ready to return to sports.

B&B Healthcare is a professional physiotherapy clinic in the Hague, specialized in physical therapy, rehabilitation of top-class athletes. One of the most frequently occurring knee injury they come across is an ACL injury. Their current ACL rehabilitation program is based on the Melbourne ACL Rehabilitation Guide 2.0[22] and consists of 5 phases and one preoperative phase. Phase 1 and 2 are spread over the first 6 weeks after surgery. The athlete will walk with crutches for the most part of these 2 phases. Phase 2 and 3 (week 2-14) are the phases in which the athlete starts to gain more strength. Starting to gain strength can already begin when an athlete is still walking on crutches. The last 2 phases, phase 4 and 5, start after approximately 14 weeks and takes place until the athlete is ready to return to sport.

Phase 5 of the rehabilitation program is called the return to sport phase[23]. 81% of the athletes who suffered an ACL injury return to regular sport and only 55% of the athletes return to competitive sports[24]. The decision whether an athlete is ready to return to sport depends on some psychological and physical tests. The physical tests at B&B Healthcare are focused on strength, balance, landing and agility work. Some more specific names of the test they do are: star excursion balance test, Y-balance test, single hop test, triple hop test, triple crossover hop test, side hop test, straight leg raise test and some sport-specific tests (Appendix I). The outcomes of these tests are based upon the Limb Symmetry Index (LSI; describes the symmetry between the involved and non-involved leg) for distance, time or number of jumps, where an LSI > 90% indicates an athlete's readiness to return to pivoting sports (sports with the most risks)[25-27]. Another test that is used worldwide to evaluate return to sport possibilities, is the Landing Error Scoring System (LESS). The LESS-test is an assessment tool for identifying potential risk of an ACL injury during a jump-landing manoeuvre where a score < 5 indicates an athlete's readiness[28,29].

Despite the fact that athletes can pass these tests based on the LSI (for distance, time or number of jumps) and LESS criteria, it does not indicate that there is no risk for future subsequent ACL injury[30]. The incidence rate of a subsequent ACL injury, compared to an initial ACL injury, is 6 times as high[31]. One of the things that preserve the high injury risk is the fact that an ACL injury results in joint specific, bilateral changes of the lower extremity kinematics[32], while the non-injured leg is also affected due to the long period of inactivity after reconstruction and therefore is not the best comparison to use for the LSI[32,33]. Another continuing risk factors (not considering intrinsic risk factors[34,35]), even though an athlete passed the return to sport tests, is that the side-to-side lower extremity kinematics are not similar[36-39]. Differences in the side-to-side kinematics during landing manoeuvres is also something that can increase the risk of an ACL injury and should be minimized prior to returning to sports[40]. Athletes who aren't matured yet (under 19 years old), demonstrate different kinematics then matured athletes in both female and male[41-43], which can explain the high ACL Injury rate for athletes younger than 19[17,18]. Female athletes are even more at risk (ACL injuries occur 4 to 6 times more often in females than in males)[11,44-46]. Malinzak et al. states that female athletes have specific knee motion patterns that more frequently brings them close to certain body positions in which non-contact ACL injuries might occur[46]. In addition, the female's anatomy, strength and hormones play an important part in their higher injury risk[47-50].

Butler et al. states that landing mechanics do not normalize over time compared to the non-injured leg. Limb asymmetries present 6 months after surgery, continued to exist at 12 months. These side-to-side kinematic differences in the lower extremities will place the athlete at a higher risk for an ACL injury. The finding of their study highlights the need for additional assessment of these side-to-side differences of the lower extremity kinematics during different return to sport tests, and so reduce the risk for a subsequent ACL injury[51]. The main question of this study is if analysing the lower extremity kinematic symmetry will add value to the current testing program at B&B Healthcare (only for the triple hop test and the triple crossover hop test). To answer the main question, 2 sub questions needed to be answered first. It is important to know which kinematics should be looked at during the return to sport tests (question 1), and what criteria should be used to analyse the ACL-R subjects (question 2). The general approach to conduct this thesis is to first find the kinematics that should be analysed, followed by setting kinematic criteria based on a self-created healthy peers database. This will lead to applying the found kinematic criteria to see if subjects with an ACL reconstruction meet these criteria.

2. Objectives

Side-to-side kinematic differences in the lower extremities places the athlete at a higher risk for an ACL injury. There is a need for additional assessment of these side-to-side differences of the lower extremity kinematics before athletes return to sport, and to reduce the risk for a subsequent ACL injury. Therefore:

- **Objective 1:** Determine which kinematics are important to analyse relative to the kinematic risk factor for a subsequent ACL rupture (chapter 3).
- **Objective 2:** Create lower extremity kinematic criteria based on the kinematics of healthy athletes (chapter 4).

With the found LSI and normative data criteria from objective 2, athletes who suffered from an ACL injury and already returned to sport can be tested to see if they differ from healthy subjects like literature suggest. Therefore:

- **Objective 3:** Measure athletes with an ACL reconstruction, who already returned to their sport, to see if their lower extremity kinematics differ from the lower extremity kinematics from their peers during the triple hop test and the triple crossover hop test, based on the created lower extremity kinematic criteria (chapters 5 and 6).

3. The most important kinematics of the lower extremities

3.1 Kinematics of the lower extremities during an ACL injury

3.1.1 Mechanism of a non-contact ACL injury

ACL injuries most commonly result from a non-contact mechanism and occur during cutting or 1-legged landing manoeuvres. A lot of researchers analysed videotapes from moments when an ACL injury occurred[15,52-59]. The kinematics of the knee are quite consistent in each case: relatively straight and in a neutral ab-/adduction position at initial contact (IC) with a rapid increase of flexion and abduction in the first 40ms after IC; externally rotated (tibia relative to femur) at IC but abruptly rotated internally during the first 40ms to change right back into external rotation after those first 40ms[19]. The straight knee landing is discussed regularly as a major cause for ACL injury[15,44,53-56.] A lot of studies also point a 'valgus collapse' as the mechanism for the injury. A valgus collapse is when the knee collapses medially due to excessive abduction and either internal or external rotation of the knee combined with internal rotation of the hip[15,53-57]. It has been agreed upon that a non-contact ACL injury happens right after IC (first 40-80ms).

3.1.2 Kinematic risk factors for a non-contact ACL injury

A non-contact ACL injury is most likely to happen immediately after IC with an almost straight, excessively abducted and rotated knee (both exo- and endorotation). Some articles also suggest it is due to flexion, abduction and rotation of the hip and ankle plantar-/dorsiflexion. A literature review was conducted as described in Figure 1, to find the kinematic risk factors for a non-contact ACL injury.

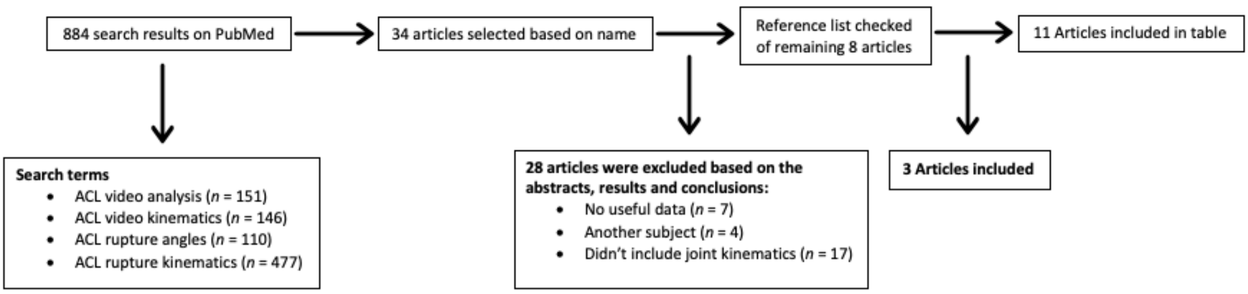

Figure 1 - Flow of information through the different phases of finding useful articles

As shown in Table 1, knee kinematics are the most important, in combination with low (<30°) hip flexion angles[60]. Most articles discuss landing and cutting manoeuvres, while Waldén et al.[56] and Cochrane et al.[15] only discuss sidestep cutting. Boden et al.[54], Hewett et al.[61] and Krosshaug et al.[62] only discussed landing manoeuvres. Koga et al.[63] were the first ones to quantify ankle joint motions in real ACL injury situations. They stated that the anterior and lateral foot placement in ACL injury situations were not different from what can be expected in non-injury game situations. Therefore, ankle kinematics doesn't indicate a higher risk for ACL injury, and they do not need to be looked at analysing the lower extremity kinematics. For both knee and hip kinematics, the rapid and abrupt change from IC to 40ms after IC is the most risky part and describes the most about individual risks[52,32,62,64]. Also, the kinematics that are similar to the kinematics of a 'valgus collapse' (internal rotation of the hip, abduction of the knee and external rotation of the knee) can be a risk factor if they are all present at the same time.

TABLE 1

Kinematic risk values for a non-contact ACL injury$^{\alpha}$

Article	Motion	Hip		Knee		Ankle	
		IC (mean)	40ms (mean)	IC (mean)	40ms (mean)	IC (mean)	40ms (mean)
Boden (2009)[54]	Fl/Ex	Increase of 19°		< 20°	> 30°	± -10°	± -10°
	Ab/Ad	-	-	± 5°	> 15°	-	-
Cochrane (2007)[15]	Fl/Ex	-	-	< 30°	-	-	-
Hewett (2005)[61]	Ab/Ad	-	-	> 5°	> 10°	-	-
Hewett (2009)[57]	Ab/Ad	-	-	F ± 10° M ± 5°	F > 15° M > 10°	-	-
Koga (2010)[52]	Fl/Ex	-	-	< 30°	> 40°	-	-
	Ab/Ad	-	-	± 0°	> 10°	-	-
	In/Ex R	-	-	± -5°	± 10°	-	-
Koga (2017)[63]	Fl/Ex	± 50°	± 50°	-	-	± 2°	± 12°
	Ab/Ad	± 20°	± 27°	-	-	± 7°	± 20°
	In/Ex R	± 30°	± 30°	-	-	± -5°	± 8°
Krosshaug (2007)[53]	Fl/Ex	< 30°	< 30°	< 30°	< 30°	-	-
Krosshaug (2007)[62]	Fl/Ex	< 30°	> 30°	< 20°	> 30°	-	-
	Ab/Ad	± 20°	± 20°	± 0°	> 15°	-	-
	In/Ex R	> 15°	> 10	± 0°	± 10°	-	-
Montgomery (2018)[59]	Fl/Ex	-	-	< 20°	-	± 10°	-
Olsen (2004)[55]	Fl/Ex	-	-	< 30°	-	-	-
	Ab/Ad	-	-	> 15°	-	-	-
	In/Ex R	-	-	-10 -> 10	-	-	-
Waldén (2015)[56]	Fl/Ex	< 40°	-	< 30°	-	-	-

$^{\alpha}$ Partially based on Carlson et al. (2016)[58]. Fl/Ex: flexion(+)/extension(-); Ab/Ad: abduction(+)/adduction(-); In/Ex R: internal(+)/external(-) rotation; IC: initial contact; 40ms: 40ms after IC.

3.1.3 Is the LSI for distance criterion sufficient to declare an athlete's readiness?

Despite the fact that athletes can pass the hop tests based on the LSI and LESS criteria, it does not indicate that there is no risk for future subsequent ACL injury[30]. The incidence rate of a subsequent ACL injury, compared to an initial ACL injury, is 6 times as high[31]. One of the things that preserve the high injury risk is the fact that an ACL injury result in joint specific, bilateral changes of the lower extremity kinematics[32], while the non-injured leg is also affected due to the long period of inactivity after reconstruction. Therefore, the non-injured leg is not the best comparison to use in the LSI calculation to determine readiness to return to sport[32,33]. Athletes demonstrated significant and clinically relevant deficits in performance for both legs compared to normative data from healthy athletes. Athletes after ACL reconstruction perform significantly less on the triple single-leg hop test (TLH) and the triple single-leg crossover hop test (TLCH) when compared to age and sex matched athletes. The normative data is shown in Table 2[65,66].

TABLE 2

Normative data (in cm) for hop tests as found in literature$^{\alpha}$

	Boys 14-19	**Girls 14-19**	**Men 20-40**	**Women 20-40**	**SEM$^{\beta}$**
TLH (cm)	583 ± 72	428 ± 54	632 ± 72	470 ± 53	15.44 – 23.18
TLCH (cm)	522 ± 77	375 ± 60	570 ± 75	406 ± 54	15.95 – 21.16

$^{\alpha}$ Represent the statistical analysis (mean ± SD) of the normative data for each group, based on the studies of Gokeler et al.[65] and Myers et al.[66]**;** TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test.
$^{\beta}$ SEM = Standard error of measurements .

Another continuing risk factor, even though an athlete passed the return to sport tests, are the different side-to-side kinematics[36-39]. Differences in side-to-side kinematics of the lower extremities during landing manoeuvres is also something that can increase the risk of an ACL injury and should be minimized prior to returning to sports[40]. Both female and male athletes who are still maturing (under 19 years old), demonstrate different kinematics then matured athletes[41-43], which can explain the high ACL Injury rate for athletes younger than 19[17,18].

3.2 Conclusion on the most important kinematics

The kinematics that will be included in this study are: hip flexion-extension, hip abduction-adduction, hip rotation, knee flexion-extension, knee abduction-adduction and knee rotation. Ankle kinematics are excluded while they do not indicate a higher risk for an ACL injury. The chosen kinematics will be evaluated at IC and 40ms after IC, while most non-contact ACL injuries happen around those moments.

4. The lower extremity kinematic criteria

4.1 Introduction

Kinematics of the lower extremities play an important part in the high incidence rate for a subsequent ACL rupture. Therefore, these kinematics should be examined. Before the kinematics of athletes with an ACL reconstruction can be assessed, criteria should be created with help of healthy athletes, while there is not an already existing kinematic database available.

Just looking at the already existing criteria for the TLH and TLCH, there are 2 criteria that are only distance based. The first distance-based criterion is LSI > 90% shows readiness to return to sport, while the second distance-based criterion uses normative data to see if athletes that pass the first criterion (LSI > 90%) are not holding back on their hops. When an athlete is not giving his/her all while hopping, the LSI criterion can be met more easily. An athlete can estimate how far he/she can hop on both legs and then make sure that the final landing on both legs is in close reach from each other. The normative data criteria that tells how far an athlete should jump compared to a healthy peers database is a more strict criterion then just the LSI > 90%. Looking at possible kinematic criteria, it is a good idea to keep the 2 criteria that are used for the jumped distance, and then create new ones based on kinematics. This means that there will be an LSI criterion for kinematics that tells what the symmetry between the side-to-side kinematics should be, and a normative kinematic data criterion that tells the kinematic ranges where the kinematics of the ACL-R subject should fall in. The main purpose for this chapter is to create both kinematic criteria based on healthy peers.

4.2 Method

4.2.1 Subjects

While women display different kinematics than men, and kinematics can change during maturation[11,41-46], it is important to create multiple criteria so ACL-R subjects can be compared to age and sex-matched peers. In total, 40 healthy athletes participated in this study (*N*=40). They were divided in four control groups (each *n*=10) based on age and gender with group 1: boys 14-19 years old, group 2: girls 14-19 years old, group 3: women 20-40 years old, and group 4: men 20-40 years old. In Table 3, a summary of the subject characteristics is shown. The characteristics of every individual subject can be found in Appendix II. Subjects were excluded from the study if they suffered from any current injury to the lower extremities which could have influenced the outcome negatively. They were also excluded if they did not participate in a sport that involves landing, cutting, and pivoting tasks with fast deceleration. All subjects were asked to wear short sleeved shirts, shorts, and athletic shoes with laces. After informed consent, the age and weight were recorded. Body dimensions such as body height, foot length, shoulder height, shoulder width, arm span, hip height, hip width, knee height, and ankle height were recorded as described in the user manual from Xsens[67]. All subjects of the same group were measured by the same examiner to eliminate inter-observer measurement errors.

TABLE 3
Summary of Subject Characteristics$^{\alpha}$

	Group 1	**Group 2**	**Group 3**	**Group 4**
No. subjects	10	10	10	10
Gender	Male	Female	Female	Male
Group	Control	Control	Control	Control
Age (yrs)	16.7 ± 1.3	14.6 ± 0.97	26.6 ± 4.3	26.20 ± 4.73
Height (cm)	184.6 ± 6.4	167.2 ± 5.78	172.6 ± 6.3	187.10 ± 5.57
Weight (kgs)	74.5 ± 9.5	55.02 ± 5.13	72.7 ± 10.8	83.66 ± 10.87

$^{\alpha}$ Represent the statistical analysis (mean ± SD) of the subject characteristics based on gender, group, age, height and weight. Extended Table of subject characteristics can be found in Appendix II.

4.2.2 Protocol for testing

Included in this study were 2 hop tests: triple single-leg hop test (TLH) and triple single-leg crossover hop test (TLCH). All testing was done in an indoor sports complex in the Hague during handball training sessions over a time period of 6 weeks. The tests were set up as shown in the drawing in Appendix III on the side-line of the handball field.

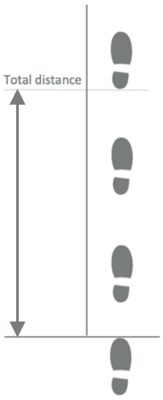

Figure 2 – TLH test

4.2.2.1 Triple single-leg hop for distance

The TLH test (Figure 2) is designed to test both strength and confidence in the reconstructed leg[68]. The test consists of the subjects standing on one leg, hopping forward as far as possible, and safely landing on the same leg after 3 consecutive jumps. The subject needed to hold the final landing for 2 seconds while the total forward hop distance was recorded. This test was performed 3 times on each leg, where the first limb to be tested was randomly chosen. The mean distance of all 3 tests were calculated to be used in the LSI calculation later on (*chapter 4.2.3.3*) .

4.2.2.2 Triple single-leg crossover hop for distance

During the TLCH test (Figure 3), the subjects hop forward as far as possible and lands safely on the same foot but on the opposite side of a line medial to the leg they are hopping on. Subjects were instructed to immediately redirect into 2 subsequent hops (forward-directed) crossing over the midline with each hop. The final landing was needed to be held for 2 seconds while the total forward hop distance was recorded. The test was performed 3 times on each leg, where the first limb to be tested was randomly chosen. The mean distance of all 3 tests were calculated to be used in the LSI calculation later on (*chapter 4.2.3.3*).

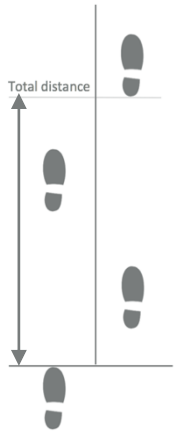

Figure 3 – TLCH test

4.2.3 Measurement set-up

Before testing, subjects were equipped with the Xsens system (Awinda, 100Hz; Xsens technologies BV, Enschede, The Netherlands), composed of 8 MTw and positioned bilaterally on the feet, shanks, mid-thighs, and one on the pelvis and sternum as described by Xsens (Lower body + sternum protocol; Figure 4)[69]. The chosen kinematics were evaluated for both tests at IC and 40ms after IC with the use of the MVN Analyzer 2019 (Xsens technologies, Enschede, The Netherlands). While only 8 MTw were used, the sample rate was100 Hz. Therefore, 40ms after IC was the 4th frame after IC.

The Xsens website itself states that the Xsens MTw Awinda is validated[70]. There are also some other studies that validated, and tested the reliability of the Xsens products, which concluded that the angles calculated by Xsens were valid[71-76]. Xsens also used the flexion/extension axes as the first motion to be calculated in the Euler sequence to prevent gimbal lock from happening, which contributes to the validity[73].

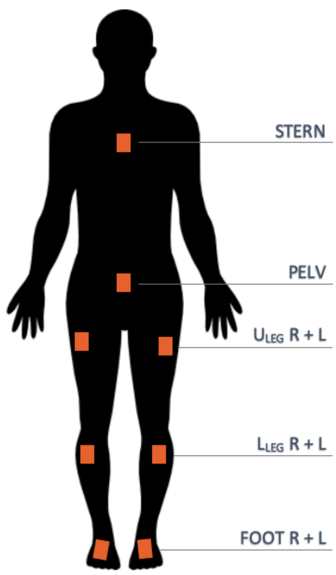

Figure 4 – Placement of the 8 MTw

A calibration of this software was needed to align all 8 MTw to the segments of the subject. The calibration was performed in a N-pose where the subjects stands upright with the feet parallel, one-foot width apart and the arms straight alongside the body with the thumbs forward. Before the start of every test, the subject was moved back to the origin (the place where the calibration started). Before exporting the data, a HD processing was done to obtain the highest quality of data.

4.2.4 Data analysis

4.2.4.1 Obtaining data

The joint angles were obtained from the *.mvnx* files with the use of MATLAB (MathWorks Inc., Natick, MA, USA). A self-written MARLAB script was used to find IC and 40ms after IC in the acceleration data and their corresponding joint angles, which were exported to Excel (Microsoft, 2016). Multiple research articles[77-81] stated that one accelerometer is enough to find IC, which is at the start of peak impact acceleration of the Z-axis according to Auvinet and Sinclair. Auvinet et al. mounted the accelerometer at the waist[79] and Sinclair et al. at the tibia[80]. Heiden et al. mounted the accelerometer at the ankle and found that IC took place at peak impact acceleration of the vertical axis (Z-axis)[81]. While Xsens needs one accelerometer on the foot, peak acceleration of the Z-axis of the foot MTw was used to determine IC. 40ms after IC was found 4 frames after the determined IC frame.

4.2.4.2 Calculating the LSI values

The most important outcome of this study was the LSI criterion for the lower extremity kinematics for all 4 of the control groups. The LSI percentages were found by using the found kinematic angles (*chapter 4.2.4.1*) for each subject, calculate the individual LSI percentage per joint motion, and then find the mean ± SD for each group with help from SPSS 25.0 (IBM Statistics, Chicago, IL, USA). For each joint motion, 9 kinematic angles were found per leg for each individual (1 kinematic angle per hop, 3 hops in one test, 3 tests in total) for which the mean was calculated. The leg with the largest jumping distance was named the dominant leg. The mean of the non-dominant leg was divided by the mean of the dominant leg and then multiplied by 100% (equation 1)[57,82].

$$LSI = \frac{Mean\ non - dominant\ leg}{Mean\ dominant\ leg} \times 100\% \quad (1)$$

While Xsens uses their own angles definition (pose during calibration is 0°), the obtained angles are both positive and negative which causes problems with calculating the LSI percentages (only for frontal and sagittal plane motions). To avoid this problem, the X-axis was rotated 90° to the left so that the new axis runs from 0° to 180° (instead of -90° to 90°) and all angles will be positive values. Due to the rotated axis, 90° was needed to be added to the joint angles of the frontal and sagittal plane (Figure 5). From this moment on, all mean joint angles shown for ab-/adduction and rotation are 90° higher than the original data recorded from Xsens.

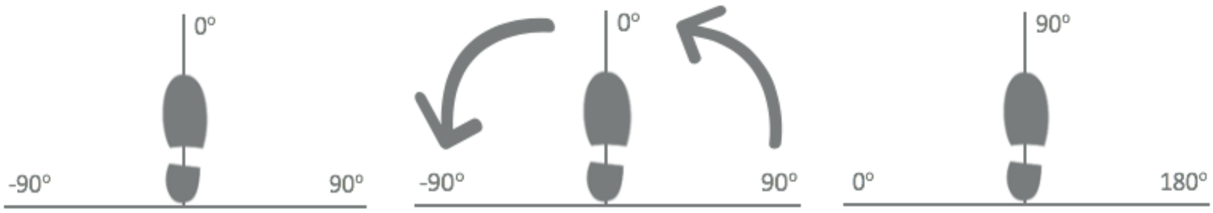

Figure 5 – Explaining the way the angles are changed (+90°). The axis rotates 90° to the left so no negative values will be used in the LSI equation (equation 1).

4.2.5 Statistical analysis of the lower extremity kinematics

The first kinematic analysis that was done, was comparing the joint angles of the dominant leg with the non-dominant leg for all joint motions (ab-/adduction, rotation, and flex-/extension for both hip and knee) individually with multiple 'paired t-tests'. After, multiple one-way ANOVA's were conducted to compare the angles per joint motion at IC with the angles per joint motion at 40ms, the angles of the TLH with the angles of the TLCH, and the angles between the four different control groups. When no significant differences were found, all angles for each joint motion, test, and moment (IC and 40ms) could be combined to one final normative kinematic data criterion, which is the mean angle plus and minus one standard deviation (68 percent confidence interval). While significant differences were found, multiple normative kinematic data criteria should be created.

The last kinematic analysis was finding an LSI value that could be used to see if athletes with an ACL reconstruction show greater side-to-side differences than healthy subjects. The found LSI percentages per individual (*chapter 4.2.4.2*) were combined to find a group, tests, moment, and leg specific mean±SD percentage. A MANOVA was conducted to compare the LSI percentages between the different groups for the six different joint motions and both tests. Again, if no significant differences were found, all LSI percentages for each joint motion, test, and moment (IC and 40ms) could be combined to one final kinematic LSI criterion. If significant differences were found, multiple kinematic LSI data criteria should be created.

4.3 Results

4.3.1 Normative kinematic data criteria

The mean ± SD angles for all joint motions and all control groups are shown in Appendix IV. Multiple paired t-test were conducted to compare the angles of the non-dominant leg with the angles of the dominant leg for all joint motions and all control groups. Multiple significant differences ($P > .05$) were found (which are also shown in Appendix IV), which denotes that the angles of the dominant and non-dominant leg cannot be combined. After, multiple one-way ANOVA's were conducted to compare the joint angles at IC with the joint angles at 40ms, the angles of the TLH with the angles of the TLCH, and the angles between the four different control groups, which all showed significant differences ($P > .05$) and, therefore, could not be combined.

Since the kinematic angles described above cannot be combined, normative kinematic criteria were made for both legs (dominant and non-dominant), both tests (TLH and TLCH), both moments (IC and 40ms) and all 4 control groups separately. The normative kinematic criteria are based on the found kinematic angles plus and minus one standard deviation (range), shown in Table 4 (for IC) and Table 5 (for 40ms).

Since the axes of the frontal- and sagittal plane are rotated 90° to the left (Figure 5), the angles in Tables 4 and 5 are defined as followed:

- Hip abduction = Above 90°
- Hip adduction = Below 90°
- Hip internal rotation = Above 90°
- Hip external rotation = Below 90°
- Hip flexion = Above 0°
- Hip extension = Below 0°
- Knee abduction = Above 90°
- Knee adduction = Below 90°
- Knee internal rotation = Above 90°
- Knee external rotation = Below 90°
- Knee flexion = Above 0°
- Knee extension = Below 0°

TABLE 4

Normative kinematic data ranges (minimum-maximum) at IC[α]

		Boys 14-19	Girls 14-19	Women 20-40	Men 20-40
TLH					
Hip ab-/adduction	Dominant leg (°)	82.50 – 101.70	85.56 – 99.60	81.94 – 97.98	92.67 – 103.39
	Non-dominant leg (°)	76.62 – 96.80	81.66 – 94.90	78.13 – 92.61	88.30 – 98.50
Hip rotation	Dominant leg (°)	82.06 – 97.38	83.42 – 94.48	83.14 – 94.24	85.14 – 99.26
	Non-dominant leg (°)	81.11 – 96.65	83.63 – 94.07	78.93 – 91.19	84.36 – 97.48
Hip flex-/extension	Dominant leg (°)	38.74 – 51.90	32.00 – 60.06	36.34 – 50.34	35.64 – 58.24
	Non-dominant leg (°)	44.92 – 59.32	35.31 – 66.43	39.83 – 54.67	41.04 – 64.60
Knee ab-/adduction	Dominant leg (°)	87.93 – 91.83	86.58 – 90.98	88.44 – 91.66	87.62 – 91.02
	Non-dominant leg (°)	88.65 – 92.37	87.59 – 92.07	88.50 – 92.06	87.70 – 92.40
Knee rotation	Dominant leg (°)	85.95 – 91.37	85.26 – 91.16	88.34 – 94.76	85.11 – 92.11
	Non-dominant leg (°)	88.46 – 94.96	87.86 – 93.32	88.45 – 96.51	88.08 – 94.68
Knee flex-/extension	Dominant leg (°)	17.80 – 32.10	17.04 – 31.16	15.35 – 32.65	17.72 – 34.88
	Non-dominant leg (°)	36.26 – 51.20	33.35 – 48.35	28.54 – 48.32	34.42 – 54.06
TLCH					
Hip ab-/adduction	Dominant leg (°)	89.87 – 100.11	90.66 – 105.30	86.23 – 99.21	85.67 – 103.79
	Non-dominant leg (°)	81.63 – 108.27	87.89 – 107.11	80.63 – 104.51	82.52 – 106.52
Hip rotation	Dominant leg (°)	85.63 – 102.95	86.55 – 95.05	86.78 – 98.22	86.34 – 97.28
	Non-dominant leg (°)	83.13 – 101.75	85.55 – 97.41	85.69 – 97.89	83.41 – 97.35
Hip flex-/extension	Dominant leg (°)	38.78 – 58.18	29.16 – 59.02	34.33 – 55.71	39.96 – 60.78
	Non-dominant leg (°)	18.36 – 69.14	19.43 – 62.67	16.85 – 61.35	20.86 – 70.40
Knee ab-/adduction	Dominant leg (°)	87.72 – 91.78	86.47 – 90.29	86.96 – 91.50	87.34 – 91.50
	Non-dominant leg (°)	85.37 – 92.07	85.16 – 95.70	84.80 – 92.66	85.07 – 95.73
Knee rotation	Dominant leg (°)	85.66 – 91.62	86.32 – 92.08	87.24 – 93.40	85.42 – 92.36
	Non-dominant leg (°)	85.75 – 93.75	86.76 – 96.84	86.63 – 96.39	85.66 – 97.38
Knee flex-/extension	Dominant leg (°)	16.19 – 36.79	18.63 – 34.19	17.68 – 31.20	16.49 – 35.95
	Non-dominant leg (°)	13.90 – 57.82	20.61 – 52.43	13.52 – 48.84	14.98 – 55.66

[α] TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; IC: Initial contact.

TABLE 5

Normative kinematic data ranges (minimum-maximum) at 40ms[α]

		Boys 14-19	Girls 14-19	Women 20-40	Men 20-40
TLH					
Hip ab-/adduction	Dominant leg (°)	86.06 – 106.30	90.07 – 103.81	88.23 – 101.15	93.63 – 108.47
	Non-dominant leg (°)	81.23 – 101.39	85.88 – 100.02	84.37 – 96.73	88.66 – 103.64
Hip rotation	Dominant leg (°)	82.81 – 102.03	87.23 – 98.97	81.79 – 97.83	86.16 – 102.42
	Non-dominant leg (°)	82.99 – 100.15	86.94 – 98.50	82.76 – 96.64	85.48 – 101.72
Hip flex-/extension	Dominant leg (°)	32.09 – 54.85	29.52 – 59.04	36.61 – 50.97	39.29 – 60.89
	Non-dominant leg (°)	38.13 – 61.99	33.73 – 66.35	40.22 – 56.24	44.34 – 67.94
Knee ab-/adduction	Dominant leg (°)	87.81 – 92.01	86.45 – 91.37	87.66 – 91.50	87.34 – 91.38
	Non-dominant leg (°)	87.50 – 92.38	87.27 – 91.17	86.54 – 92.02	87.49 – 92.45
Knee rotation	Dominant leg (°)	84.94 – 90.92	84.96 – 91.78	87.03 – 94.33	84.91 – 92.55
	Non-dominant leg (°)	87.79 – 95.13	87.48 – 92.96	89.24 – 96.90	88.54 – 95.38
Knee flex-/extension	Dominant leg (°)	17.39 – 35.13	18.32 – 30.94	16.26 – 34.30	16.80 – 37.04
	Non-dominant leg (°)	35.80 – 52.04	34.62 – 48.60	30.19 – 50.03	34.42 – 54.06
TLCH					
Hip ab-/adduction	Dominant leg (°)	87.74 – 102.60	89.79 – 104.81	82.64 – 100.66	86.04 – 105.42
	Non-dominant leg (°)	82.92 – 108.00	86.68 – 106.96	78.34 – 106.40	83.28 – 107.98
Hip rotation	Dominant leg (°)	83.98 – 103.16	88.22 – 99.20	86.33 – 102.37	86.42 – 97.02
	Non-dominant leg (°)	83.41 – 100.95	86.74 – 99.46	79.43 – 102.07	84.89 – 97.61
Hip flex-/extension	Dominant leg (°)	34.24 – 61.54	27.58 – 64.78	34.39 – 54.05	37.93 – 61.99
	Non-dominant leg (°)	18.36 – 69.14	18.38 – 68.96	11.98 – 63.00	22.57 – 69.35
Knee ab-/adduction	Dominant leg (°)	87.07 – 91.71	87.03 – 89.87	86.93 – 91.71	87.64 – 91.72
	Non-dominant leg (°)	86.91 – 93.35	85.37 – 96.15	81.25 – 94.49	86.95 – 95.65
Knee rotation	Dominant leg (°)	86.14 – 91.58	84.98 – 90.86	87.28 – 93.96	85.96 – 92.56
	Non-dominant leg (°)	87.67 – 94.69	87.01 – 97.23	82.37 – 98.09	88.21 – 97.55
Knee flex-/extension	Dominant leg (°)	18.90 – 36.64	18.42 – 34.84	18.97 – 32.05	19.04 – 38.62
	Non-dominant leg (°)	17.23 – 58.99	20.67 – 54.13	9.52 – 52.64	19.75 – 57.07

[α] TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; 40ms: 40ms after initial contact.

4.3.2 LSI for kinematics criteria

The mean ± SD for the kinematic-based LSI percentages per group and per joint motion are shown in Appendix V. A MANOVA was conducted to compare the LSI percentages between the different groups for the six different joint motions and both tests. Using Wilk's statistic, there were no significant differences between the LSI percentages of the groups for all joint motions at IC during the TLH ($P > .05$), at 40ms during the TLH ($P > .05$), at IC during the TLCH ($P > .05$) and at 40ms after IC during the TLCH ($P > .05$). No significant difference meant that the 4 different control groups could be combined to 1 bigger control group (*n*=40) for each joint motion. Multiple independent t-tests were conducted to see if there were significant differences between the kinematic angles at IC and 40ms. No significant differenced were found ($P > .05$), which meant that the angles from IC and 40ms could be combined.

TABLE 6

Final LSI percentages for kinematics$^{\alpha}$

	LSI (%)
Hip ab-/adduction	> 92.27
Hip rotation	> 94.05
Hip flex-/extension	> 96.31
Knee ab-/adduction	> 98.33
Knee rotation	> 98.11
Knee flex-/extension	> 96.03

$^{\alpha}$ Represent the final LSI percentages. LSI: Limb symmetry index.

Multiple paired T-tests were conducted to see if there were significant differences between the hop tests. No significant differences were found ($P > 0.05$), which meant that the LSI values for both hop tests could be combined. A one-way ANOVA was conducted to compare the LSI values between the different joint motions. Significant differences were found between all joint motions for both tests ($P < 0.05$), except for hip flexion/extension and knee flexion/extension ($P = 0.995$), and knee abduction/adduction and knee rotation ($P = 0.997$). Because of the significant differences that were found, the joint motions LSI percentages could not be combined. The final kinematic LSI criteria are shown in Table 6.

4.4 Conclusion on the kinematic criteria

Two different criteria for kinematics were created based on a healthy peers database. The first criterion is based on the kinematic ranges, which are different criteria for each joint motion, each control group, both legs (non-dominant and dominant), and both moments (IC and 40ms). The Normative kinematic data criteria are shown in Tables 4 and 5. The second criterion is based on an LSI percentage, which are different criteria for each joint motion. The final kinematic LSI criteria are shown in Table 6.

5. Implementing the kinematic criteria

5.1 Introduction

Kinematics of the lower extremities play an important part in the high incidence rate for a subsequent ACL rupture. These kinematics (knee and hip kinematics) should, therefore, be looked at with the use of kinematic criteria which are made in *chapter 5*. The first criterion is based on an LSI percentage, and the second criterion is based on the kinematic ranges. Athletes with an ACL injury will be assessed on the two created criteria to see how they perform compared to their healthy peers and if the analysis of the lower extremity kinematics should be implemented into the current return to sport tests.

5.2 Method

5.2.1 Subjects

A total of 13 athletes with ACL reconstruction (ACL-R group) participated in this study (*N* = 13). In Table 7, a summary of the subject characteristics is shown. The characteristics of every individual subject can be found in Appendix VI. Subjects of the ACL-R group were excluded from the study if they were not cleared to return to sport by a physical therapist. They were all asked to wear short sleeved shirts, shorts, and athletic shoes with laces. After informed consent, the age, weight, injured leg, and months after reconstruction were recorded. Body dimensions such as body height, foot length, shoulder height, shoulder width, arm span, hip height, hip width, knee height, and ankle height were recorded as described in the user manual from Xsens[67]. All subjects of the ACL-R group were measured by the same examiner to eliminate inter-observer measurement errors.

TABLE 7
Summary of Subject Characteristics$^{\alpha}$

	ACL-R group
No. subjects	13
Gender	MIxed
Age (yrs)	22.92 ± 4.21
Height (cm)	178.99 ± 8.51
Weight (kgs)	71.76 ± 7.13
Time (months)$^{\beta}$	40.62 ± 27.24

$^{\alpha}$ Represent the statistical analysis (mean ± SD) of the subject characteristics based on gender, group, age, height and weight. Extended Table of subject characteristics can be found in Appendix VI
$^{\beta}$ Time after reconstruction in months

5.2.2 Protocol for testing

Included in this study were the triple hop test and the triple crossover hop test. The testing of the ACL-R subjects was done exactly the same as the healthy athletes, described in *chapter 4.2.2*.

5.2.3 Data analysis

5.2.3.1 Measurement set-up

The measurement set-up for this study is exactly the same as the measurement set-up for creating the kinematic criteria, described in *chapter 4.2.3.1*.

5.2.3.3 Calculating the LSI values

The most important outcome of this study was the LSI criterion for the lower extremity kinematics for all 4 of the control groups. The LSI percentages were obtained by calculating the LSI percentage for all subjects separately and then find the mean. To calculate the LSI percentages for the hop test only, the average of the three-recorded trials for each limb was needed. The mean of the operated leg was divided by the mean of the non-operated leg and then multiplied by 100% (equation 2)[57,82].

$$LSI = \frac{Mean\ operated\ leg}{Mean\ non\text{-}operated\ leg} \times 100\% \qquad (2)$$

While Xsens uses their own angles definition (pose during calibration is 0°), the obtained angles are both positive and negative which caused problems with the LSI calculation (only for frontal and sagittal plane motions). *Chapter 4.2.3.3* explains what was done to avoid the both positive and negative angles problem.

5.2.4 Statistical analysis

5.2.4.1 Jumped distances

The first analysis was looking what percentage of the ACL-R group passed the tests based on the LSI > 90% and normative data criteria, both for distance, and which individuals passed these tests based on those criteria. When a subject did not pass the distance-based LSI criteria, he/she was excluded from the rest of the study while this study focusses on athletes with ACL-R reconstruction which passed the distance-based criteria.

5.2.4.2 Kinematics

The kinematic criteria made in *chapter 5* was used to test the subjects of the ACL-R group. First, each individual subject was compared to the created kinematic LSI criteria (Table 4), and after compared to the created normative kinematic data criteria (Tables 5 and 6). An overview of which subjects met the criteria, and which did not was made. Another analysis that was made, was looking at which joint motion criterion was failed the most, and which was passed the most.

5.3 Results

5.3.1 Comparison with the distance criteria

Which individuals of the ACL-R group did or did not pass the TLH and TLCH based on distance are shown in Table 8. Appendix VII shows all the individual recorded data for each individual of the ACL-R group. In total, 84.5% (*n*=11) passed the TLH based on the LSI criterion, 38.5% (*n*=5) passed the TLH based on the normative data criterion, 84.5% (*n*=11) passed the TLCH based on the LSI criterion, and 53.8% (*n*=7) passed the TLCH based on the normative data criterion. Subjects 41 and 51 did not pass any criteria and were excluded from the rest of the study.

For the ACL-R group, the normative data criterion for distance is stricter than the LSI criterion for distance. This is also true for the healthy peers (Appendix VIII; Appendix IX for individual recorded data for each individual of the control groups).

TABLE 8
ACL-R group compared to both distance-based criteria[α]

	TLH		TLCH	
	LSI > 90%	Norm. data	LSI > 90%	Norm. data
Subject 41	✗	✗	✗	✗
Subject 42	✓	✓	✓	✓
Subject 43	✓	✓	✓	✓
Subject 44	✓	✗	✓	✗
Subject 45	✓	✗	✓	✗
Subject 46	✓	✗	✓	✓
Subject 47	✓	✗	✓	✓
Subject 48	✓	✓	✓	✓
Subject 49	✓	✗	✓	✗
Subject 50	✓	✗	✓	✗
Subject 51	✗	✗	✗	✗
Subject 52	✓	✓	✓	✓
Subject 53	✓	✓	✓	✓
% passed	84.5%	38.5%	84.5%	53.8%

[α] Overview of which individuals passed the tests based on both distance criteria (LSI > 90% and normative data (norm. data); ✓: passed the test; ✗: did not pass the test; TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; LSI: Limb symmetry index.

5.3.2 Comparison with the kinematic criteria

5.3.2.1 How many of the kinematic criteria were passed?

The overall performance of all 11 ACL-R subjects that passed the tests based on the distance criteria, are shown in Figure 6 (TLH IC), Figure 7 (TLH 40ms), Figure 8 (TLCH IC), and Figure 9 (TLCH 40ms). Which criteria each individual passed is shown in Appendix X for the kinematic LSI percentages and in Appendix XI for the normative kinematic data.

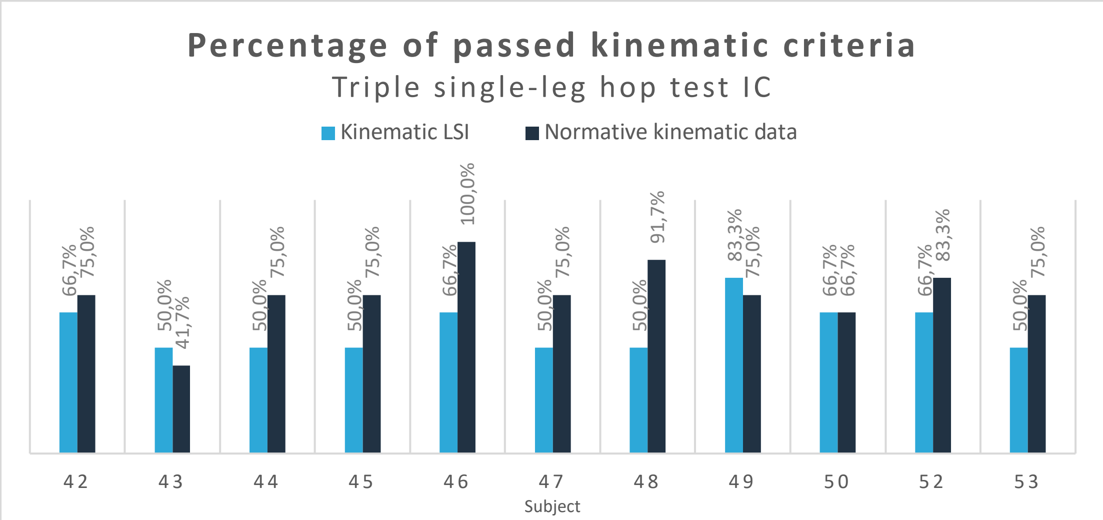

Figure 6 – Percentage of passed kinematic criteria for each individual ACL-R subject during the triple single-leg hop test at IC. IC: initial contact; LSI: limb symmetry index.

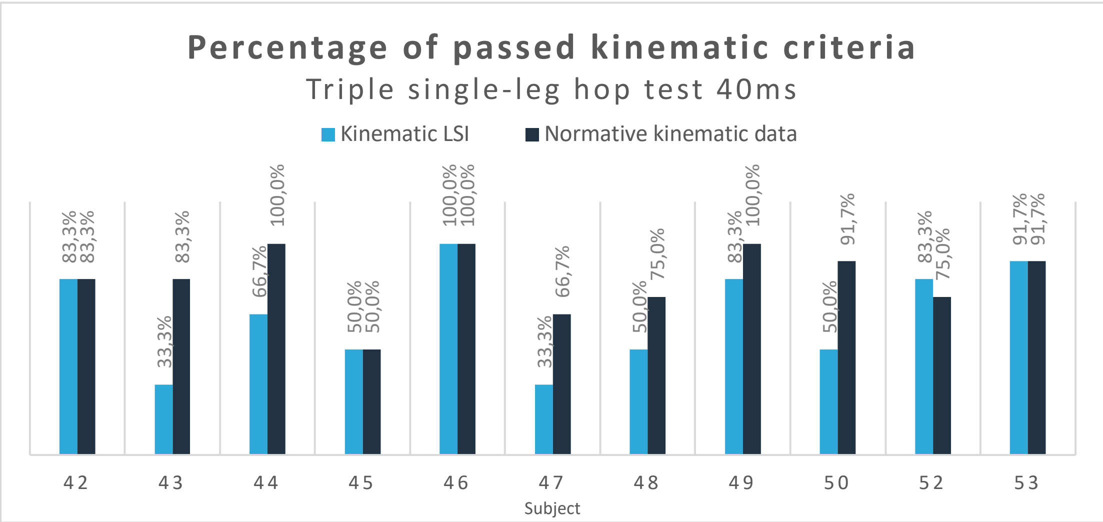

Figure 7 – Percentage of passed kinematic criteria for each individual ACL-R subject during the triple single-leg hop test at 40ms. 40ms: 40ms after initial contact; LSI: limb symmetry index.

The mean percentage of passed kinematic criteria per individual for the whole ACL-R group during the TLH is 59.1% for the kinematic LSI criteria and 75.8% for the normative kinematic data criteria at IC, and 62.1% for the kinematic LSI criteria and 83.3% for the normative kinematic data criteria at 40ms.

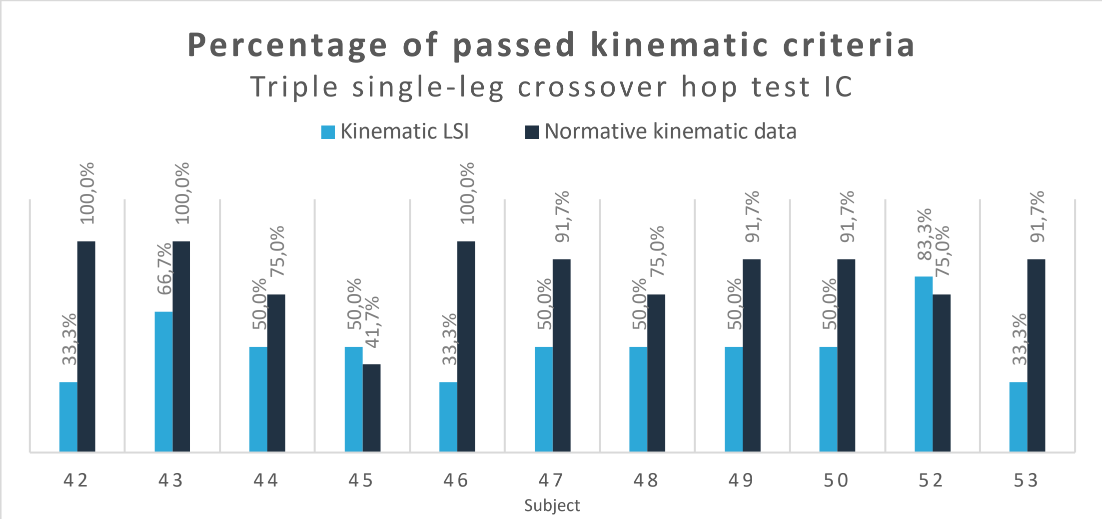

Figure 8 – Percentage of passed kinematic criteria for each individual ACL-R subject during the triple single-leg crossover hop test at IC. IC: initial contact; LSI: limb symmetry index.

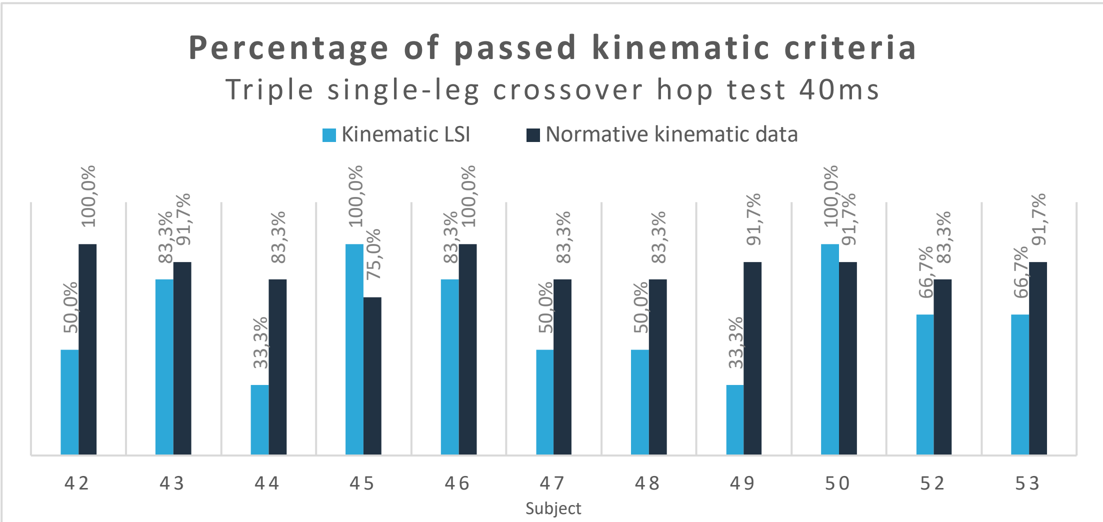

Figure 9 – Percentage of passed kinematic criteria for each individual ACL-R subject during the triple single-leg crossover hop test at 40ms. 40ms: 40ms after initial contact; LSI: limb symmetry index.

The mean percentage of passed kinematic criteria per individual for the whole ACL-R group during the TLCH is 54.5% for the kinematic LSI criteria and 87.1% for the normative kinematic data criteria at IC, and 65.1% for the kinematic LSI criteria and 89.4% for the normative kinematic data criteria at 40ms.

TABLE 9
Total percentages of passed kinematic criteria of the ACL-R group$^{\alpha}$

	Kinematic LSI criteria		**Normative kinematic data criteria**	
	IC	40ms	IC	40ms
TLH	59.1%	62.4%	75.8%	83.3%
TLCH	50.0%	65.1%	87.1%	89.4%

$^{\alpha}$Overview of the total passed kinematic criteria in %. ACL-R: ACL reconstruction; LSI: limb symmetry index.

When looking at the total amount of passed kinematic criteria for the whole ACL-R group combined, 66 criteria could be passed for the kinematic LSI at IC and 40ms separately for each test, and 132 criteria for the normative kinematic data could be passed at IC and 40ms separately for each test. The total percentages of passed criteria for the ACL-R group are shown in Table 9. A future individual ACL-R subject needs to pass (higher or equal to) all percentages shown in Table 9 to pass the overall kinematic criteria.

5.3.2.2 How often did the ACL-R subjects pass each specific kinematic criterion?

Each subject was tested based on 11 kinematic LSI criteria at both moments and each test, and 22 normative kinematic data criteria at both moments and each test. How many of those criteria each subject individually passed is shown in the Figures 6, 7, 8, and 9. These percentages does not show which criteria, specifically which joint motion, was passed the most (or the least). These percentages are shown in Figure 10 (TLH IC), Figure 11 (TLH 40ms), Figure 12 (TLCH IC), and Figure 13 (TLCH 40ms). An overview of the percentages of all joint motions, tests, and moments is shown in Table 10.

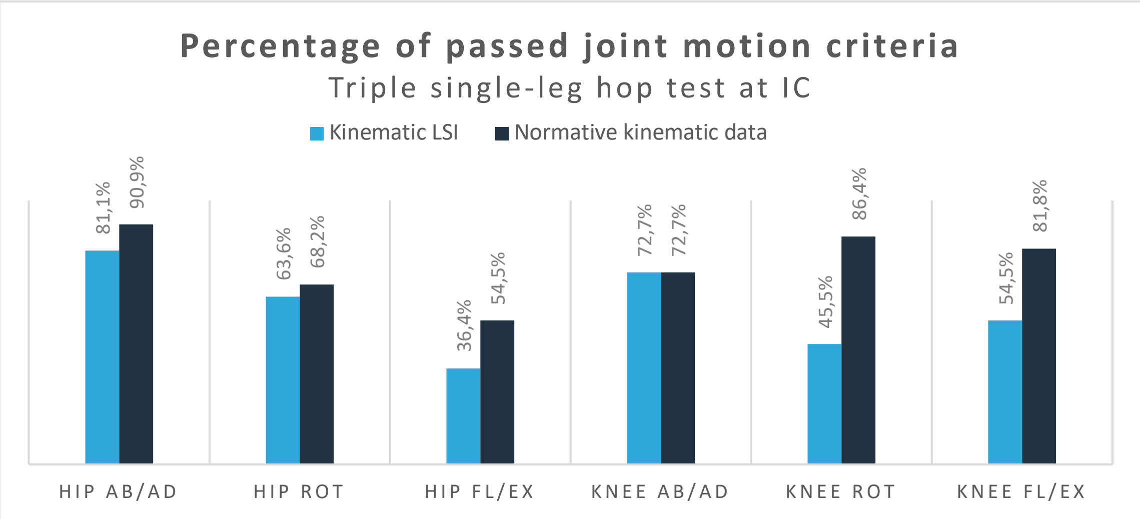

Figure 10 – Percentage of passed kinematic criteria per joint motion for the whole ACL-R group, during the TLH test at IC. AB/AD: abduction/adduction; ROT: internal/external rotation; FL/EX: flexion/extension; IC: initial contact; LSI: limb symmetry index.

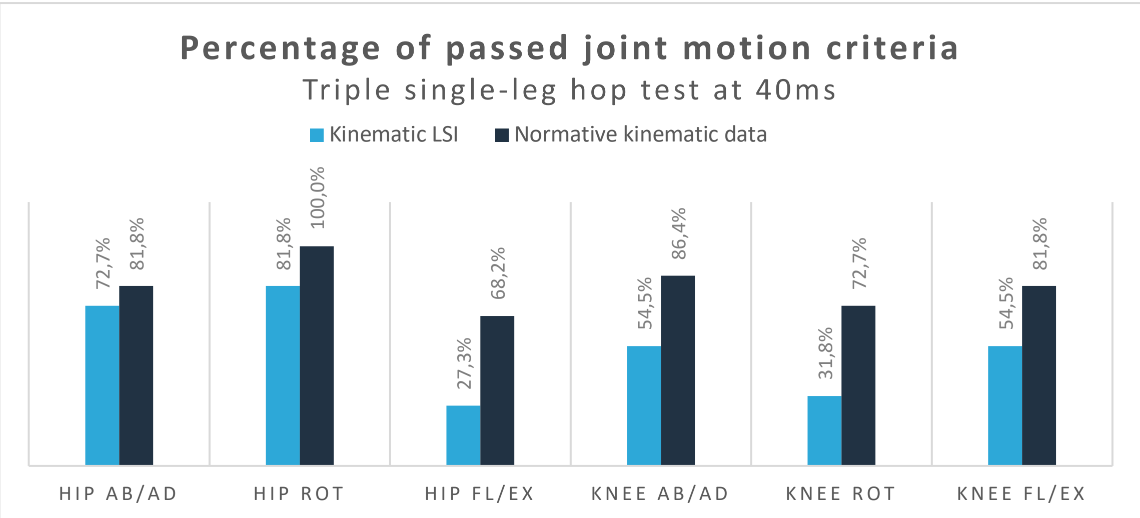

Figure 11 – Percentage of passed kinematic criteria per joint motion for the whole ACL-R group, during the TLH test at 40ms. AB/AD: abduction/adduction; ROT: internal/external rotation; FL/EX: flexion/extension; IC: initial contact; LSI: limb symmetry index.

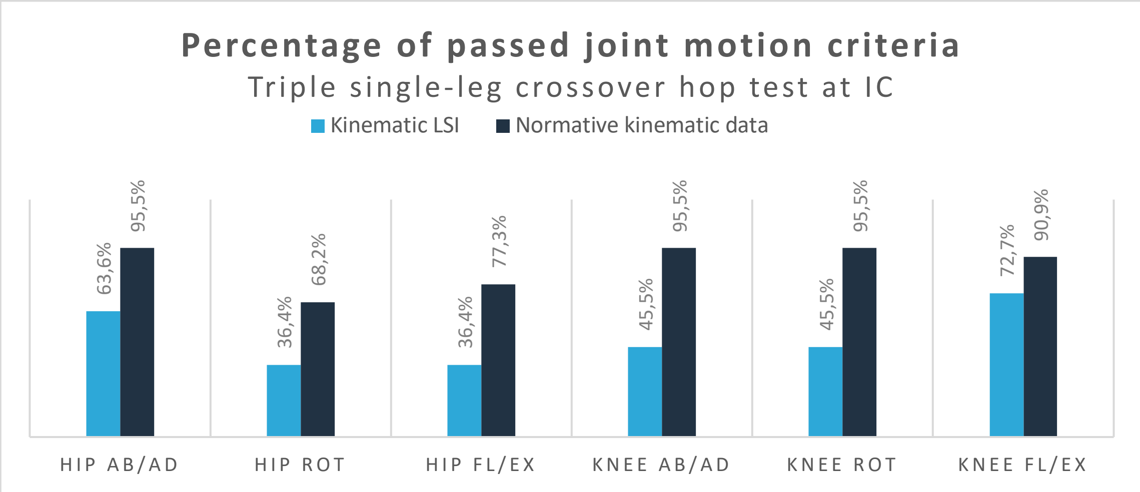

Figure 12 – Percentage of passed kinematic criteria per joint motion for the whole ACL-R group, during the TLCH test at IC. AB/AD: abduction/adduction; ROT: internal/external rotation; FL/EX: flexion/extension; IC: initial contact; LSI: limb symmetry index.

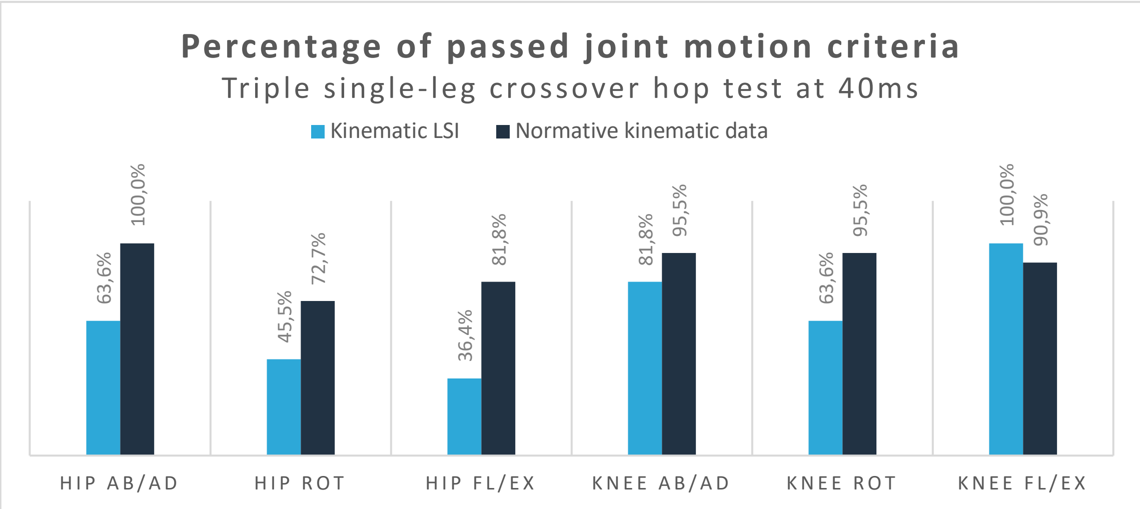

Figure 13 – Percentage of passed kinematic criteria per joint motion for the whole ACL-R group, during the TLCH test at 40ms. AB/AD: abduction/adduction; ROT: internal/external rotation; FL/EX: flexion/extension; IC: initial contact; LSI: limb symmetry index.

The kinematic joint motion criteria that were failed the most are the hip flexion/extension criteria, the hip abduction/adduction criteria were passed the most.

TABLE 10

Percentages (%) of passed kinematic criteria per joint motion$^{\alpha}$

	TLH				**TLCH**				
	Kinematic LSI		**Normative kinematic data**		**Kinematic LSI**		**Normative kinematic data**		
	IC	**40ms**	**IC**	**40ms**	**IC**	**40ms**	**IC**	**40ms**	**Total:**
Hip ab-/adduction	81.8%	72.7%	90.9%	81.8%	63.6%	63.6%	95.5%	100.0%	81.2%
Hip rotation	63.6%	81.8%	68.2%	100.0%	36.4%	45.5%	68.2%	72.7%	67.1%
Hip flex-/extension	36.4%	27.3%	54.5%	68.2%	36.4%	36.4%	77.3%	81.8%	52.2%
Knee ab-/adduction	72.7%	54.5%	72.7%	86.4%	45.5%	81.8%	95.5%	95.5%	75.6%
Knee rotation	45.5%	81.8%	86.4%	72.7%	45.5%	63.6%	95.5%	95.5%	73.3%
Knee flex-/extension	54.5%	54.5%	81.8%	90.9%	72.7%	100%	90.9%	90.9%	79.5%

$^{\alpha}$ Represent the percentages of passed kinematic criteria per joint motion. LSI: Limb symmetry index; IC: initial contact; 40ms: 40ms after IC.

5.4 Conclusion on the implemented kinematic criteria

The first conclusion Involves the distance criteria, which is the fact that the normative data criteria is stricter than the LSI criteria for distance, however has nothing to do with the created kinematic criteria. Only 2 ACL-R subjects did not pass the distance-based criteria, which were excluded from the rest of the study. Looking at the created kinematic criteria, not a single subject passed all kinematic criteria. The mean percentages of passed kinematic criteria were calculated (Table 9) and can be used for testing individual ACL-R subjects in the future. When the future individual ACL-R subject passed the same amount of more kinematic criteria than the percentages in Table 9, he/she passed based on the kinematic criteria.

Each specific joint motion was also evaluated individually. The kinematic joint motion criteria that were failed the most are the hip flexion/extension criteria, the hip abduction/adduction criteria were passed the most. Only the hip rotation normative kinematic data criterion during the TLH at 40ms, the knee flexion/extension kinematic LSI criterion during the TLCH at 40ms, and the hip abduction/adduction normative kinematic data criterion during the TLCH at 40ms were passed 100%. These were the only criteria that could possibly be excluded from future studies while all subjects passed and therefore this kinematic joint motion does not differ from their healthy peers. While these 3 criteria were the only ones that could be excluded, the were still kept for future studies.

6. Discussion

The primary purpose of this thesis was to find out if analyzing the lower extremity kinematic symmetry does add to the ACL reconstruction – return to sport tests. Two risk factors were found in literature which were yet to be looked at. One of those risk factors was the fact that just observing the LSI for distance might underestimate performance deficits and should therefore not be used alone[81-84]. Using normative data to compare the jumped distances is one of the solutions discussed in the literature. The second risk factor is the difference between the side-to-side kinematics of the lower extremities after ACL-R[28-35]. The non-dominant leg (operated leg) displays different kinematics then the dominant leg, which brings athletes closer to an ACL rupture.

The first findings of this study confirm the fact that just the LSI for distance is not the best way to decide an athlete's readiness to return to sport. The normative data criteria is a more strict criterion to see if an athlete is ready to return to sport, since more subjects passed the LSI > 90% criterion than the normative data criterion for distance and corresponds with the found research about normative data[63-66]. Therefore, B&B Healthcare should include the normative data criterion for distance in their hop tests protocol to assess an athlete's readiness more securely.

With the created kinematic LSI and normative kinematic data criteria, each subject of the ACL-R group was individually compared to their control group based on gender and age. Results showed that the majority of athletes with an ACL reconstruction did pass the hop tests based on their kinematics. Looking at the TLH test, 59.1% of all the kinematic LSI criteria and 75.8% of all the normative kinematic data criteria were passed at IC, and 62.4% of all the kinematic LSI criteria and 83.3% of all the normative kinematic data criteria were passed at 40ms. Looking at the TLCH test, 50% of all the kinematic LSI criteria and 87.1% of all the normative kinematic data criteria were passed at IC, and 65.1% of all the kinematic LSI criteria and 89.4% of all the normative kinematic data criteria were passed at 40ms. Not a single ACL-R subject passed all kinematic criteria. The mean percentages of passed kinematic criteria were calculated and can be used for testing individual ACL-R subjects in the future.

Each specific joint motion was also evaluated individually. The kinematic joint motion criteria that were failed the most are the hip flexion/extension criteria, the hip abduction/adduction criteria were passed the most. Only the hip rotation normative kinematic data criterion during the TLH at 40ms, the knee flexion/extension kinematic LSI criterion during the TLCH at 40ms, and the hip abduction/adduction normative kinematic data criterion during the TLCH at 40ms were passed 100%. These were the only criteria that could possibly be excluded from future studies while all subjects passed and therefore this kinematic joint motion does not differ from their healthy peers. While these 3 criteria were the only ones that could be excluded, it is better to still evaluate them in future studies.

Even though the findings of this study show that athletes with an ACL reconstruction do not necessarily perform less on the TLH and TLCH test based on their kinematics, this thesis highlights the need for additional assessment of the side-to-side kinematics. While the control groups (based on gender and age) existed of 10 subjects each, more research with a greater amount of controls is needed to create more reliable and valid criteria for kinematic LSI and normative kinematic data. When a greater amount of controls will be tested in future studies, more focus needs to be set on the extent of the created normative kinematic data criteria. Some ranges may overlap enough to combine them anyway, even though there was a significant difference found. Another point of discussion related to the control groups is the fact that the created criteria are also based on kinematic values of controls that did not pass the distance related criteria. This results in criteria that are less reliable then criteria based on only controls that did pass the tests based on the distance criteria.

In addition, this study had other restrictions. One of them is the fact the subjects with ACL reconstruction were already done with their rehabilitation and returned to sport a long time ago. The fact that the majority of ACL-R athletes in this study passed the kinematic criteria, may not be the same as athletes who just finished their rehabilitation. For this study, safety of the subjects was chosen over more recent reconstruction, while more recent reconstruction came with a greater risk on a subsequent ACL injury during the tests. When subjects just finished rehab, a specialist (physical therapist) needed to be present during testing and this was not possible. Another problem was finding enough athletes who recently finished rehab to participate in this study in the given time period for this thesis. Therefore, more research is necessary to see if the findings of this research also apply on athletes with a more recent ACL reconstruction.

Lastly, another restriction is that this study is only focussed on ACL ruptures while most of the time, these come with more damage to the knee than just the rupture of the ACL. No further research was done to see if the ACL-R subjects only suffered from a rupture of the ACL, or that they also had damaged their meniscus, cartilage, or other ligaments in the knee that could have influenced the test results.

7. Conclusion

The findings of this study show that athletes with an ACL reconstruction do not necessarily perform less on the TLH and TLCH test based on their kinematics. Therefore, it is unlikely necessary to buy an expensive measuring system to implement these analyses in the return to sport phase of the current testing phase in the ACL reconstruction rehabilitation program. While the size of the control groups in this study are limited, more research with a greater amount of controls is needed to create more reliable and valid criteria for kinematic LSI and normative kinematic data. The participants of this study with an ACL injury all returned to sport a long time ago. Therefore, further research is needed on the side-to-side kinematic differences of the lower extremities during the return to sport tests and athletes with a more recent ACL reconstruction. Still, the created kinematic LSI criteria and normative kinematic data criteria (based on kinematic data of controls) can be used to determine how athletes with an ACL reconstruction perform compared to their controls.

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Appendices

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Appendix I - Different return to sport tests explained

Appendix I will discuss the different return to sport tests that are used in the rehabilitation program of B&B Healthcare.

Star excursion balance test

The star excursion balance test is renowned to be a reliable measure of dynamic stability and is relatively simple, but time consuming. The test measures dynamic balance by asking athletes to balance on one leg while reaching as far as possible in eight different directions[83].

Y balance test

The Y balance test is a more simplified and much faster version of the star excursion balance test. The athlete is asked to balance on one leg whilst reaching as far as possible in three different directions. The test measures the athlete's strength, stability and balance in those three directions[84].

Single hop test

During a single hop test, the aim is to jump as far forward as possible on one leg. This is needed to be done without losing balance immediately after landing. The distance is measured from the start line to the heel of the landing leg. A limb symmetry index will be calculated with the distance measured on the injured and non-injured leg. The main goal of this test is to have less than a 10% difference between the distance jumped on the injured leg and the non-injured leg[85].

Triple hop test

During a triple hop test, the aim is to jump as far forward as possible on one leg with three consecutive jumps. This is needed to be done without losing balance in between the three hops and during the final landing. The distance is measured from the start line to the heel of the landing leg. A limb symmetry index will be calculated with the distance measured on the injured and non-injured leg. The main goal of this test is to have less than a 10% difference between the distance jumped on the injured leg and the non-injured leg[85].

Triple crossover hop test

During a crossover hop test, the aim is to jump as far forward as possible on one leg with three consecutive jumps without losing balance in between the hops and during the final landing. During the three hops, the athlete has to cross the midline. Each landing is therefore on the other side of the midline. The total distance is measured from the start line to the heel of the landing leg. A limb symmetry index will be calculated with the distance measured on the injured and non-injured leg. The main goal of this test is to have less than a 10% difference between the distance jumped on the injured leg and the non-injured leg[85].

Side hop test

The aim of the side hop test is to jump laterally as many as possible over a 30-cm distance for 30 seconds. A limb symmetry index will be calculated with the number of jumps recorded on the injured and non-injured leg. The main goal of this test is to have less than a 10% difference between the distance jumped on the injured leg and the non-injured leg[86].

Straight leg raise test

The straight leg raise test is a neurodynamic test. It checks the mechanical movement of the anterior cruciate ligament as well as its sensitivity to mechanical stress and compression. The straight leg test is a passive test where a clinician lifts the patient's leg by flexing the hip until the patient complains of pain in the back or back of the leg. Each leg will be tested individually with the normal leg being tested first[87].

Sport-specific tests

There is a variety of sport specific tests that can be used in the return to sport phase of the rehabilitation program. The test that can be used are:

- Shuttle/Yo-Yo test
- Agility T-test
- Illinois agility test
- Bruce protocol
- Timed run
- Sprint test

Two sport-specific tests will be chosen to use in the return to sport phase. Choosing these two tests depends on which test was previously performed prior to the ACL injury so an athlete is already familiar with the test. The purpose of running these sport-specific tests is to ensure people all fully ready to return to sport. The athlete's readiness is determined with the use of previous results of the athlete at that specific test. If the athlete scores better on the test than he/she did before the reconstruction, the athlete can safely return to sport. If an athlete did not perform the test prior to ACL reconstruction, an acceptable criterion will be set[22].

Appendix II - Tables with subject characteristics for all control groups

TABLE II - 1

Subject characteristics group 1: male 14-19 years old$^{\alpha}$

	Age (yrs)	Height (cm)	Weight (kgs)
Subject 1	18	187	86.1
Subject 2	17	184	77.4
Subject 3	15	188	72.9
Subject 4	16	178	62.2
Subject 5	15	179	80.9
Subject 6	17	195	85.8
Subject 7	19	194	81.4
Subject 8	18	182	72.8
Subject 9	16	176	59.5
Subject 10	16	182	66.0

$^{\alpha}$Represent the individual subject characteristics with age (years), height (centimetre), weight (kilograms).

TABLE II - 2

Subject characteristics group 2: female 14-19 years old

	Age (yrs)	Height (cm)	Weight (kgs)
Subject 11	14	171	52.2
Subject 12	16	162	58.7
Subject 13	16	170	62.2
Subject 14	16	162	52.3
Subject 15	14	179	60.4
Subject 16	14	165	46.3
Subject 17	14	161	49.6
Subject 18	14	165	55.6
Subject 19	14	171	59.4
Subject 20	14	164	53.5

$^{\alpha}$Represent the individual subject characteristics with age (years), height (centimetre), weight (kilograms).

TABLE II - 3

Subject characteristics group 3: female 20-40 years old

	Age (yrs)	Height (cm)	Weight (kgs)
Subject 21	23	170	62.3
Subject 22	25	171	72.3
Subject 23	28	182	80.2
Subject 24	29	170	67.5
Subject 25	24	178	69.2
Subject 26	23	163	70.5
Subject 27	35	171	95.3
Subject 28	32	167	63.0
Subject 29	25	182	84.1
Subject 30	22	170	62.4

$^{\alpha}$Represent the individual subject characteristics with age (years), height (centimetre), weight (kilograms).

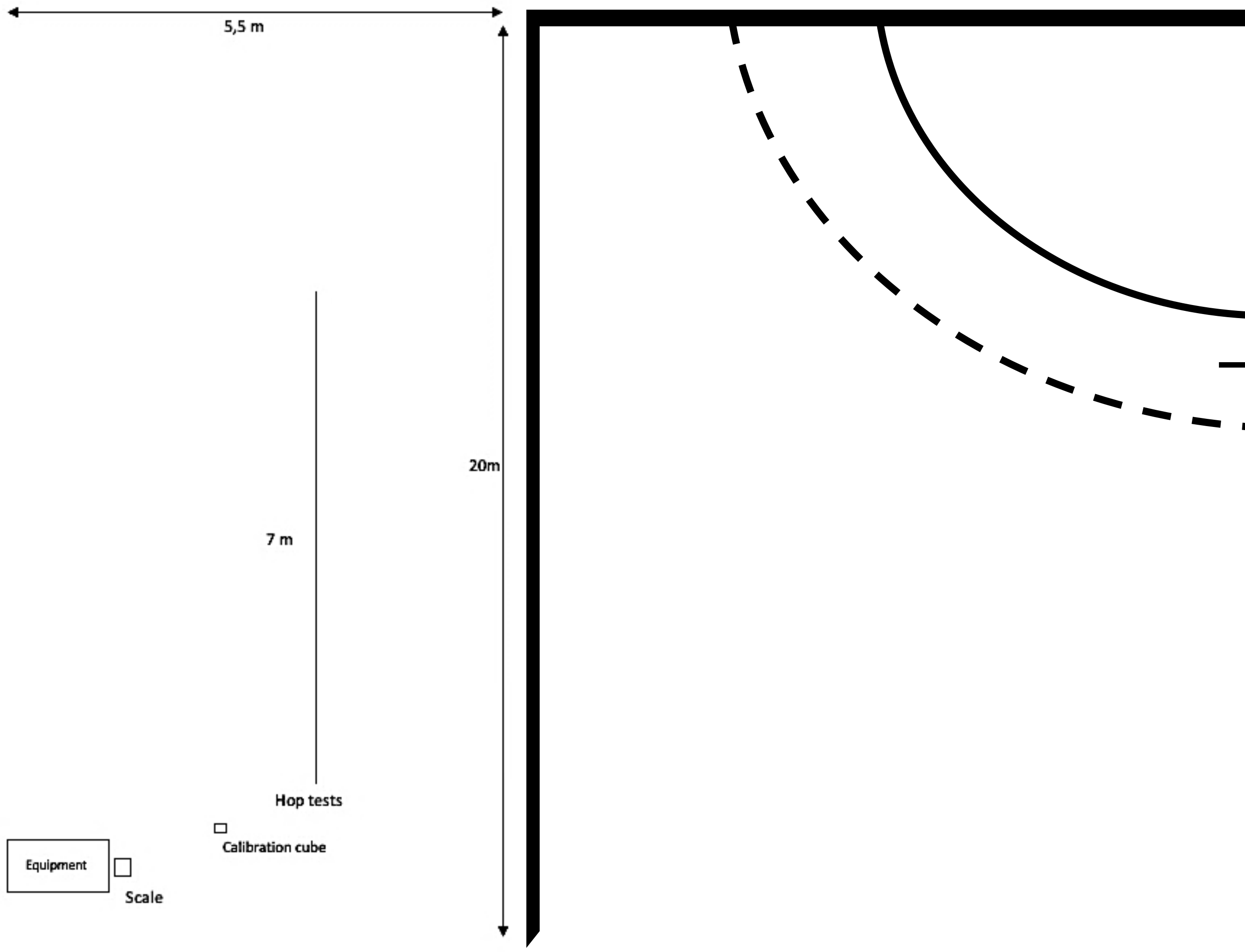
TABLE II - 4

Subject characteristics group 4: male 20-40 years old

	Age (yrs)	Height (cm)	Weight (kgs)
Subject 31	29	190	84
Subject 32	28	182	73.5
Subject 33	31	197	93.3
Subject 34	22	189	103.8
Subject 35	35	177	73.3
Subject 36	28	181	81.2
Subject 37	20	189	66
Subject 38	23	185	87
Subject 39	23	189	87.3
Subject 40	23	188	87.2

$^{\alpha}$Represent the individual subject characteristics with age (years), height (centimetre), weight (kilograms).

Appendix III - Test setup



Appendix IV - Tables with joint angles for all control groups

TABLE IV - 1

Joint angles (Mean ± SD) for both tests at IC[α]

		Boys 14-19	Girls 14-19	Women 20-40	Men 20-40
TLH					
Hip ab-/adduction	Non-dominant leg (°)	86.71 ± 10.09	88.28 ± 6.62	85.37 ± 7.24	93.40 ± 5.10
	Dominant leg (°)	92.10 ± 9.60	92.58 ± 7.02	89.96 ± 8.02	98.03 ± 5.36
	P value	<0.001*	<0.001*	<0.001*	<0.001*
Hip rotation	Non-dominant leg (°)	88.88 ± 7.77	88.85 ± 5.22	88.06 ± 6.13	90.92 ± 6.56
	Dominant leg (°)	89.72 ± 7.66	88.95 ± 5.53	88.69 ± 5.55	92.20 ± 7.06
	P value	0.466	0.901	0.471	0.053
Hip flex-/extension	Non-dominant leg (°)	52.12 ± 7.20	50.87 ± 15.56	47.25 ± 7.42	52.82 ± 11.78
	Dominant leg (°)	45.32 ± 6.58	46.03 ± 14.03	43.34 ± 7.00	46.94 ± 11.30
	P value	<0.001*	0.030*	<0.001*	0.001*
Knee ab-/adduction	Non-dominant leg (°)	90.51 ± 1.86	89.83 ± 2.24	90.28 ± 1.78	90.05 ± 2.35
	Dominant leg (°)	89.88 ± 1.95	88.78 ± 2.20	90.05 ± 1.61	89.32 ± 1.70
	P value	0.028*	0.002*	0.365	0.018*
Knee rotation	Non-dominant leg (°)	91.71 ± 3.25	90.59 ± 2.73	92.48 ± 4.03	91.38 ± 3.30
	Dominant leg (°)	88.66 ± 2.71	88.21 ± 2.95	91.55 ± 3.21	88.61 ± 3.50
	P value	<0.001*	<0.001*	0.089	<0.001*
Knee flex-/extension	Non-dominant leg (°)	43.73 ± 7.47	40.85 ± 7.50	38.43 ± 9.89	44.24 ± 9.82
	Dominant leg (°)	24.95 ± 7.15	24.10 ± 7.06	24.00 ± 8.65	26.30 ± 8.58
	P value	<0.001*	<0.001*	<0.001*	<0.001*
TLCH					
Hip ab-/adduction	Non-dominant leg (°)	94.95 ± 13.32	97.50 ± 9.61	92.57 ± 11.94	94.52 ± 12.00
	Dominant leg (°)	94.99 ± 5.12	97.98 ± 7.32	92.72 ± 6.49	94.73 ± 9.06
	P value	0.979	0.707	0.917	0.895
Hip rotation	Non-dominant leg (°)	92.44 ± 9.31	91.48 ± 5.93	91.79 ± 6.10	90.38 ± 6.97
	Dominant leg (°)	94.29 ± 8.66	90.80 ± 4.25	92.50 ± 5.72	91.81 ± 5.47
	P value	0.169	0.378	0.422	0.128
Hip flex-/extension	Non-dominant leg (°)	43.75 ± 25.39	41.05 ± 21.62	39.10 ± 22.25	45.63 ± 24.77
	Dominant leg (°)	48.48 ± 9.70	44.09 ± 14.93	45.02 ± 10.69	50.37 ± 10.41
	P value	0.101	0.274	0.025*	0.096
Knee ab-/adduction	Non-dominant leg (°)	88.72 ± 3.35	90.43 ± 5.27	88.73 ± 3.93	90.40 ± 5.33
	Dominant leg (°)	89.75 ± 2.03	88.38 ± 1.91	89.23 ± 2.27	89.42 ± 2.08
	P value	0.014*	0.001*	0.298	0.106
Knee rotation	Non-dominant leg (°)	89.75 ± 4.00	91.80 ± 5.04	91.51 ± 4.88	91.52 ± 5.86
	Dominant leg (°)	88.64 ± 2.98	89.20 ± 2.88	90.32 ± 3.08	88.89 ± 3.47
	P value	0.036*	<0.001*	0.052	<0.001*
Knee flex-/extension	Non-dominant leg (°)	35.86 ± 21.96	36.52 ± 15.91	31.18 ± 17.66	35.32 ± 20.34
	Dominant leg (°)	26.49 ± 10.30	26.41 ± 7.78	24.44 ± 6.76	26.22 ± 9.73
	P value	<0.001*	<0.001*	0.001*	<0.001*

[α] TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; IC: Initial contact.

* Denotes statistical significance

TABLE IV - 2
Joint angles (Mean ± SD) for both tests at 40ms[α]

		Boys 14-19	Girls 14-19	Women 20-40	Men 20-40
TLH					
Hip ab-/adduction	Non-dominant leg (°)	91.31 ± 10.08	92.95 ± 7.07	90.55 ± 6.18	96.15 ± 7.49
	Dominant leg (°)	96.18 ± 10.12	96.94 ± 6.87	94.69 ± 6.46	101.05 ± 7.42
	P value	0.001*	<0.001*	<0.001*	<0.001*
Hip rotation	Non-dominant leg (°)	91.57 ± 8.58	92.72 ± 5.78	89.70 ± 6.94	93.60 ± 8.12
	Dominant leg (°)	92.42 ± 9.61	93.10 ± 5.87	89.81 ± 8.02	94.29 ± 8.13
	P value	0.532	0.662	0.922	0.570
Hip flex-/extension	Non-dominant leg (°)	50.06 ± 11.93	50.04 ± 16.31	48.23 ± 8.01	56.14 ± 11.80
	Dominant leg (°)	43.47 ± 11.38	44.28 ± 14.76	43.79 ± 7.18	50.09 ± 10.80
	P value	<0.001*	0.014*	<0.001*	<0.001*
Knee ab-/adduction	Non-dominant leg (°)	89.94 ± 2.44	89.22 ± 1.95	89.28 ± 2.74	89.96 ± 2.47
	Dominant leg (°)	89.91 ± 2.10	88.91 ± 2.46	89.58 ± 1.92	89.36 ± 2.02
	P value	0.930	0.350	0.396	0.076
Knee rotation	Non-dominant leg (°)	91.46 ± 3.67	90.22 ± 2.74	93.07 ± 3.83	91.96 ± 3.42
	Dominant leg (°)	87.93 ± 2.99	88.37 ± 3.41	90.68 ± 3.65	88.73 ± 3.82
	P value	<0.001*	<0.001*	<0.001*	<0.001*
Knee flex-/extension	Non-dominant leg (°)	43.92 ± 8.12	41.61 ± 6.99	40.11 ± 9.92	44.24 ± 9.82
	Dominant leg (°)	26.26 ± 8.87	24.63 ± 6.31	25.29 ± 9.01	26.92 ± 10.12
	P value	<0.001*	<0.001*	<0.001*	<0.001*
TLCH					
Hip ab-/adduction	Non-dominant leg (°)	95.46 ± 12.54	96.82 ± 10.14	92.37 ± 14.03	95.63 ± 12.35
	Dominant leg (°)	95.17 ± 7.43	97.30 ± 7.51	91.65 ± 9.01	95.73 ± 9.69
	P value	0.851	0.719	0.683	0.952
Hip rotation	Non-dominant leg (°)	92.18 ± 8.77	93.10 ± 6.36	90.75 ± 11.32	91.25 ± 6.36
	Dominant leg (°)	93.57 ± 9.59	93.71 ± 5.49	94.35 ± 8.02	91.72 ± 5.30
	P value	0.312	0.492	0.015	0.591
Hip flex-/extension	Non-dominant leg (°)	43.75 ± 25.39	43.67 ± 25.29	37.49 ± 25.51	45.96 ± 23.39
	Dominant leg (°)	47.89 ± 13.65	46.18 ± 18.60	44.22 ± 9.83	49.96 ± 12.03
	P value	0.175	0.449	0.021*	0.151
Knee ab-/adduction	Non-dominant leg (°)	90.13 ± 3.22	90.76 ± 5.39	87.87 ± 6.62	91.30 ± 4.35
	Dominant leg (°)	89.39 ± 2.32	88.45 ± 1.42	89.32 ± 2.39	89.68 ± 2.04
	P value	0.079	<0.001*	0.053	0.002*
Knee rotation	Non-dominant leg (°)	91.18 ± 3.51	92.12 ± 5.11	90.23 ± 7.86	92.88 ± 4.67
	Dominant leg (°)	88.86 ± 2.72	87.92 ± 2.94	90.62 ± 3.34	89.21 ± 3.35
	P value	<0.001*	<0.001*	0.666	<0.001*
Knee flex-/extension	Non-dominant leg (°)	38.11 ± 20.88	37.40 ± 16.73	31.08 ± 21.56	38.41 ± 18.66
	Dominant leg (°)	27.77 ± 8.87	26.63 ± 8.21	25.51 ± 6.54	28.83 ± 9.79
	P value	<0.001*	<0.001*	0.021*	<0.001*

[α] TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; 40ms: 40ms after initial contact.
* Denotes statistical significance

Appendix V - Tables with kinematic LSI percentages for all control groups

TABLE V - 1

Summary of the LSI percentages for kinematics at IC$^{\alpha}$

	Hip ab-/ adduction	Hip rotation	Hip flex-/ extension	Knee ab-/ adduction	Knee rotation	Knee flex-/ extension
TLH						
Boys 14-19	92.35 ± 3.23	93.66 ± 6.01	93.99 ± 6.33	98.57 ± 0.65	98.68 ± 1.11	95.90 ± 3.17
Girls 14-19	91.92 ± 6.26	94.78 ± 3.15	96.21 ± 2.99	98.56 ± 1.28	98.15 ± 1.49	96.14 ± 1.86
Women 20-40	91.04 ± 6.54	92.85 ± 3.40	96.69 ± 4.51	98.17 ± 1.37	97.60 ± 1.73	96.21 ± 4.27
Men 20-40	93.41 ± 5,68	95.81 ± 2.62	97.01 ± 2.76	98.77 ± 0.81	98.19 ± 1.17	96.25 ± 4.23
TLCH						
Boys 14-19	96.22 ± 2.63	93.51 ± 4.23	96.18 ± 3.74	98.67 ± 0.88	98.38 ± 1.00	94.39 ± 3.20
Girls 14-19	97.16 ± 1.55	94.30 ± 4.18	96.28 ± 1.61	98.49 ± 1.44	97.85 ± 1.38	96.81 ± 3.42
Women 20-40	96.07 ± 2.85	91.88 ± 7.24	97.17 ± 2.08	98.19 ± 1.62	97.50 ± 2.11	95.96 ± 3.74
Men 20-40	96.76 ± 2.95	94.43 ± 6.24	96.09 ± 2.91	99.07 ± 0.95	97.51 ± 2.37	95.36 ± 3.20

$^{\alpha}$ Represent the statistical analysis (mean ± SD) of the LSI percentages per group and joint motion.
TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; LSI: Limb symmetry index; IC: Initial contact.

TABLE V - 2

Summary of the LSI percentages for kinematics at 40ms$^{\alpha}$

	Hip ab-/ adduction	Hip rotation	Hip flex-/ extension	Knee ab-/ adduction	Knee rotation	Knee flex-/ extension
TLH						
Boys 14-19	91.73 ± 3.80	93.96 ± 6.32	96.92 ± 2.76	98.51 ± 1.27	98.79 ± 1.01	96.22 ± 2.63
Girls 14-19	91.30 ± 6.52	94.65 ± 3.65	96.90 ± 2.71	98.40 ± 2.50	98.80 ± 1.06	97.16 ± 1.55
Women 20-40	91.46 ± 7.16	92.89 ± 4.99	96.07 ± 3.78	97.34 ± 1.04	97.40 ± 2.05	96.07 ± 2.85
Men 20-40	93.51 ± 5.41	97.56 ± 1.87	97.24 ± 2.19	98.83 ± 0.90	98.28 ± 1.37	96.76 ± 2.95
TLCH						
Boys 14-19	90.74 ± 4.52	93.23 ± 4.29	96.34 ± 3.76	98.03 ± 1.18	98.03 ± 0.94	95.78 ± 3.00
Girls 14-19	93.62 ± 3.68	94.10 ± 4.12	96.70 ± 1.55	98.11 ± 1.71	98.41 ± 1.21	97.06 ± 2.89
Women 20-40	90.53 ± 6.95	91.45 ± 7.72	97.22 ± 1.38	96.79 ± 1.83	97.81 ± 1.28	96.93 ± 3.77
Men 20-40	91.92 ± 5.73	94.40 ± 5.58	96.32 ± 2.74	98.59 ± 1.22	98.35 ± 1.24	95.96 ± 3.44

$^{\alpha}$ Represent the statistical analysis (mean ± SD) of the LSI percentages per group and joint motion.
TLH: Triple single-leg hop test; TLCH: Triple single-leg crossover hop test; LSI: Limb symmetry index; 40ms: 40ms after initial contact.

Appendix VI - Table with subject characteristics for ACL-R group

TABLE VI - 1
Subject characteristics for ACL-R group

	Gender	Age (yrs)	Height (cm)	Weight (kgs)	Time after reconstruction (months)
Subject 41	Female	22	165	64	7
Subject 42	Male	25	180	77.3	25
Subject 43	Female	30	183	73.4	105
Subject 44	Female	20	186	68.2	42
Subject 45	Female	22	168	60.3	22
Subject 46	Female	28	173	71.2	51
Subject 47	Female	22	170	64.0	29
Subject 48	Female	16	178	69.1	17
Subject 49	Male	30	190	88.1	42
Subject 50	Male	21	186	76.8	24
Subject 51	Male	22	178	72.8	84
Subject 52	Male	21	174	72.8	46
Subject 53	Male	19	191	74.9	34

Appendix VII - Tables with LSI for distance for ACL-R group

TABLE VII - 1

LSI for distance Triple single-leg hop test **ACL-R group**

		Distance hopped (cm)						Mean values (cm)		LSI	Normative data		
	Group	**R1**	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**(%)**	**Right**	**Left**	**SEM**
Subject 41	Women 20-40	246	269	278	340	323	327	270.3	330.0	81.9	✗	✗	✗
Subject 42	Men 20-40	559	651	651	653	639	616	620.3	636.0	97.5	✓	✓	✓
Subject 43	Women 20-40	457	501	484	510	535	532	480.7	525.7	91.4	✓	✓	✗
Subject 44	Women 20-40	299	314	322	346	351	342	311.7	346.3	90.0	✗	✗	✗
Subject 45	Women 20-40	362	391	375	309	360	361	376.0	343.3	91.3	✗	✗	✗
Subject 46	Women 20-40	362	387	403	346	340	383	384.0	356.3	92.8	✗	✗	✗
Subject 47	Women 20-40	352	417	377	336	342	373	382.0	350.3	91.7	✗	✗	✗
Subject 48	Girls 14-19	460	463	459	472	469	479	460.7	473.3	97.3	✓	✗	✓
Subject 49	Men 20-40	530	565	518	500	535	485	537.7	506.7	94.2	✗	✗	✗
Subject 50	Men 20-40	497	512	509	488	507	520	506.0	505.0	99.8	✗	✗	✓
Subject 51	Men 20-40	404	431	472	492	512	518	435.7	507.3	85.9	✗	✗	✗
Subject 52	Men 20-40	562	567	572	536	573	632	567.0	580.3	102.3	✓	✓	✓
Subject 53	Boys 14-19	518	520	529	518	553	549	522.3	540.0	96.7	✓	✗	✓

TABLE VII - 2

LSI for distance Triple single-leg crossover hop test **ACL-R group**

		Distance hopped (cm)						Mean values (cm)		LSI	Normative data		
	Group	**R1**	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**(%)**	**Right**	**Left**	**SEM**
Subject 41	Women 20-40	254	266	280	318	298	318	266.7	311.3	85.7	✗	✗	✗
Subject 42	Men 20-40	591	626	632	610	623	627	616.3	620.0	99.4	✓	✓	✓
Subject 43	Women 20-40	453	471	484	443	529	508	469.3	493.3	95.1	✓	✓	✗
Subject 44	Women 20-40	338	338	308	332	340	342	328.0	338.0	97	✗	✗	✓
Subject 45	Women 20-40	235	261	300	265	277	275	265.3	272.3	102.6	✗	✗	✓
Subject 46	Women 20-40	360	397	385	373	395	378	380.7	382.0	100.3	✓	✓	✓
Subject 47	Women 20-40	364	369	337	328	331	361	356.7	340.0	95.3	✓	✗	✓
Subject 48	Girls 14-19	462	439	483	482	465	517	461.3	488.0	94.5	✓	✓	✗
Subject 49	Men 20-40	527	526	548	475	497	490	533.7	487.3	91.3	✓	✗	✗
Subject 50	Men 20-40	454	479	485	465	476	515	472.7	485.3	102.7	✗	✗	✓
Subject 51	Men 20-40	254	266	280	318	298	318	266.7	311.3	85.7	✗	✗	✗
Subject 52	Men 20-40	591	626	632	610	623	627	616.3	620.0	99.4	✓	✓	✓
Subject 53	Boys 14-19	453	471	484	443	529	508	469.3	493.3	95.1	✓	✓	✗

Appendix VIII - Percentages of passed distance criteria control groups

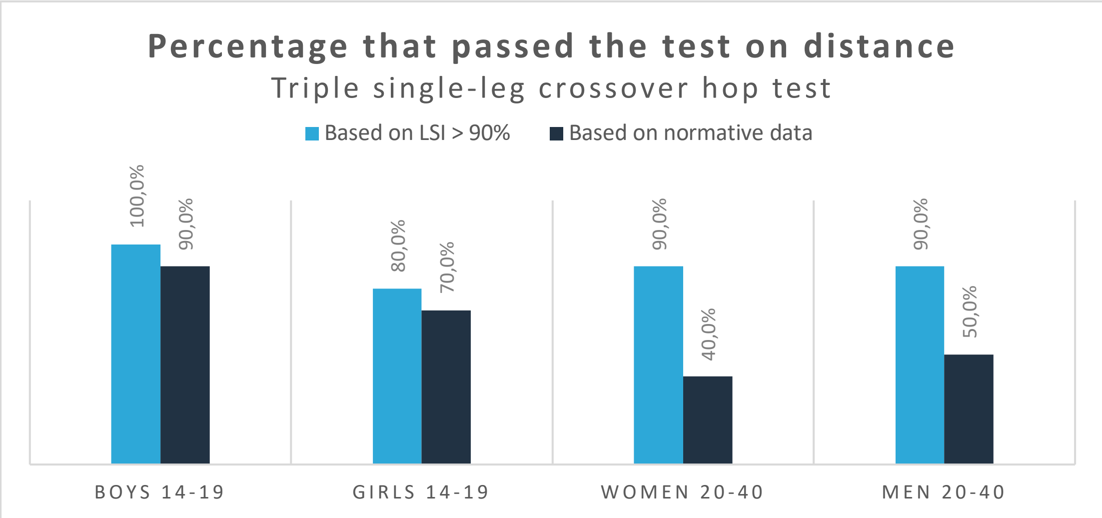


Figure VIII-1 – Percentage per group that did pass the single-leg triple hop test based on the LSI criterion of >90% and the normative data, both for distance

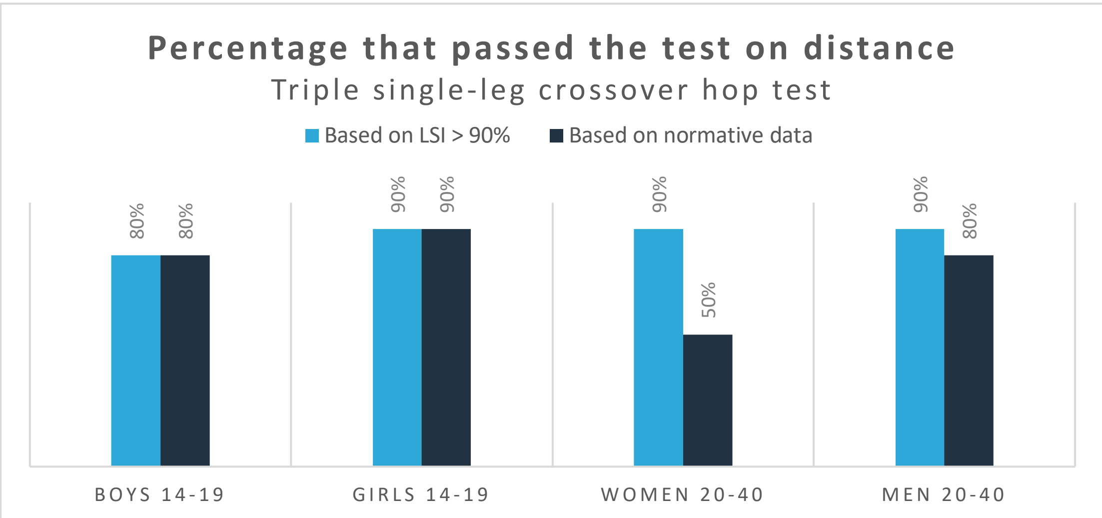


Figure VIII-2 – Percentage per group that did pass the single-leg triple crossover hop test based on the LSI criterion of >90% and the normative data, both for distance

Appendix IX - Tables with LSI for distance for all control groups

Green = Athlete passed the criterion from B&B Healthcare, LSI>95%
Red = Athlete did not pass the criterion from B&B Healthcare, LSI >95%

TABLE IX - 1
LSI for distance Triple single-leg hop test **Boys 14-19**[α]

	Distance hopped (cm)						Mean values (cm)		LSI (%)	Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**		**Right**	**Left**	**SEM**
Subject 1	541	547	562	534	561	545	550.0	546.7	99.4	✓	✓	✓
Subject 2	533	534	546	567	610	577	537.7	584.7	92.0	✓	✓	✗
Subject 3	587	596	596	522	570	596	593.0	562.7	94.9	✓	✓	✗
Subject 4	449	449	439	483	486	496	445.7	488.3	91.3	✗	✗	✗
Subject 5	641	611	627	596	620	612	626.3	609.3	97.3	✓	✓	✓
Subject 6	572	552	557	585	546	568	560.3	566.3	98.9	✓	✓	✓
Subject 7	627	661	631	675	689	674	639.7	679.3	94.2	✓	✓	✗
Subject 8	593	616	618	617	634	645	609.0	632.0	96.4	✓	✓	✓
Subject 9	543	515	490	550	568	573	516.0	563.7	91.5	✓	✓	✗
Subject 10	505	488	522	511	537	525	505.0	524.3	96.3	✗	✓	✓

[α]LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 2
LSI for distance Triple single-leg crossover hop test **Boys 14-19**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 1	514	532	523	541	491	523	523.0	518.3	99.1	✓	✓	✓
Subject 2	460	501	500	463	546	506	487.0	505.0	96.4	✓	✓	✓
Subject 3	458	482	490	485	486	546	476.7	505.7	94.3	✓	✓	✗
Subject 4	420	438	433	428	432	431	430.3	430.3	100.0	✗	✗	✓
Subject 5	580	596	560	575	580	573	578.7	576.0	99.5	✓	✓	✓
Subject 6	540	593	577	526	557	565	570.0	549.3	96.4	✓	✓	✓
Subject 7	669	654	671	671	684	703	664.7	686.0	96.9	✓	✓	✗
Subject 8	575	590	578	608	598	601	581.0	602.3	96.5	✓	✓	✗
Subject 9	426	486	500	533	562	530	470.7	541.7	86.9	✓	✓	✗
Subject 10	378	418	435	443	501	532	410.3	492.0	83.4	✗	✓	✗

[α]LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 3
LSI for distance Triple single-leg hop test **Girls 14-19**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 11	488	522	541	445	514	539	517.0	499.3	96.6	✓	✓	✓
Subject 12	301	341	326	295	342	355	322.7	330.7	97.6	✗	✗	✓
Subject 13	361	383	381	365	381	370	375.0	372.0	99.2	✓	✗	✓
Subject 14	416	457	421	413	418	437	431.3	422.7	98.0	✓	✓	✓
Subject 15	414	421	408	379	438	391	414.3	402.7	97.2	✓	✓	✓
Subject 16	495	494	464	383	464	424	484.3	423.7	87.5	✓	✓	✗
Subject 17	333	339	375	341	383	392	349.0	372.0	93.8	✗	✗	✓
Subject 18	365	415	385	304	341	352	388.3	332.3	85.6	✓	✗	✗
Subject 19	384	405	477	376	395	445	422.0	405.3	96.0	✓	✓	✓
Subject 20	351	408	459	395	362	375	406.0	377.3	93.0	✓	✓	✗

[α]LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 4
LSI for distance Triple single-leg crossover hop test **Girls 14-19**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 11	589	447	475	482	473	509	503.7	488.0	96.9	✓	✓	✓
Subject 12	313	323	359	323	365	394	331.7	360.7	92.0	✓	✓	✗
Subject 13	311	330	312	315	332	333	317.7	344.7	92.2	✓	✓	✗
Subject 14	331	333	341	351	373	387	335.0	370.3	90.5	✓	✓	✗
Subject 15	368	372	352	371	369	343	364.0	361.0	99.2	✓	✓	✓
Subject 16	470	463	450	416	443	413	461.0	424.0	92.0	✓	✓	✗
Subject 17	240	284	275	321	312	350	266.3	327.7	81.3	✗	✓	✗
Subject 18	320	382	416	332	370	396	372.7	366.0	98.2	✓	✓	✓
Subject 19	349	418	436	339	406	428	401.0	391.0	97.5	✓	✓	✓
Subject 20	256	290	359	289	345	315	301.7	316.3	95.4	✗	✓	✓

[α]LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 5
LSI for distance Triple single-leg hop test **Women 20-40**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 21	406	352	396	368	424	401	384.7	397.7	96.7	✗	✗	✓
Subject 22	437	426	426	397	379	393	429.7	389.7	90.7	✓	✗	✗
Subject 23	427	412	444	452	437	397	427.7	428.7	99.8	✓	✓	✓
Subject 24	434	438	426	420	458	457	432.7	445.0	97.2	✓	✓	✓
Subject 25	422	437	443	461	484	456	434.0	467.0	92.9	✓	✓	✗
Subject 26	381	402	403	346	374	373	395.3	364.3	92.2	✗	✗	✗
Subject 27	268	244	257	315	290	306	256.3	303.7	84.4	✗	✗	✗
Subject 28	298	308	333	312	341	313	313.0	322.0	97.2	✗	✗	✓
Subject 29	462	484	486	442	468	466	477.3	458.7	96.1	✓	✓	✓
Subject 30	341	348	335	381	354	355	341.3	363.3	93.9	✗	✗	✓

[α]LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 6

LSI for distance Triple single-leg crossover hop test **Women 20-40**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 21	366	391	376	386	378	395	377.7	386.3	97.8	✓	✓	✓
Subject 22	365	350	330	336	362	349	348.3	349.0	99.8	✗	✗	✓
Subject 23	387	343	362	364	341	359	364.0	354.7	97.4	✓	✓	✓
Subject 24	425	433	443	428	446	454	433.7	442.7	98.0	✓	✓	✓
Subject 25	329	396	408	412	421	444	377.7	425.7	88.7	✓	✓	✗
Subject 26	328	335	327	279	306	346	330.0	310.3	94.0	✗	✗	✓
Subject 27	231	253	249	254	267	274	244.3	265.0	92.2	✗	✗	✓
Subject 28	287	313	336	322	300	314	312.0	312.0	100.0	✗	✗	✓
Subject 29	416	445	456	384	456	465	439.0	435.0	99.1	✓	✗	✓
Subject 30	311	337	313	291	304	349	320.3	314.7	98.3	✗	✗	✓

$^{\alpha}$LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 7

LSI for distance Triple single-leg hop test **Men 20-40**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 31	542	550	561	514	563	579	551.0	552.0	99.8	✗	✗	✓
Subject 32	586	584	576	550	570	615	582.0	578.3	99.4	✓	✓	✓
Subject 33	571	557	562	576	650	656	563.3	627.3	89.8	✓	✓	✗
Subject 34	591	658	647	571	598	576	632.0	581.7	92.0	✓	✓	✗
Subject 35	519	592	535	522	561	549	548.7	544.0	99.1	✗	✗	✓
Subject 36	681	713	718	685	705	725	704.0	705.0	99.9	✓	✓	✓
Subject 37	366	384	407	387	410	422	385.7	406.3	94.9	✗	✗	✓
Subject 38	442	556	572	514	489	486	523.3	496.3	94.8	✗	✗	✗
Subject 39	645	666	686	716	741	763	665.7	740.0	90.0	✓	✓	✗
Subject 40	433	415	422	417	410	438	423.3	421.7	99.6	✗	✗	✓

$^{\alpha}$LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

TABLE IX - 8

LSI for distance Triple single-leg crossover hop test **Men 20-40**

	Distance hopped (cm)						Mean values (cm)			Normative data		
	R1	**R2**	**R3**	**L1**	**L2**	**L3**	**Right**	**Left**	**LSI (%)**	**Right**	**Left**	**SEM**
Subject 31	478	485	549	500	526	544	504.0	523.3	96.3	✓	✓	✓
Subject 32	502	555	575	549	592	573	544.0	571.3	95.2	✓	✓	✗
Subject 33	523	488	547	577	564	547	519.3	562.7	92.3	✓	✓	✗
Subject 34	561	522	582	512	516	492	555.0	506.7	91.3	✓	✓	✗
Subject 35	516	490	501	463	504	486	502.3	484.3	96.4	✓	✗	✓
Subject 36	638	634	610	668	668	692	627.3	676.0	92.8	✓	✓	✗
Subject 37	361	397	418	429	432	404	392.0	421.7	93.0	✗	✗	✗
Subject 38	501	573	607	563	583	593	560.3	579.7	96.7	✓	✓	✓
Subject 39	601	615	632	702	715	709	616.0	708.7	86.9	✓	✓	✗
Subject 40	395	404	402	383	406	424	400.3	404.3	99.0	✗	✗	✓

$^{\alpha}$LSI: Limb symmetry index; Green = passed the criterion, Red = did not pass the criterion; ✓= passed the criterion, ✗ = did not pass the criterion

Appendix X - Tables of the comparison between the kinematic LSI percentages of the ACL-R subjects and the created kinematic LSI criteria

TABLE X - 1

Mean LSI percentages of subject 42 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	96.30	97.72	95.35	98.51	92.01	91.69	98.90	98.93	94.89	98.88	98.81	98.89
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✓	✗	✓	✓	✓
TLCH												
LSI (%)	91.61	92.93	91.61	92.70	93.76	93.51	98.52	99.18	95.41	96.80	97.32	97.12
Falls within range?	✗	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 2

Mean LSI percentages of subject 43 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	95.92	99.66	97.85	99.58	93.69	94.96	97.64	98.03	99.64	97.24	91.77	94.92
Falls within range?	✓	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗
TLCH												
LSI (%)	96.40	98.73	96.99	99.46	93.30	93.96	98.29	99.15	99.52	98.49	96.74	97.36
Falls within range?	✓	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 3

Mean LSI percentages of subject 44 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	90.32	88.46	90.11	94.93	94.65	94.43	99.88	99.39	98.68	99.50	97.16	96.74
Falls within range?	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓
TLCH												
LSI (%)	91.23	91.05	91.46	93.48	92.84	93.89	99.51	99.83	99.08	98.01	96.17	99.61
Falls within range?	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 4

Mean LSI percentages of subject 45 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	95.45	94.82	94.65	94.69	95.15	94.91	99.76	97.19	95.65	99.20	93.70	94.20
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✗	✗
TLCH												
LSI (%)	95.63	94.99	94.38	99.07	99.95	98.18	97.78	98.56	96.35	99.68	95.21	97.24
Falls within range?	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 5

Mean LSI percentages of subject 46 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		Hip rotation		Hip flex-/ extension		Knee ab-/ adduction		Knee rotation		Knee flex-/ extension	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	97.47	96.61	93.29	97.66	96.51	96.62	99.22	99.29	97.48	98.95	98.95	99.18
Falls within range?	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓
TLCH												
LSI (%)	97.34	96.17	93.88	96.09	95.83	94.75	97.98	99.06	96.94	99.00	96.33	99.25
Falls within range?	✓	✓	✗	✓	✗	✗	✗	✓	✗	✓	✓	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 6

Mean LSI percentages of subject 47 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		Hip rotation		Hip flex-/ extension		Knee ab-/ adduction		Knee rotation		Knee flex-/ extension	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	90.81	90.57	95.65	96.32	92.13	91.37	99.45	97.90	97.71	99.67	97.23	95.68
Falls within range?	✗	✗	✓	✓	✗	✗	✓	✗	✗	✓	✓	✗
TLCH												
LSI (%)	90.13	92.22	90.31	92.29	93.19	94.80	99.26	99.76	98.89	99.18	99.86	98.04
Falls within range?	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 7

Mean LSI percentages of subject 48 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		Hip rotation		Hip flex-/ extension		Knee ab-/ adduction		Knee rotation		Knee flex-/ extension	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	92.93	94.48	90.82	91.41	95.28	95.31	98.41	98.77	94.15	96.93	97.01	98.46
Falls within range?	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓
TLCH												
LSI (%)	95.72	98.85	88.15	89.83	96.66	96.67	97.68	98.12	95.84	95.78	99.28	99.53
Falls within range?	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 8

Mean LSI percentages of subject 49 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		Hip rotation		Hip flex-/ extension		Knee ab-/ adduction		Knee rotation		Knee flex-/ extension	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	93.57	94.96	95.99	98.81	96.94	98.37	98.99	98.04	98.13	98.71	95.52	98.83
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓
TLCH												
LSI (%)	94.49	93.98	92.87	90.55	91.35	93.91	99.01	98.09	99.20	97.78	93.87	97.27
Falls within range?	✓	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 9

Mean LSI percentages of subject 50 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	99.23	99.41	95.57	97.68	96.48	94.11	98.13	97.39	98.33	99.98	89.91	91.86
Falls within range?	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗
TLCH												
LSI (%)	98.97	97.65	97.56	98.45	99.22	99.88	98.13	98.35	97.56	99.41	94.07	96.95
Falls within range?	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 10

Mean LSI percentages of subject 52 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	93.86	94.03	85.92	88.34	97.54	96.45	99.04	98.61	96.65	99.29	97.10	98.94
Falls within range?	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✓
TLCH												
LSI (%)	92.69	90.54	84.49	86.87	99.59	99.92	98.51	99.58	100.0	99.77	99.37	96.13
Falls within range?	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE X - 11

Mean LSI percentages of subject 53 compared to the kinematic LSI criteria for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH												
LSI (%)	93.64	88.70	99.46	96.90	94.36	95.51	97.91	98.41	98.38	98.74	95.42	94.81
Falls within range?	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✗	✗
TLCH												
LSI (%)	90.15	85.96	94.95	99.15	94.42	95.38	97.87	99.58	97.90	99.75	98.54	98.79
Falls within range?	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

Appendix XI - Tables of the comparison between the kinematic angles of the ACL-R subjects and the normative kinematic data

TABLE XI - 1

Mean joint angles of subject 42 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	94.99	99.67	99.81	101.55	68.23	63.97	89.11	89.25	86.21	87.37	30.27	26.87
Falls within range?	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓
Non-dominant leg	88.74	93.55	96.71	100.52	73.20	69.25	91.06	90.66	93.34	91.30	44.85	42.01
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	91.47	91.31	95.17	93.03	55.59	54.37	90.10	90.58	90.85	91.57	28.84	30.09
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	86.71	86.94	95.27	93.19	59.63	58.91	90.09	91.40	92.29	94.32	43.35	45.92
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 2

Mean joint angles of subject 43 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	91.65	89.43	92.03	92.79	62.37	65.63	88.50	89.43	87.54	87.75	33.94	31.33
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✓	✗	✓	✗	✓
Non-dominant leg	88.40	89.19	91.73	92.04	65.98	70.12	88.40	89.19	88.75	89.76	50.61	49.70
Falls within range?	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	✗	✓
TLCH (°)												
Dominant leg	90.64	90.99	90.05	90.00	52.76	55.20	90.64	90.99	87.86	88.18	23.75	27.38
Falls within range?	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
Non-dominant leg	90.17	88.43	92.12	92.54	58.12	60.45	90.17	88.43	91.27	91.14	43.46	46.01
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 3

Mean joint angles of subject 44 compared to the normative data range for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	98.18	98.26	88.87	90.23	37.94	39.71	88.85	87.76	88.40	88.77	25.52	30.17
Falls within range?	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	94.30	94.12	89.02	89.52	42.74	44.90	88.07	87.90	91.00	90.90	40.07	44.27
Falls within range?	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	88.68	89.64	80.08	82.53	31.10	30.42	88.75	88.19	89.58	87.95	28.90	25.57
Falls within range?	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
Non-dominant leg	83.41	85.70	84.51	83.68	35.34	36.65	87.53	88.05	91.46	92.75	44.46	43.75
Falls within range?	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 4

Mean joint angles of subject 45 compared to the normative data range for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	96.33	97.88	90.60	93.12	50.31	54.48	86.42	85.32	84.52	85.73	30.30	37.29
Falls within range?	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✓	✗
Non-dominant leg	90.20	92.40	86.49	85.52	55.10	61.83	89.94	91.74	89.71	90.72	47.64	53.76
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗
TLCH (°)												
Dominant leg	91.95	93.61	85.75	87.89	57.54	54.40	86.63	87.26	88.37	88.97	38.39	43.70
Falls within range?	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗
Non-dominant leg	85.53	87.78	81.90	84.72	62.88	59.06	92.54	93.08	90.42	91.01	56.12	57.84
Falls within range?	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 5

Mean joint angles of subject 46 compared to the normative data range for both legs and both hop tests at IC and 40ms[α]

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	91.37	93.90	85.79	93.76	43.32	47.83	89.57	90.09	91.43	88.30	24,98	24.91
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	86.02	89.65	88.17	91.33	49.37	54.71	89.44	91.17	92.38	91.95	41.96	44.60
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	93.74	91.40	91.96	88.02	48.14	42.08	90.27	88.27	89.13	91.09	23.78	29.28
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	89.04	86.22	90.28	87.76	54.24	47.11	90.08	90.32	93.35	92.88	40.88	45.62
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[α] TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 6

Mean joint angles of subject 47 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	86.92	87.43	81.47	95.48	35.36	38.83	91.60	92.11	94.62	95.02	22.92	25.78
Falls within range?	✓	✗	✗	✓	✗	✓	✓	✗	✓	✗	✓	✓
Non-dominant leg	82.23	84.23	86.29	98.58	39.00	40.83	89.68	89.30	94.83	93.90	40.63	43.70
Falls within range?	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	95.73	97.00	85.17	86.23	46.07	48.23	91.09	91.43	92.45	93.97	26.13	25.62
Falls within range?	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓
Non-dominant leg	90.79	91.33	89.59	90.98	51.19	51.19	87.80	89.52	94.52	94.68	46.52	46.37
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 7

Mean joint angles of subject 48 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	99.52	103.50	88.53	88.57	39.57	39.93	87.53	86.57	83.71	83.49	23.93	27.15
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓
Non-dominant leg	91.09	94.24	89.27	91.32	43.53	44.52	88.52	87.01	89.40	86.69	40.65	41.53
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓
TLCH (°)												
Dominant leg	92.49	99.07	97.47	100.48	45.99	44.42	88.95	88.62	88.91	87.12	27.44	27.99
Falls within range?	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	86.05	93.16	97.65	101.66	50.10	49.16	89.62	88.67	92.23	90.51	42.69	42.15
Falls within range?	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 8

Mean joint angles of subject 49 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	94.31	95.44	85.00	98.51	32.96	43.70	89.79	90.00	89.49	89.14	30.49	36.54
Falls within range?	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	89.74	90.08	87.62	100.07	35.82	45.68	89.80	89.76	90.26	90.71	44.21	51.32
Falls within range?	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	100.79	101.01	88.55	91.49	29.19	32.14	88.88	89.12	87.81	88.42	25.09	28.78
Falls within range?	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓
Non-dominant leg	94.50	95.85	88.67	90.62	33.77	37.42	91.60	91.51	91.44	92.77	42.63	47.45
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 9

Mean joint angles of subject 50 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	99.75	100.21	84.04	88.64	40.65	43.80	87.57	89.08	86.60	84.17	33.14	26.30
Falls within range?	✓	✓	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓
Non-dominant leg	94.51	96.16	86.50	88.23	40.17	46.52	87.01	89.57	88.65	89.88	50.16	48.13
Falls within range?	✓	✓	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	98.98	99.17	87.94	86.47	45.41	44.86	89.23	87.42	85.15	86.28	20.72	33.64
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓
Non-dominant leg	93.95	93.90	88.55	86.86	48.31	46.69	89.34	88.10	88.67	89.35	38.75	52.47
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 10

Mean joint angles of subject 52 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	93.30	92.02	100.85	98.60	40.74	40.08	89.51	88.40	90.75	88.33	31.96	32.46
Falls within range?	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	88.73	87.39	99.10	95.96	43.13	42.64	89.31	88.29	91.29	88.90	47.55	46.73
Falls within range?	✓	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓	✓
TLCH (°)												
Dominant leg	99.40	99.28	86.64	83.30	37.53	39.55	88.65	89.73	87.71	88.33	28.43	31.69
Falls within range?	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	94.37	96.52	87.55	83.36	38.40	42.54	88.07	88.66	90.65	89.10	46.10	41.44
Falls within range?	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

TABLE XI - 11

Mean joint angles of subject 53 compared to the normative data range for both legs and both hop tests at IC and 40ms$^{\alpha}$

	Hip ab-/ adduction		**Hip rotation**		**Hip flex-/ extension**		**Knee ab-/ adduction**		**Knee rotation**		**Knee flex-/ extension**	
	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms	IC	40ms
TLH (°)												
Dominant leg	97.29	92.46	87.94	84.35	41.18	44.77	87.72	90.28	89.36	91.60	42.61	34.40
Falls within range?	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✗	✓
Non-dominant leg	93.76	85.66	87.13	86.64	48.38	51.96	88.77	90.54	92.03	92.03	58.42	51.18
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
TLCH (°)												
Dominant leg	91.10	102.56	88.42	88.84	49.03	37.25	89.59	88.36	90.84	89.68	36.53	36.25
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-dominant leg	83.17	99.64	89.92	87.38	54.88	45.41	90.20	90.16	90.88	92.25	50.72	52.92
Falls within range?	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

$^{\alpha}$ TLH: Triple single-leg hop test; TLCH: Triple Single-leg crossover hop test; LSI: Limb symmetry index; ✓: passed the criterion; ✗: did not pass the criterion.

Appendix XII - Thesis proposal

January 2019

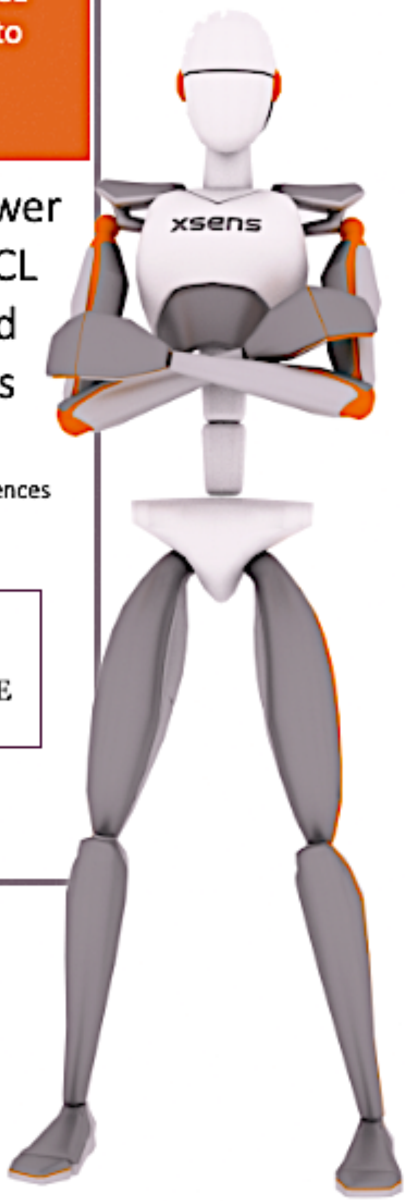
How can analysing the lower extremity kinematics (with the Xsens MVN Awinda) be implemented into the ACL reconstruction - return to sports tests?

Kinematics of the lower extremities after ACL reconstruction and returning to sports

Human Kinetic Technology
The Hague University of Applied Sciences
Thesis Proposal

In collaboration with:

Demi Loof - 13007378



Study Progress
Achieved Educational Credits (EC's) in modules 9 till 11 (max 36): **33 credits**
Minor: **Premaster Human Movement Sciences VU** *Finished:* **Yes**
Finished internship 2: **Yes**
Total free EC's earned: **36 credits**
Remaining tests (+module): **None**

Date: 08/01/2019

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1. Subject

Area of activity: Rehabilitation and Sports
Area of profession: analyst and researcher

Name of collaborative company: B&B Healthcare
Contact person: Jordy van Tol

2. Preface

Anterior cruciate ligament (ACL) rupture is one of the most common sports injuries worldwide[1,2]. The ACL runs diagonally across the center of the knee and mainly provides rotational stability to the knee joint and prevents the tibia from sliding out in front of the femur (anterior instability)[3]. An ACL injury happens mostly to young athletes (aged 14 – 40 years) who participate in landing, cutting and pivoting sports with fast decelerations[4,5,6,7], while around 70% of the ACL injuries result from a 'noncontact' mechanism[8]. Noncontact is defined by Marshall et al.[9] as "Forces applied to the knee at the time of injury resulted from the athlete's own movements that did not involve contact with another athlete or object".

Rehabilitation after an ACL rupture is prolonged and intensive which is needed to restore the knee function, strength and stability as it was prior to the injury[10]. Most of the time, an ACL reconstruction is seen as a golden standard of treatment to gain full recovery. This especially for young athletes who want to return to sports on their previous or a high level. But even with the ACL reconstruction, there is no certainty that someone can return to sports safely and without any risks of a future subsequent ACL injury[11].

Female athletes have the highest incidence of a subsequent ACL injury to the contralateral knee. Athletes between 14-19 years old have the highest ACL injury rate to either knee, which is also associated with higher levels of activity[12,13]. Estimates of the likelihood that an athlete will incur a subsequent ACL injury range between 3%[14] and 12%[15] to 30%[16]. Due to the high subsequent injury rate, it is important to make sure an athlete is fully ready to return to sports.

In the rehabilitation process, return to sports is called phase 4[17] or phase 5[18]. Most of the time, the decision whether an athlete is ready to return to sports is depending on some physical tests. The physical tests are focused on strength, balance, landing and agility work. The functional testing consists of: star excursion balance test, single hop test, triple hop test, triple cross over hop test, side hop test, single leg raise test and some sport-specific tests. The outcome of these tests is based upon the Limb Symmetry Index (LSI) for distance or time only. Another test that is used worldwide to evaluate return to sport possibilities, is the Landing Error Scoring System (LESS). The LESS-test is an assessment tool for identifying potential risk of an ACL injury during a jump-landing manoeuver[19,20]. An LSI > 90% and a LESS score < 5 indicates an athlete's readiness to return to sports based on the earlier named parameters distance and time[21].

Despite the fact that athletes can pass these tests based on the LSI and LESS criteria, it doesn't necessarily indicate that the side-to-side kinematics are similar[22,23]. Differences in side-to-side kinematics of the lower extremities during landing manoeuvers is also something that can increase the risk of an ACL injury. Athletes who aren't matured yet (under 19 years old), demonstrate different kinematics then matured athletes in both female and male[24], which can explain the high ACL Injury rate for athletes younger than 19[12,13]. Female athletes are even more at risk (ACL injuries occur 4 to 6 times more in females than in male)[7,25-27]. Malinzak et al.[27] states that female athletes have specific knee motions patterns that more frequently brings them close to certain body positions in which noncontact ACL injuries may occur.

Butler et al.[28] state that landing mechanics do not normalize over time compared to the non-injured leg. Limb asymmetries present 6 months after surgery, continued to exist at 12 months. These side-to-side kinematic differences in the lower extremities will place the athlete at a higher risk for an ACL injury. The finding of their study highlights the need for additional assessment of these side-to-side differences of the lower extremity kinematics before athletes return to sports and so reduce the risk for a subsequent ACL injury. Therefore, the aim of this study is to examine the possibilities of implementing analysis of the lower extremity kinematics into the existing return to sports tests based on a new examined LSI criterion for kinematics next to the already existing LSI criteria for distance and time.

3. Methods

Subjects
A total of 50 athletes will participate in the study. They will be divided in 4 control groups based on age and gender (group 1: female 14-19 years old, group 2: male 14-19 years old, group 3: female 20-40 years old, group 4: male 20-40 years old), and one group where athletes had suffered from a unilateral ACL-reconstruction (ACL-R group). Subjects will be asked to wear short sleeved shirts, shorts and athletic shoes with laces. After informed consent, the age, weight and dominant/uninjured leg will be recorded. The dominant leg will be determined for each subject by asking which leg would be used to kick a ball as Van Melick et al.[29] described as an accurate question to determine leg dominance. Subjects are excluded from the study if they suffer from any injury to the lower extremities which can influence the outcome negatively or if they don't participate in a sport that involves landing, cutting and pivoting tasks with fast deceleration. Body dimensions such as body height, foot length, shoulder height, shoulder width, arm span, hip height, hip width, knee height and ankle height will be recorded as described in the user manual from Xsens[30]. All subjects of the same group will be measured by the same examiner to eliminate measurement errors.

Test Protocol
While the risk of an ACL injury is greatest in sports that involves landing, cutting and pivoting tasks with fast deceleration and there is no need to examine similar motions in different tests, only some test will be discussed and used for this study. The tests that are going to be used are: triple hop test, triple cross hop test, LESS-test and the Agility T-test, as all these tests require different lower extremity motions. The tests will be conducted in a random chosen order to eliminate fatigue. The *triple hop test* consists of the subjects standing on one leg and hop 3 times as far forward as possible, with the final landing on the same leg. The subject needs to hold the final landing for 2 seconds while the total forward hop distance is recorded. During the *triple cross hop test*, the subjects hop forwards 3 times while alternately crossing over a tape marking. The final landing is needed to be hold for 2 seconds while the total forward hop distance is measured. The *LESS-test* is conducted where subjects jump from a 30-cm high box into a landing square (made with tape) at a distance of 50% their height away from the box (drop vertical jump). The test is evaluated through an adapted landing error scoring sheet based on the scoring sheet as described by Padua et al.[20]. The final test is the *Agility T-test*. Subjects need to complete a T-shaped parkour as fast as possible. The subject start at cone A before sprinting 10 meters to cone B. Then they cut 90º to the left and shuffles 5 meters sideways to cone C. Then shuffle 10 meters sideways to cone D on the right, before shuffling back to cone B and running backwards to cone A. Every time a subject passes a cone, they need to touch it. The time it takes the subject to complete will be recorded. Every test will be repeated three times for each leg, except the Agility T-test. The Agility T-test will be repeated 2 times in total, where the subject starts shuffling to the left in the first trial and to the right in the second trial.

Kinematic analysis
Before testing, subjects are equipped with the Xsens MVN Awinda motion tracker system which is strapped on as described in the Xsens user manual[31] on just the lower extremities and the sternum. Kinematics will be evaluated for all 4 tests at IC and peak flexion with the use of the MVN Analyzer 2019 (Xsens, Enschede). The kinematics included in this study are all joint angles of the lower extremities including the trunk (trunk flexion-extension, trunk lateral flexion, hip flexion-extension, hip abduction-adduction, hip rotation, knee flexion-extension, knee abduction-adduction, knee rotation, ankle dorsiflexion-plantarflexion, ankle abduction-adduction and ankle eversion-inversion). A calibration of this software is needed to align all

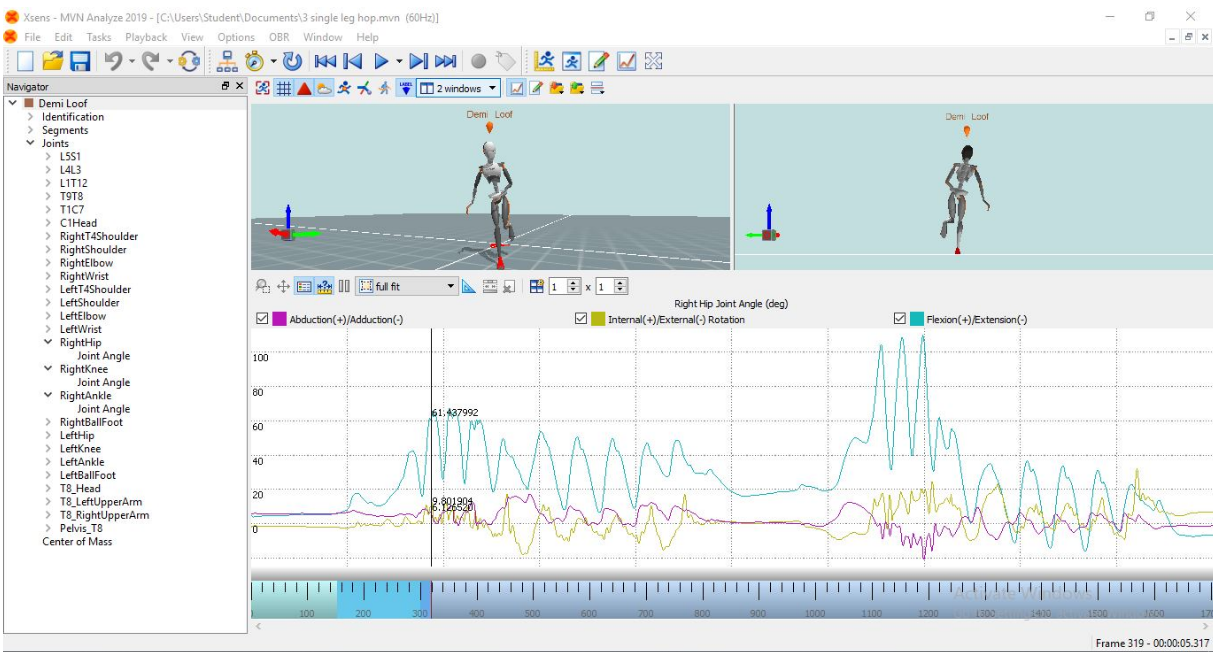

Figure 2 Screenshot taken from software MVN Analyzer 2019 (Xsens, Enschede)

8 motion trackers to the segments of the subject. The calibration is performed in a N-pose where the subjects stands upright with the feet parallel, one-foot width apart and the arms straight alongside the body with the thumbs forward. Before the start of every test, the subject will be moved back to the origin (the place where the calibration started). The final kinematics can be evaluated in the MVN analyzer software itself, as it shows the exact joint angle values on every sample (Figure 1). The shown angles are valid, as MVN Analyzer uses the flexion-extension as the first motion to be calculated in the Euler sequence to prevent Gimbal Lock from happening.

Statistical analysis

The final statistics will be done in IBM SPSS Statistics (version 25.0). The most important outcome of this study is the LSI criteria for the lower extremity kinematics for all 4 of the control groups. The LSI values can be obtained by calculating the LSI value for all subjects separately and then find the mean. To calculate the LSI values, the average of the three-recorded trials for each limb is needed. Then the average of the non-dominant/injured limb is divided by the average of the dominant/uninjured limb and multiplied by 100%. This LSI value will be used to test if the ACL-R group is showing the side-to-side differences that Butler et al.[28] stated. This comparison can be made without the use of SPSS but can also be measured with an independent t-test. Optional comparisons can be made for the specific kinematic differences between the dominant/uninvolved and the not-dominant/involved leg, male and female athletes, the 14-19 years old and 20-40 years old control group and between an ACL-R subjects and their specific control group. These optional comparisons can be made with the use of a MANOVA.

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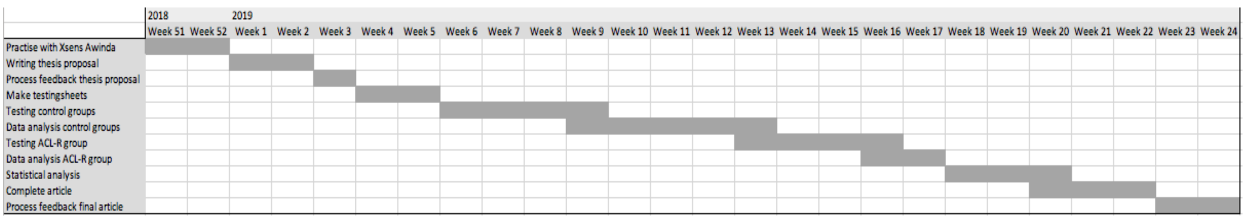
5. Planning

Date:	Goal:
December 19 – December 21, 2018	Practise with Xsens Awinda
January 7, 2019	Appointment with B&B Healtcare to evaluate thesis proposal
January 6 – January 8, 2019	Writing thesis proposal
January 8, 2019	Handing in thesis proposal for feedback
January 9, 2019	pilot measurement
January 10 – January 16, 2019	Process feedback in final thesis proposal
January 16, 2019	Hand in final thesis proposal
January 21 – February 3, 2019	Make testing sheets and protocols
February 4 & 11, 2019	Testing subjects: males 14-19 years old
February 18 & March 13, 2019	Testing subjects: females 14-19 years old and females 20-40 years old
March 5 & 12, 2019	Testing subjects: males 20-40 years old
February 27 – March 27, 2019	Data analysis of all 4 control groups
March 27 – April 19, 2019	Testing ACL-R group
April 19 – April 28, 2019	Data analysis of ACL-R group
April 29 – May 17, 2019	Statistical analysis
May 20 – May 31, 2019	Complete article
May 31, 2019	Hand in article for feedback
June 3 – June 12, 2019	Process feedback in final article
June 12, 2019	Hand in final article!



Appendix XIII - Evaluation of the personal learning objectives

The personal learning objectives that were set up in the beginning of the graduation period were:

- **Communication (A6):** I want to write a research article in English which suffice the criteria that's set for research articles.
- **Testing and doing research (B3):** I want to make sure this research article is valid, so that B&B healthcare can implement my founding's in their testing protocol for rehabilitation after an ACL reconstruction. Therefore, this thesis should be of a high standard with a lot of subjects and the correct use of the measurement equipment and analyse software.
- **Social and communicative skills (P9):** Because my thesis is in collaboration with B&B Healthcare, I need to consult with a physiotherapist about everything I am doing. The number of subjects is very big, I need to communicate the test protocols to them, so they will do exactly what I need them to do. I need to be clear in what I say and make sure they understood me before starting the test.

At first the **Communication (A6)** learning objective. Before the graduation period started, I wanted to write a research article in English for my thesis. During the graduation period, it became clear that an article was not sufficient to show all my work and make clear what I did over the past 20 weeks. With both my supervisors, we agreed upon writing a report instead of an article. I still did it in English on which I am very proud.
The second learning objective was **Testing and doing research (B3)**. I did my best to find and measure as many subjects as possible. I ended up with 53 subjects which was a lot of testing evenings worth. I wanted to test more subjects, which unfortunately was not possible in the time period I got for finishing my thesis. I still think it is a valid research, but a recommendation for further research is to make the healthy peers database larger. I also found myself very competent with Xsens and its software while I was asked to help in the lab skills lessons of human movement technology.
The third and last learning objective was **Social and communicative skills (P9)**. Every test went very well and did not take long at all to conduct. This can be dedicated to my explanation or to the ease of the tests. Every 4 weeks, I met my external supervisor to talk him through everything I had done so far and what was new since last I saw him. I also maintained contact with both my supervisors from The Hague University of Applied Sciences very often.