Pivoting around the ACL

Towards individualising care for ACL-injured patients

Mark Zee

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Mark Johannes Maria Zee

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Chapter 1

General Introduction

Introduction

The Anterior Cruciate Ligament: Anatomy, Function and Injury

The anterior cruciate ligament (ACL) has a central role in a well-functioning knee. The ACL originates on the medial wall of the lateral femoral condyle in the intercondylar notch of the femur and runs inferiorly and anteriorly towards its insertion on the tibia, just anteromedially of the tibial spine (see Figure 1). The course of the ACL contributes to its function as the main stabiliser for movements of the tibia in relation to the femur. Besides its primary function in controlling anterior-posterior (AP) laxity, it is recognised that the ACL has an important role in limiting the rotation of the tibia relative to the femur.[10] In collaboration with the posterior cruciate ligament, the ACL is responsible for an adequate roll-back mechanism in the knee joint. This mechanism creates a roll-glide movement of the femur to ensure that the femur does not roll off the tibia during flexion of the knee.

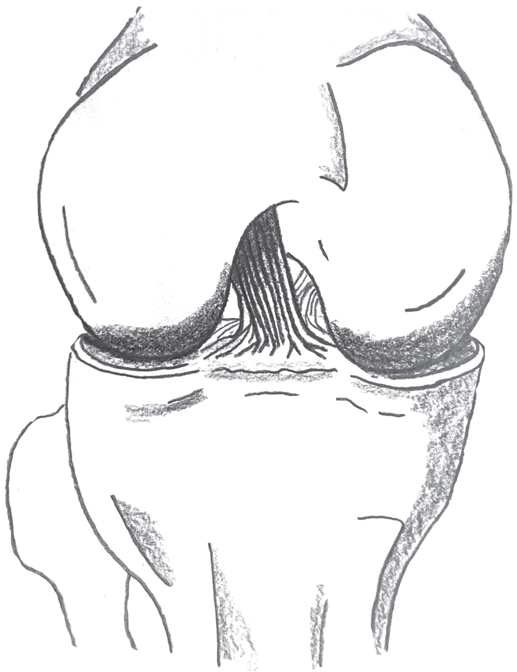

Figure 1. Anatomical drawing of the knee

The course of the ACL makes it susceptible to injuries from activities that combine a valgus force with internal rotation of the tibia with respect to the femur. This most commonly occurs with external rotation of the trunk and femur when the foot is firmly planted, for instance during pivoting movements in sports like soccer, handball and basketball.[1] Most ACL ruptures are caused by non-contact injuries.[1] The incidence of ACL injuries is estimated at 81:100,000.[1,9] In recent years the epidemiology of ACL injuries has shifted from traditionally the adolescent population to a higher incidence in the paediatric population, and from a predominantly male group to more female athletes. The highest increase in ACL injuries was seen in girls aged 13-15, at 143%.[34]

Due to parental and social pressure to perform well, children are encouraged to expose themselves to high-intensity training at a pre-pubertal age. Heightened exposure to pivoting sports enhances the risk of ACL injury. Also, the increased popularity of female football has boosted female participation in that sport. Unfortunately, female sex is associated with increased risk of ACL injury in pivoting sports.[1,29]

All in all, ACL injuries are expected to increase over the coming years; this is already reflected in a rising incidence of ACL reconstructions among adolescents over the past decade.[14]

ACL Reconstruction: A Brief History

Spontaneous healing of the ACL without surgical treatment is unlikely to occur. The presence of synovial fluid in the knee joint inhibits the formation of a provisional bridge between the two stumps after ACL rupture and thus primary healing is counteracted.[8,20] In addition, gravity causes the distal end to descend towards the posterior cruciate ligament, which again is unfavourable for primary healing. Still, a tear of the ACL is not always a reason for surgery. Some patients can manage well in the presence of ACL deficiency. Surgical treatment is indicated if instability of the knee persists despite conservative treatment.[19]

In the early 20th century, repair of the ACL was first described using catgut sutures. In 1903, Mayo-Robson was the first to publish satisfying short-to mid-term results.[25] The patient in question had reported his leg to be 'perfectly strong' with a follow-up of eight years. However, by 1916 Feagin and Curl had concluded that 'it was our hope that anatomic repositioning of the residual ligament would result in healing. Unfortunately, long-term follow-up evaluations do not justify the hope.'[7] ACL repair was by then considered a non-viable option and the focus turned towards ACL reconstruction.

In 1917 Hey Groves published a technique using a strip of the fascia lata which was detached from its insertion and directed through a tunnel that was drilled in the tibia. This technique still forms the basis for current intra-articular reconstructions of the ACL. Almost 20 years later, in 1934, Galleazi was the first to report on the use of a hamstring tendon graft to reconstruct the ACL.[4] At around the same time Campbell used the patellar tendon as a graft, a technique popularised a few years later by McIntosh. In 1963 the patellar tendon technique was revolutionarily altered by Jones.[16] His technique included harvesting the middle third of the patellar tendon along with a patellar bone block, while leaving the graft attached to the tibial tuberosity. Because of inadequate length of the graft, the femoral tunnel had to be located anteriorly on the medial wall of the lateral condyle of the femur. In 1969 Franke was the first to describe use of a free bone-patellar tendon-bone (BPTB) graft. By 1990 this technique was considered the gold standard and became known as the Jones procedure, honouring the pioneering work performed by Jones in the early 1960s.[4] Around the turn of the 21st century, a shift was made towards use of a hamstring graft.[10] This evolved from a single-strand semitendinosus graft to a quadrupled combined gracilis/semitendinosus graft. The hamstring and BPTB grafts are still considered the primary choices for ACL reconstruction, followed by quadriceps tendon graft and allografts. Nowadays the choice of graft should be patient-specific, based on clinical demands, patient characteristics and patient expectations.[21]

With the rise of arthroscopic treatments in the 1960s and 1970s, the number of ACL reconstructions have risen enormously. First only the tibial tunnel was drilled arthroscopically-assisted, but with the development of arthroscopic surgical guides for the femoral tunnel it became possible to create both tunnels from outside-in under arthroscopic control.[3] The transtibial technique has made ACL reconstruction widely available. In this technique the tibial tunnel is drilled first, then the femoral tunnel is drilled through the tibial tunnel. This ensures isokinetic placement of the graft. A real anatomical reconstruction is hardly ever achieved using this technique though, as the femoral origin site is not in line with the tibial insertion site. Both in vitro and in vivo, the transtibial 'isometric' technique shows achievement of proper anteroposterior stability. The construct, however, is not capable of effectively withstanding rotational forces as the tunnels are in line with each other. In up to 25% of patients a residual positive pivot shift phenomenon was present after ACL reconstruction, indicating rotational laxity.[3] It was assumed that this persistent rotational laxity plays an important role in hampering return to sports after ACL reconstruction. Towards the end of the 20th century, the goal of ACL reconstruction shifted from *return to vigorous work* to *return to sports*. Where the first outcome mentioned was achieved in many patients, return-to-sports rates were poor. This led to the development of an 'anatomic' ACL reconstruction technique, in which the tunnels are located at the footprints of the native ACL. An example of an anatomic ACL reconstruction is shown in Figure 2. A 2020 survey among surgeons involved in the ACL study group showed that 97% of surgeons prefer an anatomic ACL reconstruction, defined as a tunnel position within the footprints of the native ACL.[28]

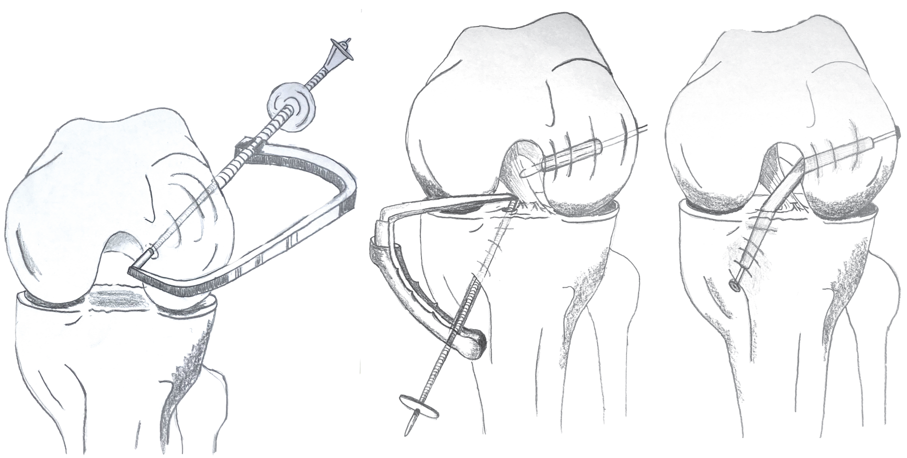

Figure 2. Example of an anatomic ACL reconstruction in which the femoral and tibial tunnels are drilled independently

Biomechanical Outcome after Modern ACL reconstruction

Biomechanical studies show that ACL reconstruction in its current form does not restore normal knee kinematics.[11,22,33] Gait analysis evidences that during level walking the ACL-reconstructed knee is less internally rotated [26,33] and during downhill running it is more externally rotated.[30] Although these studies indicate that rotational kinematics are not restored after ACL reconstruction, the question remains of whether tibial rotation is also abnormal during pivoting sports activities, as this may be a reason why patients do not return to their preinjury level of sports. The rotational laxity of the knee is determined by the range of motion that is allowed in the axial plane. This is why it’s important to measure the range of tibial rotation rather than the relative position of the tibia.

Several factors may influence or relate to the range of tibial rotation – first and foremost the ACL itself: although cadaveric studies show that the ACL is an important constrainer for internal and external rotation,[17] in vivo studies evidence conflicting results.[27,30] Therefore the exact role of the ACL, and of the ACL graft after reconstruction, in limiting in vivo range of tibial rotation remains unknown. The role of the surrounding muscles with respect to the range of tibial rotation and whether this may be different during low- and high-demand activities has not yet been determined either.

Excessive range of tibial rotation may affect clinical outcome after ACL reconstruction. And there are many different ways to assess clinical outcome after this procedure. On the one hand there is the technical success of the operation in terms of knee stability, graft survival and the occurrence of complications, yet there is also the patient’s perception of the success of the operation. In recent decades, patient-reported outcomes have received increasing attention in the evaluation of orthopaedic care. In assessing value-based healthcare, the added value for the patient is an important determinant.

Many constructs can be assessed using patient-reported measures. Most commonly used constructs in ACL reconstruction outcomes assess patient satisfaction, subjective knee function, and psychological factors like fear of reinjury, kinesiophobia, and psychological readiness to return to sports.

Both subjective knee function and psychological readiness to return to sports have been studied extensively in the context of ACL reconstruction. However, although not much is known about the link between knee kinematics and subjective knee function and/or psychological readiness to return to sports, a strong association is possible.

The range of tibial rotation could be related to muscular activity but also to bony anatomy. Anatomical (bony) factors such as the tibial slope are related to the amount of anterior tibial translation,[5] but this has not been studied for the range of tibial rotation. As shown in Figure 3, a steeper posterior tibial slope leads to more anteriorly directed forces on the tibia as the femur pushes down on the tibial plateau during stance.

Dejour et al. showed in a cadaveric study that, in the absence of the ACL, every increase of 10° in posterior tibial slope leads to a 6-mm increment of passive anterior tibial translation.

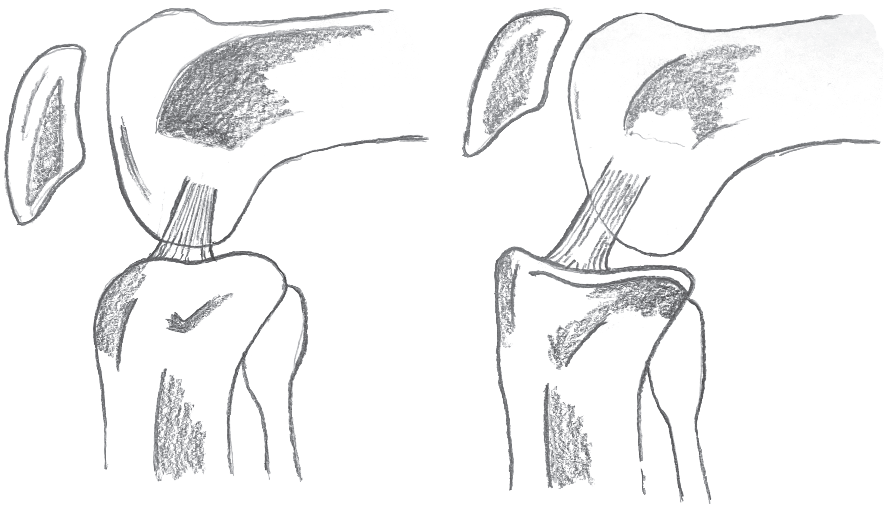

Figure 3. Infographic on the link between posterior tibial slope and passive anterior tibial translation.

The geometry of the tibial plateau can theoretically also contribute to the range of tibial rotation. As the lateral compartment of the knee is the more mobile part of the joint, a steeper slope of the lateral compartment may be related to a greater range of tibial rotation. During a bending motion of the knee, the lateral femoral condyle slides from a central position on the tibia in extension to a far posterior position on the tibia in flexion, whereas on the medial side of the knee this is present to a much lesser extent. The latter is due to restrictions based on the geometry of the medial compartment where the medial femoral condyle is concave and the medial tibial plateau is convex, as illustrated in Figure 4.

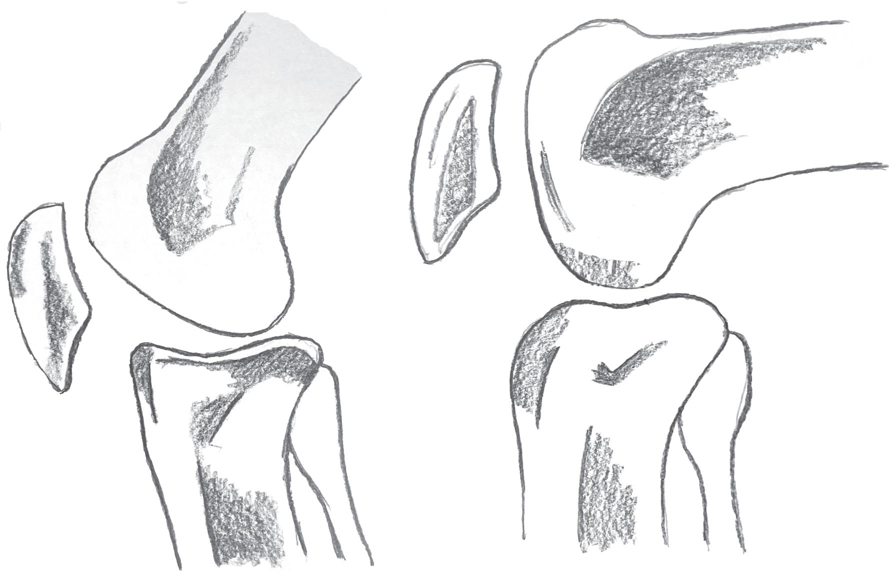

Figure 4. Schematic representation of the anatomic difference between the medial (left side) and lateral (right side) compartments of the knee in relation to the convexity of the tibial plateau.

This physiological difference between the medial and lateral compartments induces a natural rotatory movement in the knee during flexion and extension. If there is a steeper posterior tibial slope in the lateral compartment compared to the medial compartment, this rotational movement may be increased. It is still unknown to what extent these anatomical features relate to range of tibial rotation.

Current 'anatomic' ACL reconstruction: where does it go wrong?
The aim of an anatomic ACL reconstruction is for a graft to be implanted on the native footprints of the ACL on the femur and tibia. Current surgical techniques seem to fall short in creating a constant and reliable result for a femoral tunnel position at the optimal, individual anatomic footprint of the ACL. Surgeons using an 'anatomic' ACL reconstruction technique have been shown to deviate 4-5 mm from their intended femoral tunnel position.[24] This may be the result of poor visibility of the footprint during surgery as it is hidden in the intercondylar notch. Besides, large variability has been shown in the exact anatomic location of the footprints of the ACL between patients.[23]

Although femoral and tibial bone tunnels are drilled through surgical guide instruments to optimise positioning, current surgical techniques still depend on the intraoperative identification of landmarks and measurements to determine the femoral footprint of the ACL. The use of anatomical landmarks to ensure anatomic positioning of the graft is associated with a high risk of femoral tunnel malpositioning, which is related to early-to-midterm failure of the graft.[13,15] Non-anatomical placement of the ACL graft can lead to residual rotational laxity and is associated with a higher rate of graft failure, i.e. elongation or re-rupture. It is demonstrated that surgical inaccuracy, and in particular inaccuracy in femoral tunnel positioning, is an important factor causing ACL graft failure.[13] This can be devastating for the patient, leading to additional injury to knee structures such as menisci, requiring additional surgery, and causing prolonged absence from or even cessation of sports activities.

To provide consistent results, determination of the native ACL footprint should not be dependent of surgeon's experience or intraoperative visual control, and individual variation should be taken into account. A way to solve this is to identify the femoral footprint before surgery and to create a patient-specific instrument to ensure a femoral tunnel emerging at the native ACL position. This may improve biomechanical outcome after ACL reconstruction.

Rehabilitation and Return to Sports after ACL Reconstruction

Rehabilitation after ACL injury – with or without reconstruction –- has a noticeable effect on functional outcome.[2,18] It is therefore important not to solely focus on the surgical aspect of ACL reconstruction, but also to optimise the rehabilitation process after the intervention.

ACL reconstruction is typically followed by a rigorous rehabilitation programme to enhance knee strength and function.[2] ACL rehabilitation aims to prepare patients for return to daily activities, work and sports. Positive associations are shown between ACL rehabilitation and clinical outcome after ACL reconstruction.[2] However, current postsurgical rehabilitation is considered 'uniquely heterogeneous'.[12] Favourable in the Dutch situation is the fact that a rehabilitation guideline for anterior cruciate ligament surgery has been published by the Royal Dutch Society for Physiotherapy.[31] This guideline divides the rehabilitation process into three different phases. In the first phase the aim is to reduce effusion, regain range of motion and restore normal gait. In the second phase rehabilitation focuses on regaining strength and facilitating participation in sport-specific tasks and work. In the third and final phase comes preparation of the patient for return to sports and/or physically demanding work.[31] In practice, this means that in the first weeks the focus will be on passive mobilisation of the knee done by the physiotherapist, possibly making use of electrical stimulation of the quadriceps. Over time, patients start cycling on a home trainer and perform strength exercises for the quadriceps, hamstring, calf and gluteal musculature (squatting, leg presses, etc.). Typically two physiotherapy sessions per week are needed at this stage. In phase 2 neuromuscular training including jumping and quick alterations of directions are introduced with and without distraction. In phase 3 individual on-field training is commenced.[31] Overall, rehabilitation after ACL reconstruction takes another nine to twelve months after surgery and patient compliance with postoperative rehabilitation is a key factor in return to sports.[6] Despite this, a recent report by Della Villa et al. shows that only 18% of patients are fully compliant and 27% are moderately compliant with rehabilitation after ACL reconstruction.[6] High self-motivation, athletic identity, high self-efficacy, high self-confidence, positive self-talk and proper social support are facilitators for adherence to rehabilitation programmes after this procedure.[32]

Because of the importance of proper rehabilitation after ACL reconstruction, improving compliance with rehabilitation will have a major effect on outcome. As the majority of patients that injure their ACL participate in pivoting sports, predominantly football, current rehabilitation protocols focus on return to pivoting sports.[1] Before actual field training can commence, lots of hours have been spent at the gym to regain knee strength. This may be a reason why overall compliance is low. Patients may not be motivated to rehabilitate, as they 'just want to play the game' (i.e. return to sports). Challenging patients during rehabilitation and focusing on the output of the movement instead of the movement itself may trigger patients to be more compliant with the rehabilitation. This may not be the case for all patients after ACL reconstruction, but by providing more options for rehabilitation a more patient-specific rehabilitation can be achieved, stimulating intrinsic motivation.

General aim of this thesis

The general aim of this thesis is to optimise the biomechanical and functional outcome after ACL reconstruction. Therefore, the main focus lies on the effects of ACL reconstruction on knee kinematics, especially range of tibial rotation. The aim of the first part of the thesis is to study the effect of an ACL graft on range of tibial rotation and the link between this range of tibial rotation and subjective knee function and psychological readiness to return to sports in sports-related activities. An additional aim is to gain insight into the link between range of tibial rotation and the slope of the tibial plateau. The second part of the thesis focuses on individualising ACL reconstruction and rehabilitation. The aim of the second part of the thesis is to develop a patient-specific guide to ensure a femoral tunnel position in the native footprint of the ACL. Final aim is to determine the feasibility of an alternative rehabilitation protocol after ACL reconstruction.

Outline of the thesis

The first question to be answered is whether there is evidence that ACL reconstruction can indeed reduce the increased range of tibial rotation which is present in the ACL-deficient knee. **Chapter 2** reports on a literature review to quantify the role of ACL reconstruction in limiting the range of tibial rotation. The study focuses on the passive range of tibial rotation in the anaesthetised patient, and thus investigates the mere mechanical impact of the ACL graft. The next question, reported in **Chapter 3**, is whether increased range of tibial rotation can be measured during high-demand activities in the ACL-deficient knee and what the effect of an ACL reconstruction is on this range of tibial rotation.

We hypothesise that when the range of tibial rotation is greater, poorer subjective knee function and poorer psychological readiness are present. In **Chapter 4** a study is presented on the correlation between objective range of tibial rotation and both subjective knee function and psychological readiness. To this end, we conducted a study imitating a real in-sports knee landing. Furthermore, the hypothesis that a steeper posterior tibial slope, especially in the lateral compartment of the knee, increases the range of tibial rotation will be tested. **Chapter 5** examines the correlation between range of tibial rotation during high-demand tasks and amount of posterior tibial slope.

To develop an accurate patient-specific guide to create a femoral tunnel at the anatomic origin of the native ACL during ACL reconstruction, we must first identify the native origin of a torn ACL on MRI. In **Chapter 6** we determined the intraobserver and interobserver reliability of determining the femoral footprint of the torn ACL on MRI scans. The knowledge gained in **Chapter 6** was instrumental towards developing this guide, and in **Chapter 7** the first in vitro results are presented on its accuracy.

Besides improving to individualise the surgical technique, tailoring the rehabilitation may be an important adjunct to improve return to sports outcomes after ACL reconstruction. Some patients may benefit from an alternative to the current available rehabilitation programmes, depending on their sports preferences. As current rehabilitation programmes can be experienced as repetitive and boring, a new, more challenging rehabilitation programme was developed: knee rehabilitation on skates (KROS). The results of the feasibility study are reported in **Chapter 8.**

Chapter 9 highlights the results of the studies and discusses them in a broader perspective. Clinical implications and recommendations for future research are presented.

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Chapter 2

The effect of ACL reconstruction on range of tibial rotation

a systematic review of current literature and a recommendation for a standard measuring protocol

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Abstract

Background: Tibial rotation is a hot topic in ACL surgery and many efforts are being made to address rotational stability. The exact role of the ACL in controlling tibial rotation in clinical studies is still unknown.

Purpose: The purpose of this systematic review is to quantify the effect of ACL reconstruction on the amount of tibial rotation based on the current available literature.

Study Design: Systematic review

Methods: August 2019 a literature search was performed in the Pubmed and Embase databases. Two independent reviewers reviewed titles and abstracts as well as full text articles. A total of 2383 studies were screened for eligibility. After screening of title and abstracts 178 remained for full text assessment. Ultimately 13 studies were included for analysis. A quality assessment using the Risk of Bias in randomized trials (RoB 2.0) and the Risk Of Bias In Non-randomised Studies – of Interventions (ROBINS-1) was performed.

Results: The included studies in this review report ACL reconstruction resulting in an average reduction of 17-32%. In current literature a gold standard for measuring tibial rotation is lacking. Major differences between the study protocols were found. Several techniques for measuring tibial rotation have been used, each with its own limitations. Most articles lack proper description of accompanying injuries.

Conclusion: CAS studies showed that ACL reconstruction achieves a reduction of 17-32% of range of tibial rotation, when comparing pre- and postoperative individuals. Whether it returns to pre-injury levels remains unclear. Normal values for the range of tibial rotation in ACL deficient and ACL reconstructed patients cannot be provided based on the current available literature due to lack of a uniform measuring techniques and protocols. The authors therefore advocate uniformity in measuring tibial rotation.

Introduction

A rupture of the anterior cruciate ligament (ACL) is a common sports injury, often leading to prolonged absence or even cessation of sports activities. Next to its primary role in restraining anterior tibial translation, the ACL is an important factor in the rotational stability of the knee.[4,7]

Although the current practice supports reconstruction as an important factor in returning to sports activities, and good results after transtibial ACL reconstruction are generally achieved,[1,5] a large group of patients still reports residual laxity in the form of 'giving way' and/or a positive pivot shift.[1] In order to address this phenomenon the double bundle reconstruction technique and the 'anatomic' reconstruction technique have been developed. Both techniques show in vitro better control of rotational laxity.[28,30] In recent years accessory extra-articular stabilizing techniques (e.g. ALL reconstruction, Lemaire procedure etc.) have been re-introduced to better control rotational laxity. However, a scientific basis to support this trend is lacking.

In vivo, the available studies only use subjective tests to measure the amount of postoperative rotational laxity (e.g. pivot shift). As no generally accepted gold standard for measuring tibial rotation exists, comparing outcomes between studies is not possible . The conclusions and outcomes on the amount and the direction of tibial rotation in ACL deficiency and after ACL reconstruction are contradicting. As well increased internal rotation as increased external rotation have been reported. This leads to inconclusive results.

The authors aim to set the first step in developing a standard, valid and reproducible protocol for measuring tibial rotation. The purpose of this systematic review is to create an overview of the influence of the reconstructed ACL on, objectively measured, tibial rotation.

Two research questions were formulated:

1. Does range of tibial rotation increase after rupture of the anterior cruciate ligament?
2. Does ACL reconstruction lead to decreased range of tibial rotation?

Material and Methods

In August 2019 a literature search was performed in the Pubmed database using the search terms:

(anterior cruciate ligament[tiab] OR ACL[tiab] OR “Anterior Cruciate Ligament”[Mesh]) AND (“Rotation”[Mesh] OR rotat*[tiab]) AND (“Tibia”[Mesh] OR tibia[tiab] OR tibial[tiab] OR knee[tiab]) NOT (animal NOT human).

Next the Embase database was searched using

(‘tibia’/exp OR tibia:ab,ti OR tibial:ab,ti OR knee:ab,ti) AND (‘rotation’/exp OR rotat*:ab,ti) AND (‘anterior cruciate ligament’/exp OR ‘anterior cruciate ligament’:ab,ti OR acl:ab,ti NOT (animal NOT human).

Duplicates were removed using RefWorks. Titles and abstracts were screened to match the inclusion criteria.

Exclusion criteria were as follows:

(1) Pivot shift test without quantification of rotational instability
(2) newly developed devices to measure tibial rotation, without any form of reference
(3) any descriptions other than internal/external rotation in degrees
(4) Patients included with concomitant injury to the anterolateral structures

(5) Studies using cadavers
(6) Studies using a Motion Capture Systems/in vivo tracking systems
(7) no English or Dutch full text available

According to the PRISMA guidelines, two independent reviewers reviewed titles, abstracts and full text articles. In case of debate on inclusion of an article a third independent reviewer was consulted.

Next a quality assessment was performed. Two reviewers independently assessed the methodological quality of all the selected studies. For non-randomised trials the 7-item Risk Of Bias In Non-randomised Studies – of Interventions (ROBINS-I) tool was used.[29] To assess the quality of the included randomised trials the five-item Risk of Bias in randomized trials (RoB 2.0) tool was used.[17] Both tools are recommended by the Cochrane Scientific Committee to be used in systematic reviews.

Results

A total of 2383 studies were screened for eligibility. After screening of title and abstracts 222 remained for full text assessment. 44 articles had no English full text available or were abstract only reports of scientific presentations. After reading full text another 165 were excluded based on the exclusion criteria listed above. Ultimately, four studies describing ACL deficient subjects and nine studies describing tibial rotation in ACL reconstructed subjects were included for analysis. See Figure 1.

All included full text articles were explored for the amount tibial rotation measured. If applicable, internal and external tibial rotation were noted separately. An overview of reported ranges of tibial rotation is provided in Tables 1 and 2.

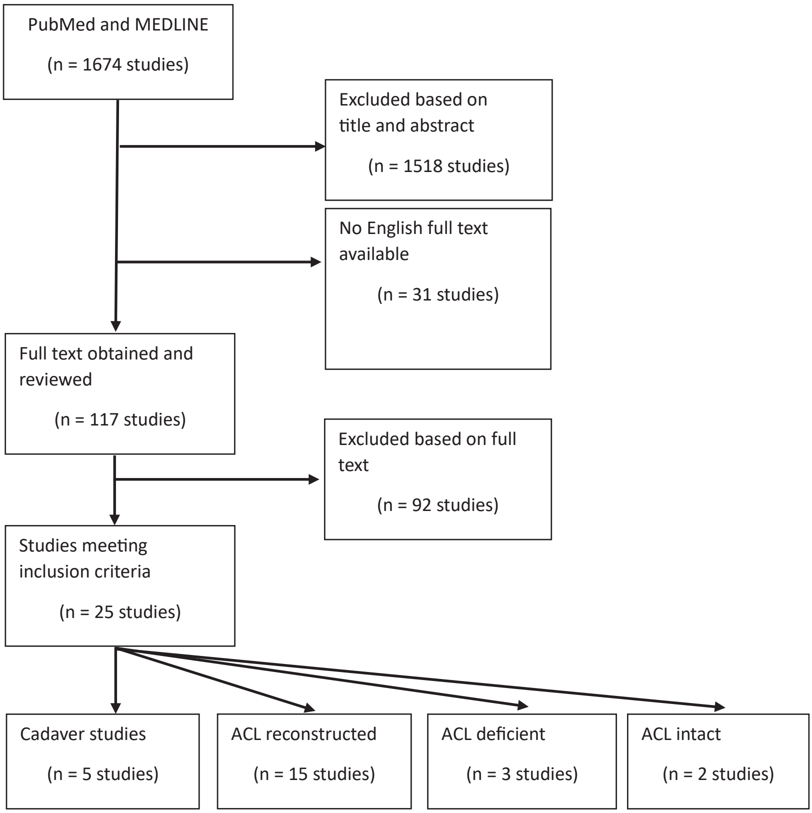

Figure 1. Flow diagram detailing the results of the literature search.

Patients with ACL deficiency

There were four studies on subjects with ACL deficiency, see table 3.[6,13,15,23] In two studies[6,15] Magnetic Resonance Imaging (MRI) was used to evaluate tibial rotation. Haughom[15] applied a compressive force of 44 Newton (N) axial load and 3,35 N internal and external rotational torque and reported a significant difference between ACL deficient and ACL intact subjects. Also, a significant difference between ACL deficient knees and their contralateral intact knees was reported. Barance[6], when studying unloaded knees, did not demonstrate a significant difference in rotation between ACL intact and ACL deficient subjects.

Miyaji[23] studied tibial rotation in subjects performing a wide based squat using 3D Computed Tomography (CT) and biplanar fluoroscopy. No significant difference was shown between ACL deficient and contralateral intact knees in terms of range of tibial rotation. Grassi[13] used CAS to evaluate knee kinematics in ACL deficient subjects. Grassi tried to link the kinematic pattern, acquired by CAS, to bony morphology, which was evaluated by MRI. An indirect correlation between the lateral posterior tibial slope and rotational laxity was presented.[13]

Patients after ACL reconstruction

Nine studies were retrieved in which ACL reconstructed knees were analysed for the range of tibial rotation. In six ACLR studies a CAS system was used during surgery to perform pre- and postoperative measurements. Three studies were classified as “other evaluation method”. See table 4 and 5.

Computer Assisted Surgery (CAS)

In six studies, during ACL reconstruction, the CAS software was used to measure range of tibial rotation before and after reconstruction of the ACL.[9-12,20] In all of these studies, a manual force was applied in order to rotate the tibia. Maximum internal and external rotations were applied to the foot of the anesthetized patient and associated values of maximum internal and external rotation of the knee were recorded. All studies showed a reduction of total range of tibial rotation of 17-32% after ACL reconstruction. See Tables 1 and 2.

Two studies compared single bundle reconstruction with double bundle reconstructions.[11,20] In one study by Debieux, no significant difference regarding range of tibial rotation between the two techniques was detected.[11] The other study by Lee[20] showed less total rotation when performing double bundle reconstruction compared to single bundle at 30 and 60 degrees of flexion. Apart from the fact that amount of the applied force rotation was not recorded, all of these studies using CAS were graded to have a moderate to severe risk of bias in selection of subjects and/or confounding. See Figures 2 and 3.

Minguell was the only one to perform a study randomizing between a anteromedial portal technique (AMP) and a transtibial drilling technique (TT) to create the femoral tunnel.[22] The AMP group showed a more anatomic positioning of the graft in both sagittal and coronal planes. Preoperative there was no differences in range of tibial rotation between the groups. Postoperative the AMP group showed a significant difference regarding the improvement of absolute values of internal rotation (AMP: 4.9 deg, TT: 3.8deg, p = 0.016). However in terms of range of tibial rotation no difference is observed. Both techniques reduces the amount of total tibial rotation by 19%.[22] See tables 1 and 2.

Other measuring methods

Three more studies were retrieved studying tibial rotation after ACL reconstruction.[16,18,26] Hemmerich[16] used MRI to evaluate tibial rotation where Nordt[26] used CT scans. Both applied a 5Nm torque. Kidera[18] acquired 3D CT and biplanar fluoroscopy during squatting to evaluate tibial rotation after double bundle ACL reconstruction. This is the same technique as used by Miyaji[23] to study ACL Deficient subjects. A decrease in range of tibial rotation of 13.5% after ACLR is shown by Kidera, although this did not reach statistical significance. In this study, no significant difference between the injured and contralateral intact leg was reported. (14,9 and 14,5 degrees respectively).

Both studies of Nordt and Kidera are graded to have a serious risk of selection and confounding bias. See Figure 2.

Overall rating of quality of evidence

The majority of included studies were observational studies. Only four randomized controlled trials were included. According to the GRADE classification[14] the overall quality can be rated as low to very low. This is based on inconsistencies, imprecisions and risk of bias.

An overview of the quality assessment of the included trials is provided in Figures 2 and 3.

Evidence statements according to GRADE

Very Low Evidence: ACL rupture leads to increase of range of tibial rotation.

Low Evidence: ACL reconstruction leads to decrease of range of tibial rotation in relation to the injured state.

Table 1. Range of Tibial Rotation During Testing at Fixed Flexion Angle. Values for rotation are reported in degrees as mean or as mean ± SD.

	Measuring method	ACL status	Group specifics	Internal rotation	External rotation	Range of rotation	Relative improvement in rotation after ACL Reconstruction
0° of flexion							
Lee[20]	CAS	ACL def	na	11.9 (4.3)	9.1 (3.5)	20.5 (6.1)	28%
		SB recon	na	8.3 (3.3)	6.5 (2.6)	14.8 (5.0)	
		ACL def	na	11.8 (4.3)	9.9 (3.3)	21.8 (6.5)	23%
		DB recon	na	8.4 (2.6)	8.4 (2.8)	16.7 (3.9)	
Hemmerich[16]	MRI	ACL int	M	9.6 (4.3)	6.2 (3.0)	15.8	5%
		ACL def	M	9.1 (2.5)	8.0 (4.7)	17.1	
		SB recon	M	9.4 (1.3)	6.8 (2.7)	16.2	
		ACL int	F	9.5 (2.7)	7.0 (2.6)	16.5	25%
		ACL def	F	10.2 (4.1)	10.6 (1.6)	20.8	
		SB recon	F	9.4 (4.9)	6.3 (2.9)	15.7	
15° of flexion							
Haughom[15]	MRI	ACL int	na	dnr	dnr	8.3 (3.6)	na
		ACL control	na	dnr	dnr	7.7 (5.6)	
		ACL def	na	dnr	dnr	15.7 (6.9)	
		ACL int	na	dnr	dnr	13.6 (4.7)	
		ACL control	na	dnr	dnr	10.0 (4.3)	
		ACL def	na	dnr	dnr	15.1 (4.3)	
20° of flexion							
Nordt[26]	CT	ACL int	na	10.8	7.4	18.2	na
		SB recon	na	8.7	9.1	17.8	
30° of flexion							
Christino[9]	CAS	ACL def	M + F	21.86 (4.37)	17.08 (3.80)	38.9	25%
		SB recon	M + F	14.99 (4.39)	14.29 (3.52)	29.28	
		ACL def	M	20.45 (4.15)	17.0 (4.09)	37.45 (5.2)	25%
		SB recon	M	13.86(4.2)	14.39 (3.21)	28.25 (4.6)	
		ACL def	F	24.05 (3.79)	17.21 (3.34)	41.27 (4.77)	25%
		SB recon	F	16.75 (4.11)	14.13 (3.97)	30.89 (5.49)	

Table 1. continued

	Measuring method	ACL status	Group specifics	Internal rotation	External rotation	Range of rotation	Relative improvement in rotation after ACL Reconstruction
Christino[10]	CAS	ACL def	Adult	21.5	16.9	38.4	25%
		SB recon	Adult	14.4	14.2	28.7	
		ACL def	Adolesc	23.3	17.7	40.9	23%
		SB recon	Adolesc	17.1	14.5	31.6	
Debieux[11]	CAS	ACL def	na	21.3 (7.0)	15.0 (4.2)	36.3	21%
		SB recon	na	16.7 (5.1)	12.0 (4.6)	28.7	
		ACL def	na	21.1 (6.9)	17.9 (5.4)	39	20%
		DB recon	na	17.3 (4.8)	13.9 (5.0)	31.2	
Garcia-Bogalo[12]	CAS	ACL def	na	19 (3.62)	19.6 (3.26)	38.6	25%
		SB recon	na	12.2 (3.76)	16.9 (4.42)	29.1	
Lee[20]	CAS	ACL def	na	17.3 (3.9)	16.2 (3.7)	33.5 (4.5)	21%
		SB recon	na	13.7 (3.9)	12.8 (3.7)	26.6 (4.8)	
		ACL def	na	17.4 (4.4)	18.5 (4.0)	35.4 (5.0)	32%
		DB recon	na	11.5 (4.1)	12.5 (4.8)	24.0 (7.0)	
Hemmerich[16]	MRI	ACL int	M	8.9 (4.8)	14.6 (5.6)	23.5	5%
		ACL def	M	11.2 (3.6)	13.1(3.7)	24.3	
		SB recon	M	10.2 (3.6)	13.0 (5.3)	23.2	
		ACL int	F	8.8 (3.7)	13.9 (4.7)	22.7	-13%
		ACL def	F	8.3 (3.6)	12.6 (4.5)	20.9	
		SB recon	F	9.7 (3.7)	14.0 (7.4)	23.7	
Minguell[22]	CAS	SB AMP def	na	18.3(4.3)	18.1 (5)	36.4	19%
		SB AMP recon	na	13.4 (3.9)	16.1(2.3)	29.5	
		SB TT def	na	17.4 (3.8)	17.3 (4.3)	34.7	19%
		SB TT recon	na	13.6(3.7)	14.6 (4.1)	28.2	
Grassi[13]	CAS	ACL def	na	dnr	dnr	25.4	na
60° of flexion							
Lee[20]	CAS	ACL def	na	19.2 (4.7)	14.8 (3.4)	34.6 (6.9)	17%
		SB recon	na	14.4 (3.1)	13.3 3.7)	28.7 (4.8)	
		ACL def	na	18.6 (4.5)	16.6 (4.9)	33.9 (6.6)	26%
		DB recon	na	13.4 (4.5)	11.7 (3.0)	25.1 (5.1)	

Table 1. continued

	Measuring method	ACL status	Group specifics	Internal rotation	External rotation	Range of rotation	Relative improvement in rotation after ACL Reconstruction
90° of flexion							
Lee[20]	CAS	ACL def	na	16.6 (3.3)	16.1 (4.1)	32.7(5.7)	24%
		SB recon	na	11.3 (3.6)	13.3 (3.8)	24.7 (5.2)	
		ACL def	na	16.2 (5.2)	15.2 (4.1)	31.4 (6.4)	25%
		DB recon	na	10.9 (5.2)	12.8 (3.8)	23.7 (7.7)	
Grassi[13]	CAS	ACL def	na	dnr	dnr	29	na

Na = not applicable; dnr = data not reported; Adolesc = adolescent; def = deficient; F =female; int =intact; M = male;

recon = reconstruction; MRI = Magnetic Resonance Imaging; CT = Computed Tomography; CAS = Computer Assisted Surgery; ACL = anterior cruciate ligament; SB = single bundle; DB = double bundle

Table 2. Range of tibial rotation during dynamic testing in ACL deficient individuals

Author	Measuring method	Groups	Range of tibial rotation in degrees (SD)	Action performed
Miyaji[23]	Biplanar fluoroscopy	ACL intact	19.3 (7.2)	Wide-based squat, flexion phase
		ACL deficient	15.9 (5.7)	Wide-based squat, flexion phase
		ACL intact	20.0 (6.8)	Wide-based squat, extension phase
		ACL def	16.0 (5.7)	Wide-based squat, extension phase
Barance[6]	MRI	coper ACL deficient	4.5 (1.9)	0°-30° of active flexion
		non-coper ACL deficient	4.7 (2.7)	0°-30° of active flexion
		healthy control	5.8 (2.6)	0°-30° of active flexion

def, = deficient; int = intact; MRI = magnetic resonance imaging

Table 3. Study characteristics ACL deficient studies

Author	Measuring Method	Groups	Group specifics	Measurements	Action performed
Barrance[6]	MRI	Coper n =9 Noncoper n =9 Control n= 9	na	na	0°-30° of active flexion
Haughom[15]	MRI	Healthy controls n= 16 ACL deficient n= 11 ACLD CLI n = 11	Controls male n =8 Controls female n=8 ACLD male n =5 ACLD female n= 6	15°	3.35N IR and ER force and 44N axial force
Miyaji[23]	Fluoroscopy + 3D CT	ACLD subjects n= 35	ACLD n = 35 ACLD CLI n = 35	Flexion phase Extension phase	Wide based squat
Grassi[13]	CAS	ACLD subjects n = 42	na	30° and 90°	Manual rotational force

ACLD = anterior cruciate ligament deficient, CLI = contralateral intact, IR = internal rotatory, ER = External rotatory,

deg = degree, na = not applicable

Table 4. study characteristics ACLR subjects evaluated using CAS

Author	Design	Population	Groups	Surgical technique	Measurements	Force applied
Christino[9] (2015)	Retrospective	n=143	ACL-deficient ACL-reconstructed Male Female	anatomic SB hamstring and patella tendon	30° of flexion	manually
Christino[10] (2014)	Retrospective	n=113	ACL-deficient ACL-reconstructed Adults Adolescents	SB hamstring and patella tendon	30° of flexion	manually
Debieux[11]	RCT	n=20	ACL-deficient SB reconstruction DB reconstruction	anatomic SB and DB hamstring tendon	30° of flexion	manually
Garcia-Bogalo[12]	Retrospective	n=20	ACL-deficient ACL-reconstructed	anatomic SB 13 hamstring 4 patella 3 allograft	30° of flexion	manually
Lee[20]	RCT	n=42	ACL-deficient SB reconstruction DB reconstruction	anatomic SB and DB hamstring tendon	30° and 60° of flexion	manually
Minguell[22]	RCT	N= 116	ACL-deficient AMP technique TT technique	56 AMP 58 TT	30° of flexion	manually

ACL = Anterior Cruciate Ligament, SB = Single Bundle, DB = Double Bundle, RCT = randomised controlled trial, AMP = anteromedial portal, TT = transtibial

Table 5. study characteristics ACLR subjects evaluated using other evaluation methods

Author	Design	Population	Groups	Surgical technique	Measuring Method	Measurements	Force applied
Hemmerich[16]	RCT	n=32	Control SB reconstruction DB reconstruction*	anatomic SB and DB hamstring tendon	MRI	0° and 30° of flexion	manually mean 5.2Nm
Nordt[26]	Retrospective	n=21	Control SB reconstruction	BPTB	CT	20° of flexion	5Nm
Kidera[18]	Cross-sectional	N = 10	ACL-deficient⁺ ACL- reconstructed⁺	DB, hamstrings	2D/3D CT	dynamic	squatting

ACL = anterior cruciate ligament, SB = Single Bundle, DB = Double Bundle, BPTB = Bone Patellar Tendon Bone, RCT = Randomised Controlled Trial, MRI = Magnetic Resonance Imaging, CT = Computed Tomography,

* no data available on DB reconstruction group, ⁺ same subject pre- and postoperative

Figure 2. Analysis, according to ROBINS-I, for potential bias in included non-randomised trials.

Study	Potential bias for confounding	Potential selection bias	Potential bias in classification in interventions	Potential bias due to deviations from intended interventions	Potential bias due to missing data	Potential bias in measurement of outcome	Potential bias in selection of the reported result
Barrance[6]	L	L	na	na	NI	M	L
Haughom[15]	M	M	na	M	M	L	L
Miyaji[23]	L	S	na	na	NI	L	L
Grassi[13]	L	L	na	na	NI	L	L
Christino[9] (2015)	S	M	na	na	S	L	M
Christino[10] (2014)	S	M	na	na	NI	L	M
Garcia-Bogalo[12]	M	M	na	na	M	NI	L
Nordt[26]	S	S	na	na	NI	L	M
Kidera[18]	S	M	na	na	NI	L	L

L = low risk of bias M = moderate risk of bias S = serious risk of bias NI = no information na = not applicable

Figure 3. Quality assessment, according to RoB 2.0, of included randomized controlled trials

Study	Method of randomisation	Bias arising from the randomization process	Bias due to deviations from intended interventions	Bias due to missing outcome data	Bias in measurement of the outcome	Bias in selection of the reported result
Debieux[11]	Random number generation	L	L	L	S	L
Lee[20]	Unclear	S	L	L	S	L
Hemmerich[16]	Random allocation sequence	L	L	L	L	L
Minguell[22]	Computer-generated sequence into 2 groups, allocation ratio of 1:1	L	L	L	L	L

L = low risk of bias M = moderate risk of bias S = serious risk of bias NI = no information na = not applicable

Discussion

The studies regarding ACL deficient subjects differed too much in study protocols to compare results in a proper manner. Therefore, no general conclusion can be drawn on the amount of range of tibial rotation in ACL deficient subjects.

The included studies in this review report ACL reconstruction resulting in an average reduction of 17-32% of tibial rotation when comparing pre- and postoperative state. This finding seems to be consistent over different flexion angles. A study comparing it with a pre-injury state is yet to be designed, so whether it returns to pre-injury levels remains unclear.

Studies using Pivot shift test without an objective, external measurement technique for rotational measurement were excluded. Previous work by Musahl showed a wide variation in pivot shift technique as well as clinical grading between examiners.[24] Therefore the use of pivot shift as a sole measurement technique was regarded as a too subjective.

Several techniques for measuring tibial rotation have been used: MRI, biplanar fluoroscopy, CAS, motion capture systems and several newly developed devices. For the purpose of this review studies using motion capture systems have been excluded. The endless possibilities in (cutting) manoeuvres make comparison between studies very hard. Newly developed devices to measure tibial rotation were excluded when no reference method (e.g. CAS) was used as a comparison. A remarkable outlier in table 1 is the study performed by Hemmerich. Hemmerich used MRI scans before and after ACLR to compare the range of tibial rotation. Reported values are out of range when comparing them to the results of the other studies reported in table 1. Most likely this is the result of a different measuring technique. As Hemmerich is the only study using the MRI technique, the authors cannot validate their outcome.

Each measuring method has his own limitations. [21] When using CAS, sensors are placed on the tibia and femur which can be detected by infrared cameras. Measuring intra-operative rotation during computer assisted surgery has shown a high reliability and is easily applied and very reproducible. Skin and soft tissue movement are eliminated and pure bony movements are measured. Although there were differences between the patients studied (see table 4) it can be concluded, based on the included studies, that in both single and double bundle ACL reconstruction, the range of tibial rotation after ACL reconstruction is diminished directly after the reconstruction. On the down side, CAS is used intra-operatively, which eliminates muscle tone, as in cadaveric research, and is essentially in an unloaded situation. As a consequence, a reduced intraoperative range of tibial rotation cannot be related to the clinical situation. As measuring with CAS instruments is an invasive procedure, preferably performed during surgery, it is hard to re-evaluate subjects over time. Also, a comparison with normal pre-injury state is difficult. Using intraoperative measurements may also be incomparable to the clinical situation: First, after reconstruction, lengthening of the graft occurs after 2000 cycles of knee flexion-extension under moderate loading.[8] Due to creep of the ACL graft, lengthening of up to 20mm has been reported[8] , which may lead to residual, or perhaps renewed, laxity. Second, when hamstring tendons have been harvested to be used as a graft, one of the active stabilising structures counteracting external rotation of the tibia is weakened.

CAS however is a very accurate and reproducible tool to measure tibial rotation. A single examiner reproducibility of rotatory laxity is shown to be as little as 1,6 degrees.[21] Although motion capture systems show promising results in respect to accuracy[31] and skin motion artefact reduction tools have become more precise[3], the current literature regarding the use of motion capture systems in ACL reconstruction is too diverse to advise on a standard protocol. MRI, CT and biplanar fluoroscopy are only of limited use in studying a dynamic situation such as tibial rotation.

Another issue is the difference in patient characteristics and the intactness of other stabilising structures around the knee joint. In clinical studies, Haughom[15] and Christino[10] report a higher range of tibial rotation in females, which is not supported by Hemmerich.[16] Also, adolescents have shown to have higher range of tibial rotation compared to adults.[10]

The menisci, the capsule, the anterolateral ligament and the iliotibial band restrain the amount of internal rotation.[19] Concomitant injury to these structures may lead to an increased range of tibial rotation. None of the included studies reported if there was any meniscal injury, even though the influence of an intact meniscus on stability is well known.[2,25,27]

Study limitations and future research

The range of tibial rotation in the context of ACL insufficiency and reconstruction is a challenge which has not been answered yet. Internal and external rotation can only be measured in relation to a neutral position, which can be challenging to determine, especially when using repeated measurements over time. More over the knee demonstrates an internal as well as an external rotation moment during movement. For that reason, in this review only articles reporting the total range of tibial rotation are included. Total range of tibial rotation is of key importance in relating excessive tibial rotation to clinical giving way: an increased internal rotation may not lead to increased laxity when external rotation is reduced.

All the included studies lack proper description of the included participants and previous history of the knee. Three studies used randomisation between single bundle and double bundle reconstruction.[11,16,20] None of these studies used a blinded observer.

Due to the lack of uniformity in measuring techniques and study protocols, only descriptive statistics are provided. Meta-analysis or even providing means and averages is not statistically justified.

This review focussed on the role of the ACL in restraining rotational laxity. Other stabilising structures (i.e. iliotibial band, anterolateral ligament etc.) were not taken into account. No further analysis has been performed to evaluate the influence of the type of graft or surgical technique. Considered the presence of a lot of confounding variables, case-matching may be critical in future research to isolate the influence of the ACL on tibial rotation.

Clinical recommendations

When using CAS for evaluation of tibial rotation the authors would recommend a uniform measuring protocol. Based on findings in Tables 1 and 2, this protocol should contain measurements at 0, 30 and 60 degrees of flexion and a maximum of 5 Nm of rotational force. With more than 60 degree of knee flexion, no more increase in range of tibial rotation is seen, plus it would be of less clinical importance given the fact that the stance phase in most activities will not include a knee flexed to more than 90 degrees of flexion.

Conclusion

There is no a gold standard for measuring tibial rotation in current literature. Compared to the pre-operative state, an ACL reconstruction seems to achieve a reduction of 17-32% of range of tibial rotation, measured with CAS. Whether it returns to pre-injury levels remains unclear.

Based on the reviewed literature the use of CAS in studying ACL deficient and ACL reconstructed subjects shows reproducible results. However there are still many varying protocols being used. This review shows that, when using CAS, a maximum force of 5 Nm and flexion angles of 0,30 and 60 degrees are sufficient to detect relevant differences between the ACL deficient and ACL reconstructed state.

Normal values for the range of tibial rotation in ACL deficient and ACL reconstructed patients cannot be provided based on the current available literature due to lack of a uniform measuring techniques and protocols. The authors advocate uniformity in measuring tibial rotation as described above.

When future research is focussed around a uniform research protocol a meta-analysis might become within reach.

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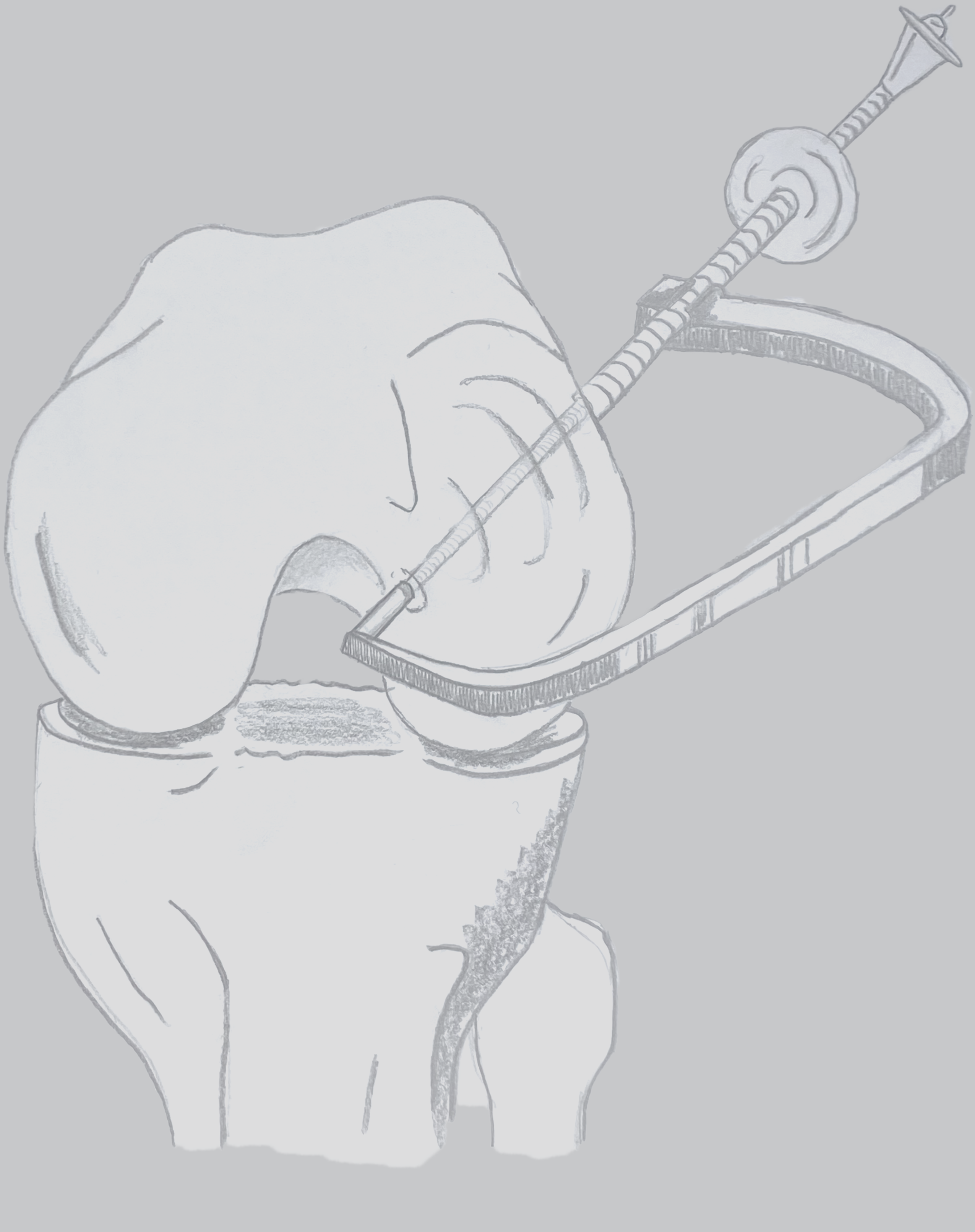

Chapter 3

High demand tasks show that ACL reconstruction is not the only factor in controlling range of tibial rotation.

A preliminary investigation.

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Abstract

Background: Excessive range of tibial rotation (rTR) may be a reason why athletes cannot return to sports after ACL reconstruction (ACLR). After ACLR, rTR is smaller in reconstructed knees compared to contralateral knees when measured during low-to-moderate-demand tasks. This may not be representative of the amount of rotational laxity during sports activities. The purpose of this study is to determine whether rTR is increased after ACL injury compared to the contralateral knee and whether it returns to normal after ACLR when assessed during high-demand hoptests, with the contralateral knee as a reference.

Methods: Ten ACL injured subjects were tested within three months after injury and one year after reconstruction. Kinematic motion analysis was conducted, analysing both knees. Subjects performed a level-walking task, a single-leg hop for distance and a side jump. A paired t-test was used to detect a difference between mean kinematic variables before and after ACL reconstruction, and between the ACL-affected knees and contralateral knees before and after reconstruction.

Results: RTR was greater during high-demand tasks compared to low-demand tasks. Preoperative, rTR was smaller in the ACL-deficient knees compared to the contralateral knees during all tests. After ACLR, a greater rTR was seen in ACL-reconstructed knees compared to preoperative, but a smaller rTR compared to the contralateral knees, even during high-demand tasks.

Conclusion: The smaller rTR, compared to the contralateral knee, seen after a subacute ACL tear may be attributed to altered landing technique, neuromuscular adaptation and fear of re-injury. The continued reduction in rTR one year after ACLR may be a combination of this neuromuscular adaptation and the biomechanical impact of the reconstruction.

Trial Registration: The trial was registered in the Dutch Trial Register (NTR: www.trialregister.nl, registration ID NL7686).

Key Terms: Anterior cruciate ligament injury, motion capture system, in vivo analysis, range of tibial rotation, knee

Introduction

In the population of young athletes, return to sports after ACL reconstruction (ACLR) has become an increasingly relevant outcome. A review of literature shows that a mere 55% of athletes can return to a competitive form of sports after ACLR.[1] Historically, reconstruction techniques have focused on restoring anterior tibial translation. However, it is known that the ACL also plays an important role in limiting tibial rotation.[13] Excessive tibial rotation can potentially lead to giving way. This persistent feeling of giving way may be a reason why athletes cannot perform at their pre-injury level of sports.

Tibial rotation has so far been measured during low-to-moderate-demand tasks (e.g. walking, cutting, pivoting). Increased tibial rotation is demonstrated in chronic ACL deficiency compared to healthy knees. After ACLR, decreased rTR compared to healthy knees has been shown.[7-10,12,22,25,26,29,31,36,40,42,43]

Decreased tibial rotation after ACLR does not comply with a potential persistent feeling of giving way after ACLR. One reason might be, that up to now, subjects have not been tested under sports related circumstances. While cutting and pivoting are considered relevant for sports activities, hoptests have the potential to test the combination of eccentric and concentric power and strength and neuromuscular coordination and knee stability.[37] We consider the fact that patients experience more rotational instability during high-demand activities like jumping, ultimately hampering return to sports rates.

Successful performance on a battery of hop tests is recommended as one of the criteria for return to sports, as these tasks simulate high-demand activities during pivoting sports, albeit in a controlled environment.[14,19,33] Measuring tibial rotation during hop tests using motion capture systems may provide more insight into knee kinematics during return-to-sports activities.

We hypothesize that range of tibial rotation (rTR) is greater in the ACL deficient knee compared to the contralateral intact knee and remain similar after ACLR when measured during high-demand functional tasks, replicating sports activities, while a decrease is seen during low-demand tasks, as is seen in previous studies. This study aims to determine rTR before and after ACLR, assessed during low- and high-demand functional tests.

Methods

Design

This trial was set up as a multicentre prospective cohort study. Martini Hospital and University Medical Center Groningen, both large teaching hospitals, served as recruiting centres. The study protocol was reviewed and approved by the Institutional Review Board of University Medical Center Groningen (registration ID 2015/524, UMCG trial register no. 201501098). The trial was registered in the Dutch Trial Register (NTR: www.trialregister.nl, registration ID NL7686).

Participants

From June 2016 to June 2018 all patients diagnosed with ACL injury in one of the participating hospitals were consecutively screened for eligibility to participate in the study. Inclusion criteria were: (1) age 18-35 years, (2) unilateral ACL rupture confirmed by physical examination, (3) less than three months post-injury at time of diagnosis, (4) at least six weeks of conservative therapy, (5) intact contralateral knee on physical examination, (6) absence of concomitant injury to cartilage, bone, meniscus or other ligaments on MRI. Exclusion criteria were: (1) any history of fractures, osteotomy or previous ligament reconstructive surgery in the lower extremities or spine, (2) neurological conditions leading to musculoskeletal disorders, (3) any other musculoskeletal pathology of the lower limbs (i.e. concomitant ligamental injuries or meniscal injuries), (4) inability to complete questionnaires in Dutch.

As presence or absence of any concomitant knee injury can influence the degree of tibial rotation; as injury to the menisci and anterolateral structures of the knee are known to play a role, we only included subjects without concomitant injury to the knee.

Conservative therapy prior to testing was initiated upon diagnosis and consisted of physiotherapy sessions at least 2 times per week. Pre-rehabilitation was performed according to the Dutch guideline on ACL injury and focused on decrease of effusion, increase of range of motion and quadriceps and hamstrings strengthening exercises.

Surgical procedure

All subjects underwent anatomic, single-bundle ACLR using a semitendinosus/gracilis graft as part of usual care. Both tendons were doubled to create a four-strand graft. The femoral tunnel was created independent of the tibial tunnel via an anteromedial portal technique. For femoral fixation a suspension type fixation was used (Endobutton, Smith&Nephew, London, UK). After pretensioning (60N), tibial fixation was performed by using a PEEK screw and plug (Biosure PK, Smith&Nephew, London, UK). Surgical procedures were performed by two orthopaedic surgeons experienced in ACLR. Surgeon allocation was dependent on site of inclusion.

Motion data collection

The motion data collection was performed at the motion lab of UMCG's Department of Rehabilitation Medicine. The motion lab consists of a 9m walkway with two 40x60 cm force plates (AMTI; Watertown, MA, USA) embedded in the floor. An 8-camera optoelectronic motion capture system (VICON MX, Vicon Motion Systems Ltd., Oxford, UK) sampling at 100Hz was used. The position of 22 14mm spherical markers distributed on the lower extremities according to Hayes and Davis was recorded.[11] Marker placement was performed by the same researcher during this study. After static and dynamic calibration, joint centres were calculated using VICON Nexus software v2.8 (VICON MX, Vicon Motion Systems Ltd., Oxford, UK). For the complete procedure and its sensitivity, see Keizer and Otten (2020).[21]

All subjects performed three tasks: (1) level walking at a self-selected pace; (2) a single-leg hop for distance (SLHD, maximum forward jump, jumping and landing on the same leg) (see Fig. 1); and (3) side jump (maximum sideways jump, jumping from and landing on the same leg) (see Fig. 2).

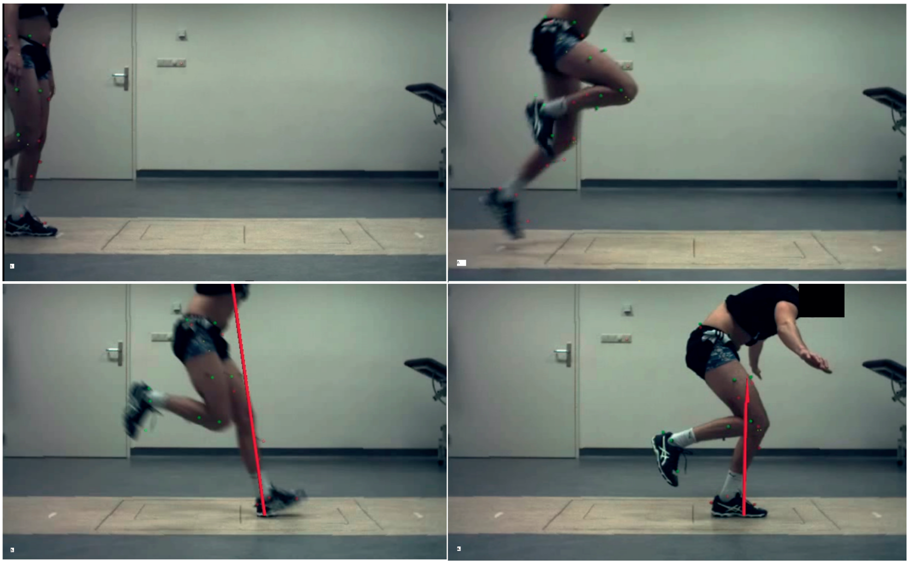

Figure 1. Example of a single-leg hop for distance

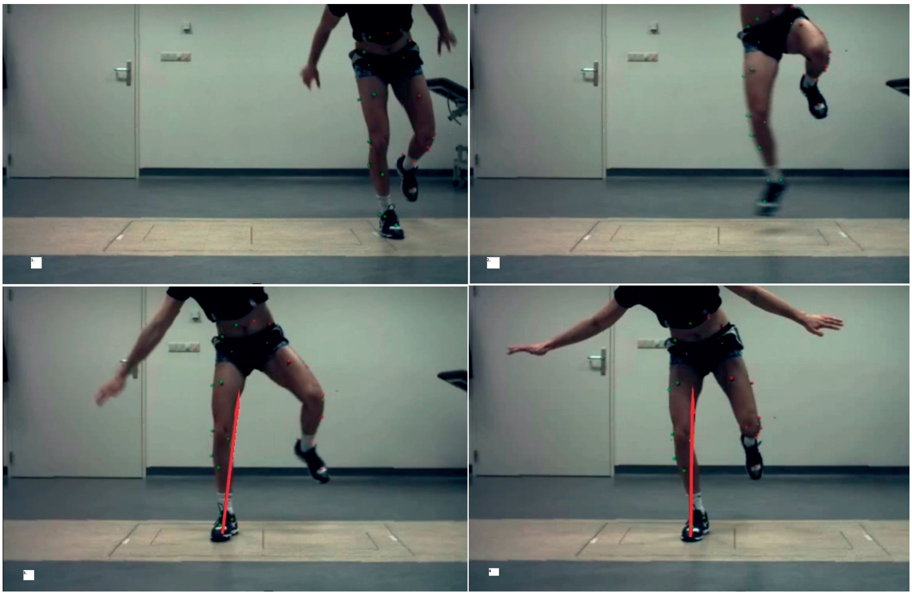

Figure 2. Example of a side jump

All jump trials were performed with hands in free motion and with sports shoes on. To familiarize subjects with the procedure and to make sure the entire foot landed on the force plate, subjects were asked to perform a dry run of the SLHD consisting of three practice trials. The median of the three practice hops was used to determine the starting distance from the force plates. For the side jump, leg length (greater trochanter tip to lateral malleolus tip) was used to determine the starting distance. Three approved trials per task were recorded for each knee to minimize the chances of data loss. Trials were approved when tasks were performed correctly (i.e. stable landing for at least 3 seconds), the entire foot landed on the force plate, and all markers were left in place. Approximately 13 months after the first trial – 12 months after ACLR – the testing procedure was repeated.

Data processing

The positions of the markers provided data to determine pelvic, femoral, tibial and foot segments. Using VICON Nexus software v2.8 and an additional custom MATLAB v9.7 script (The MathWorks Inc., Natick, MA, USA), three-dimensional angular displacements and translations in the knee joint were calculated. Data processing and analysis started at initial contact and continued for 200ms. Initial contact was defined as the moment at which the vertical ground-reaction force (GRF) was >5% of the body weight. All data were smoothed using the cross-validated quintic spline. Raw 3D marker position data were filtered using a low-pass frequency convolution filter of 10Hz with zero lag. A maximum gap (temporary absence of marker identification) of ten frames was accepted to fill in using the software. If a trial contained gaps exceeding 2.5 ms smoothing of the data could not be performed and was therefore rejected. If at least two successful trials were available for a kinematic variable, the variable was included in the analysis. Kinematic variables quantified and included were: maximum knee flexion, maximum knee extension, maximum knee valgus, maximum knee varus, anterior tibial translation, range of tibial rotation and knee flexion moment. Knee flexion moment was calculated from the GRF vector and its lever arm to the centre of the knee of the stance leg. To quantify anterior tibial translation and knee angles, two coordinate systems were reconstructed in the tested knee using the customized MATLAB script based on the method of Boeth et al.[6] One system was reconstructed in the femoral segment (parent system) and one in the tibial segment (child system). The motion of each coordinate system was consistent with the movement of the respective segment. Anterior tibial translation was quantified in millimetres using the relative movement of the centre of rotation of the tibial coordinate system relative to the centre of rotation of the femoral coordinate system in the local tibial coordinate system. Tibial rotation was quantified by the angle between the two axes of rotation, as described by Keizer and Otten.[21] Flexion/extension, varus/valgus angles were obtained using scalar products as in the equations explained by Robertson et al.[38]

Statistical analysis

Statistical analysis was performed using SSPS (v23; IBM Corp, Armonk, NY, USA). Since we had a small sample size, determining the distribution of the rTR was important for choosing appropriate statistical tests. A Shapiro-Wilk test was performed and did not show evidence of non-normality. Based on this outcome, and after visual examination of the QQ plot, we decided to use parametric tests. Means were calculated for each subject over the trials to obtain one value for each kinematic parameter per task. If at least two successful trials were available for a kinematic variable, the variable was included in analysis. To compare means of a kinematic variable a paired t-test was used with a significance level of $p<0.05$. Three comparisons were made regarding the means of all kinematic data:

- Comparison of the pre-operative ACL-deficient knee vs. the post-operative ACL reconstructed knee (different time, same knee)
- Comparison of the pre-operative ACL-deficient knee vs. the pre-operative contralateral ACL-intact knee (same time, different knee)
- Comparison of the post-operative ACL-reconstructed knee vs. the post-operative contralateral ACL-intact knee (same time, different knee)

Results

A total of 394 subjects with ACL injury were screened for participation in the study. 57 subjects met the inclusion and exclusion criteria and were asked to participate in the study. Ten subjects provided informed consent and were included in the study. All subjects underwent pre-rehabilitation as described before. Six males and four females remained and completed the primary testing procedures. At follow-up, one year after surgery, seven subjects participated (n=7), as one subject had sustained a re-rupture (four months after reconstruction, due to a new trauma) and two subjects were lost to follow-up as they moved away from the Groningen region. The first measurements from the subjects lost to follow-up were included only in the pre-operative analyses comparing ACL deficient knees to the contra-lateral intact knees.

The patient who re-tore its ACL displayed less range of tibial rotation in both knees during level walking, compared to the group mean. During high demand activities no major differences regarding rTR were found. The rTR for the subject with the re-tear of the ACL were as follows for the ACL deficient knee: level walking 6.9 (SD 1.1) degrees, SLHD 16.2 (SD 0.5) degrees and SJ 15.4 (SD 0.9) degrees. For the ACL intact knee the rTR was 10.6 (SD 0.2) degrees during level walking, 25.7 (SD 2.6) degrees during the SLHD and 22.8 (SD 3.2) degrees during the SJ.

Patient characteristics are presented in Table 1. No additional injuries to the menisci or cartilage were observed during surgery. No post-operative complications were reported. The mean distances for the SLHD were 105 cm (SD 33) for the ACL-deficient knees and 131 cm (SD 28) for the contralateral intact knees pre-operatively (significant difference, p=0.01). One year after ACLR the SLHD was 115 cm (SD 50) for the ACL-reconstructed knees and 124 cm (SD 42) for the contralateral intact knees (non-significant difference, p=0.11).

A mean limb symmetry index for the SLHD test of 88% was achieved one year post-operatively. Four out of seven participating subjects had returned to sports activities 12 months post-operatively, three of them at their pre-injury level, based on participants reports.

Kinematic outcome

During the first test 1080 values were acquired (ten subjects, two knees, six variables, three trials for walking, three trials for SLHD and three trials for side jump). A total of 50 values had to be discarded due to technical errors (4.6%, n=10 in normal walking, n=27 in SLHD, n=13 in side jump) which were evenly distributed over the subjects. Seven participants performed the second test, leading to acquisition of 756 values, 30 of which had to be discarded due to technical errors (3.9% n=18 in normal walking, n=12 in SLHD, n=0 in side jump). No variables had to be discarded due to missing data.

Table 1. Patient characteristics (n=10) and timeline.

	Mean (SD)
Age	24 (4.4) years
Total body length	184 (10) cm
Total body weight	81.3 (8.9) kg
Body mass index	24.0 (2.1) kg/m^2
Dominant leg injured	8 out of 10
Injury to first test interval	3.2 (1.2) months
Injury to surgery interval	4.6 (2.5) months
Surgery to second test interval (n=7)	11.7 (1.9) months
First to second test interval (n=7)	13 (1.1) months

A significant difference between mean rTR in ACL-deficient knees compared to ACL-reconstructed knee was shown during the side jump. During all functional tests, a greater rTR was demonstrated after ACL reconstruction than shortly after ACL injury. This difference was only significant during the side jump (18.2 vs. 15.1, p=0.04). The same trend was seen during level walking and the SLHD, but these differences in rTR were not significant. These results are displayed in table 2; the values represent the data from the seven subjects who were available for both pre-operative and post-operative measurements. Before reconstruction, as shown in Table 3, rTR was smaller in ACL-deficient knees than in ACL-intact knees, although this difference was not significant.

Table 2. Mean range of tibial rotation for ACL-deficient and ACL-reconstructed knees (same knee, different timepoint) during level walking, SLHD and side jump. N=7.

	***Range of tibial rotation* (degrees (SD))**		
	ACL-deficient	**ACL-reconstructed**	**P-value†**
Level walking	13.0 (2.2)	14.1 (3.9)	0.38
SLHD	16.3 (5.0)	17.4 (4.0)	0.39
Side Jump	15.1 (5.3)	18.2 (4.7)	0.04*

SLHD = single-leg hop for distance, SD = standard deviation

† Results of paired t-test comparing means of ACL-deficient and ACL-reconstructed knees

* indicates a significant result

Table 3. Mean range of tibial rotation for ACL-deficient and ACL-intact knees, both tested within three months after ACL injury, during level walking, SLHD and side jump. N=10.

	Range of tibial rotation (degrees (SD))		
	ACL-deficient	**ACL-intact**	**P-value†**
Level walking	13.7 (4.1)`	16.4 (5.6)	0.21
SLHD	16.9 (3.7)	19.4 (5.5)	0.21
Side Jump	16.6 (5.8)	20.7 (3.6)	0.08

SLHD = single-leg hop for distance, Nm = newton-metre, SD = standard deviation

† Results of paired t-test comparing means of ACL-deficient and ACL-reconstructed knees

After reconstruction a significant difference in rTR between ACL-reconstructed and contralateral ACL-intact knees was found, as shown in Table 4: a significantly smaller rTR was observed in ACL-reconstructed knees compared to contralateral ACL-intact knees during all high-demand functional tests.

Table 4. Mean range of tibial rotation for ACL-reconstructed and ACL-intact knees, both tested one year after ACLR, during level walking, SLHD and side jump. N=7.

	***Range of tibial rotation* (degrees (SD))**		
	ACL-reconstructed	**ACL-intact**	**P-value†**
Level walking	14.1 (3.9)	16.8 (4.6)	0.09
SLHD	17.4 (4.0)	22.8 (4.3)	0.01*
Side Jump	18.2 (4.7)	22.8 (5.6)	0.03*

SLHD = single-leg hop for distance, SD = standard deviation

† Results of paired t-test comparing means of ACL-deficient and ACL-reconstructed knees

* indicates a significant result

Figure 3 is a graphical representation of the results displaying mean rTR in ACL deficient, ACL intact and ACL reconstructed knees during the three different tasks.

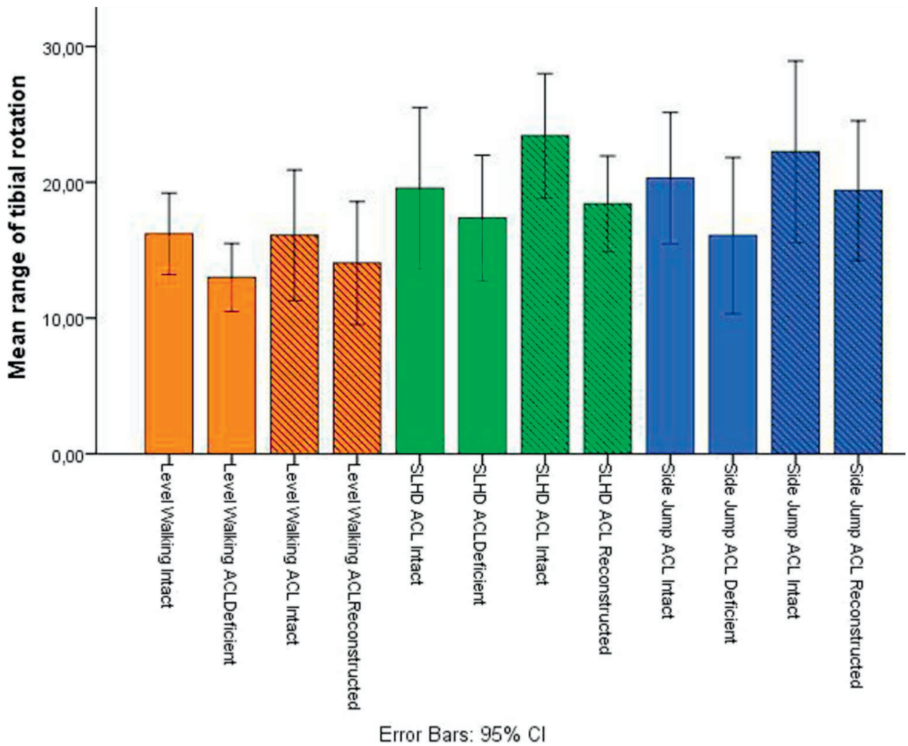

Figure 3 A bar chart illustrating mean rTR with a 95% confidence interval in ACL deficient knees, ACL intact knees both pre-and post-operative and ACL reconstructed knees during level walking, the SLHD and the side jump. Orange bars represent data obtained from level walking. Green bars represent data from a single leg hop for distance and blue bars represent data from a side jump. Bars with diagonal lines represent data from measurements one year after ACL reconstruction whereas bars without lines represent data from the pre-operative measurements, within 3 months after ACL injury.

The supplemental material appendix A shows an overview of the means of maximum knee flexion, maximum knee extension, maximum knee valgus, maximum knee varus, knee flexion moment and maximum anterior tibial translation. No significant difference was seen in maximum knee flexion, maximum knee extension, maximum knee valgus, maximum knee varus or knee flexion moment during the SLHD and side jump between ACL-deficient and contralateral ACL-intact knees. During level walking ACL-deficient knees showed significantly less maximum knee extension than contralateral intact knees (5.5° vs. 3.5°, p=0.02). This difference became apparent towards toe-off and not on initial contact.

ACL-reconstructed knees showed more maximum knee flexion (60.7° vs. 53.0°, p=0.03) and less maximum knee extension (22.8° vs. 19.4°, p=0.03) during the SLHD compared to the ACL-deficient knees. During level walking ACL-reconstructed knees showed less maximum knee flexion than contralateral ACL-intact knees (41.1° vs. 43.6°, p=0.04).

During the SLHD the knee flexion moment was 5-6 times higher compared to level walking and 3 times higher compared to the side jump. There was no significant difference in the generated knee flexion moment between the injured and contralateral intact knees. See supplemental material Appendix A.

Discussion

The main finding of our study was that, when measuring rTR in patients with a subacute ACL tear, a decrease in rTR compared to the contralateral knee was observed. Furthermore, one year after ACLR the rTR remained less than the contralateral knee. A combination of altered muscular contraction patterns and landing strategies may be responsible for these findings, rather than the result of the ACLR.

We observed a greater rTR during high-demand activities than during low-demand activities. During the hop tests the knees were exposed to a knee flexion moment six times higher than during level walking (Appendix A). The hop tests have thus been a way of presenting a biomechanical challenge as well as a psychological one, in which fear of new injury may also have played an important role. Psychological factors like kinesiophobia, self-efficacy and fear of re-injury have been determined as important in ACL rehabilitation.[2] By asking subjects to perform a complex high-demand task, the effects of potentially deployed compensatory mechanisms become measurable. Hypothetically, a compensatory mechanism including altered muscular contraction may explain our findings, both before and after surgery. The exact mechanism of compensation cannot be determined based on our results, but as increased hamstring muscle activity can reduce anterior tibial translation[39], and increased activity of the m. biceps femoris in collaboration with the iliotibial band can be responsible for counteracting the rotational forces, we hypothesise that even shortly after the injury a neuromuscular adaptation in patients with ACL-deficient knees may occur. Neuromuscular control is the result of a complex integration of vestibular, somatosensory and visual stimuli and is affected by situational awareness, arousal and attention.[18] Muscular contraction is continuously fine-tuned on the anticipated demands of the knee to preserve joint equilibrium and stability. After ACL injury, it is suggested that the central nervous system relies more on visual feedback and spatial awareness, as the biomechanical feedback is disturbed.[18] Accordingly, previous studies showed that muscle activation patterns of patients with an ACL-injured knee and after an ACLR are modified compared to healthy knees.[5,16,24,39] This 'increased stiffening' strategy as compensation for perceived instability has been proposed before; by altering jumping technique (less high and less far), and landing technique (less knee flexion), more stiffness is introduced in the knee joint.[16] Altered landing techniques were also demonstrated by Keizer et al. in healthy subjects with intact ACLs but with higher knee laxity.[20] In our study we also observed less maximum knee flexion in ACL-deficient knees compared to ACL-reconstructed knees, but there were no or only very small differences between the affected and the contralateral ACL-intact knees in terms of maximum knee flexion. When muscular compensation and, through this, altered landing kinematics indeed are a valid explanation for our observations, this mechanism would prevent symptomatic knee laxity in chronic ACL deficiency too. Yet, in the acute phase, shortly after a traumatic event, fear of re-injury may contribute to increased stiffening as well[41], and as the fear diminishes over time this can cause the knee laxity to become clinically apparent. We therefore hypothesise that a combination of an altered landing strategy, altered muscular contraction patterns and fear of re-injury can lead to a smaller rTR in ACL-affected knees.

Our results differ from other study results regarding rTR in ACL deficiency. Cadaveric studies and studies in passive situations have shown that rupture of the ACL allows more, passive, rotation of the tibia.[44] An increased rTR in ACL deficiency compared to healthy knees has also been shown during functional yet low to moderate demand tasks.[7,31,36,42,43] Results from these studies are shown in Table 5. As seen in table 5, we measured a smaller rTR after ACLR compared to the contralateral intact knee, as did other authors.

Table 5. Overview of reported values for range of tibial rotation using motion capture systems.

Author	Task performed	ACL status	Range of tibial rotation
Zee (current study)	SLHD	Intact	19.4°
		Deficient	16.9°
		SB reconstruction	18.4°
Cheng [7]	Jump off platform, pivot 90°	Intact	6.7°
		Deficient	13.5°
		SB reconstruction	7.8°
		DB reconstruction	7.5°
Lam[25]	Jump off platform, pivot 90°	Deficient	12.6°
		SB reconstruction	8.9°
Misonoo[31]	Jump off platform, pivot 45°	Intact	20.8°
		SB reconstruction	21.4°
		DB reconstruction	22.0°
Ristanis[36]	Step off stairs, pivot 90°	Intact	19.0°
		SB reconstruction	18.6°
Tsahouras[42]	Standing, pivoting 60°	Intact	13.9°
		Deficient	15.1°
		SB reconstruction	13.4°
		DB reconstruction	13.4°
Tsahouras[43]	Step off stairs, pivot 60°	Intact	14.2°
		Deficient	15.3°
		SB reconstruction	12.7°
		DB reconstruction	13.9°

ACL = anterior cruciate ligament, SLHD = single-leg hop for distance, SB = single bundle, DB = double bundle

Two key features of our study are distinctly different from previous research, which could explain the differences found in the ACL-deficient knees: we performed our tests within three months after injury and used high-demand tasks. Firstly, time since injury is an important aspect when measuring rTR in ACL-deficient knees, as it seems that in the acute phase subjects are able to limit rTR. Testing more than one year after the injury, both Cheng and Tsarouhas found a greater rTR in ACL-deficient knees compared to contralateral intact knees.[7,42,43] Miyaji et al., on the other hand, studied ACL-deficient subjects with a median time since injury of 10 weeks (range 3.3–450 weeks, mean 47 weeks) and observed a smaller rTR in the ACL-deficient knees compared to uninjured contralateral knees during a wide based squat.[32] This is in accordance with our findings. These findings emphasise the influence of *time since injury* on knee kinematics after ACL injury. In the acute setting, subjects exhibit different jumping strategies during activities (protective secondary to recent trauma) than weeks later. Weeks later, the secondary stabilizers of the knee may have stretched due to the altered mechanical load in the absence of the ACL. This may lead to an alteration of kinematics of the knee with the passage of time.

Our study provides additional information for the debate on rTR due to a new measurement moment, namely in the acute phase after an ACL rupture. This also puts the post-operative measurements in a different light. Ristanis and Tsarouhas demonstrated that, after ACLR, rTR is smaller compared to contralateral-intact knees. [36,42,43]This has been attributed to overconstrainment of the graft.[31] It is questionable whether the reduced rTR post-operatively can be attributed to overtightening of the graft, as a smaller rTR was also found in ACL-deficient knees before ACLR (and even smaller compared to post-ACLR). Again, perhaps altered landing strategy, altered muscular contraction patterns and fear of re-injury should be taken into account more. Also, it has been shown in dogs that intact sensory nerves around the knee, probably by influencing protective muscular reflexes, play an important role in preventing the acutely unstable knee from rapid breakdown.[34] Our study may indicate that these strategies have already started at the initial evaluation within 3 months after injury and are indelible by one year after reconstruction.

Secondly, our study differs from previous research in terms of the used functional tasks: our subjects performed both low and high-demand functional tasks as opposed to previously reported low-to-moderate-demand functional tasks. Our results of rTR during level walking (low demanding) are comparable to earlier reports, both pre- and post-operatively.[4] The rTR has not been previously measured using a motion capture system while the subjects were performing a SLHD or a side-jump. A hop test is a complex, high-demand task in which a lot of force is generated in the knee, and can also induce fear of injury. As seen in the supplemental material appendix A over 5-6 times more knee flexion moment is applied to the knee during the SLHD compared to level walking. This is therefore likely the best functional test to mimic sports activities, but in a safe clinical setting. We recommend using hop tests when measuring rTR in the context of ACL injury or after ACLR. Plus, the uniform use of hop tests ensures that studies can be compared.

In our study a return to sports rate of four out of seven (57%) was achieved 12 months after ACL reconstruction which is representative for the recreational athlete according to the literature.[3] This emphasizes the lengthy recovery after ACLR. Return to sports within 12 months after ACLR may not be a realistic goal in all patients undergoing ACLR and pre-operative counselling should take this into account. Rehabilitation programmes that include perturbation training, agility training, vision training and sport specific skill training are essential after ACL injury and reconstruction.[18] The neuromuscular system adapts to unaccustomed loads, also known as overload.[17] Therefore for optimization of the neuromuscular system, changes in volume and intensity of training is needed, as without this, there is no need for the neuromuscular system to improve.[17] A periodized rehabilitation program aims to optimize the principle of overload. Rehabilitation planned according to the periodization concepts could allow better integration of the needs of the patients to return to sport.[17] When paying special attention to postural control and proprioceptive function of the knee during rehabilitation, significant smaller knee abduction moments were observed compared to traditional rehabilitation programmes, indicating better knee stability. [35]

Study strengths and limitations

A strength of our study is the fact that we measured rTR in contrast to absolute values of rotation. Other papers focusing on absolute values of tibial rotation showed that ACL-deficient subjects tend towards a more externally rotated tibia.[45] It is difficult to repeat the measurements with this method: subsequent measurements with marker placement in a slightly different position with respect to bony landmarks will lead to major differences[30], hence in a longitudinal study design the use of absolute values of rotation is not preferred. A relative outcome such as range of rotation is more reliable and allows for repeatable measurements over time.

In our study we used the contralateral intact knee as a comparison. There is sparse literature available that shows that the contralateral intact knee also shows an altered movement pattern after an ACL injury. This has been particularly demonstrated in the postoperative phase during hop testing.[15] Whether this occurs immediately after the injury is unclear. It also has been shown that abnormal geometrical characteristics in the knee, that may be present bilaterally, pose a risk factor for ACL injury.[27] Whether and how this affects the kinematics of the knee is unclear. We can compare our results to available literature regarding healthy knees. Liu et al studied knee kinematics during walking and running in healthy subjects.[28] Although the study of Liu et al use a different method to measure range of tibial rotation it can serve as a basis to compare our results to. Liu showed a rTR of 14.0 ± 4 degrees during walking at 3km/h and 15.5 ± 4.1 degrees during walking at 5km/h. These results seem comparable to our results during level walking, although we have not recorded the walking pace of our subjects. Also, leg dominance may be a potential confounder. In our population 8 out of 10 ACL injured knees were dominant legs. Whether and how this influenced our results is unclear.

Small sample size is an issue that has to be taken into account when evaluating our results. The narrow inclusion and exclusion criteria are mainly responsible for the small sample size. Subjects with concomitant injury were excluded as injury to the menisci and anterolateral structures of the knee are known to influence degree of tibial rotation.[23] This narrows the number of eligible subjects.

As some subjects with a recent ACL injury may have been reluctant to participate in the study after being informed on the hop test, a certain amount of selection bias may be present. Although the inclusion criteria were strictly based on the Dutch guideline for ACL injury, the motivation for definite participation could have been subject to individual variables like available time or fear for reinjury. Subjects with a greater feeling of giving way may not have participated.

Despite these limitations, in these patients we have objectively measured that rTR in the ACL-deficient knee is not greater than in the contralateral ACL-intact knee shortly after ACL injury. Further research is needed to elucidate why rTR is not higher or even lower in acute ACL injury. Up to now we have found no evidence to suggest that persistent increased rotational laxity hampers return to play after ACLR. Special attention to neuromuscular control, subjective knee function and psychological factors may help us better understand which factors play an important role in whether objective knee instability occurs, which ultimately may hamper return to sports rates. In this light, testing subjects in circumstances that replicate sport activities, i.e. using hoptests, is crucial.

Conclusion

No increase in range of tibial rotation is shown in subacute ACL-injured knees compared to contralateralal intact knees during high demand tasks. One year after ACL reconstruction, a smaller range of tibial rotation is observed compared to ACL-intact knees. Further research into altered motor control strategies and psychological factors like fear of re-injury could elucidate this unexpected phenomenon. We propose the use of hop tests as high-demand, complex tasks when evaluating range of tibial rotation both before and after ACL reconstruction.

Declarations

Ethical Approval statement

The study protocol was reviewed and approved by the Institutional Review Board of University Medical Center Groningen (registration ID 2015/524, UMCG trial register no. 201501098). The trial was registered in the Dutch Trial Register (NTR: www.trialregister.nl, registration ID NL7686).

Informed Consent statement

Informed consent was obtained from all individual participants included in the study. The authors affirm that human research participants provided informed consent for publication of the images in Figures 1a, 1b, 1c, 1d, 2a, 2b, 2c and 2d.

Competing interest statement
The authors have no relevant financial or non-financial interests to disclose.

Author contribution statement
Zee, van Raaij, Hijmans, van den Akker- Scheek and Diercks contributed to the study conception and design. Material preparation, data collection and analysis were performed by Zee and Keizer. The first draft of the manuscript was written by Zee and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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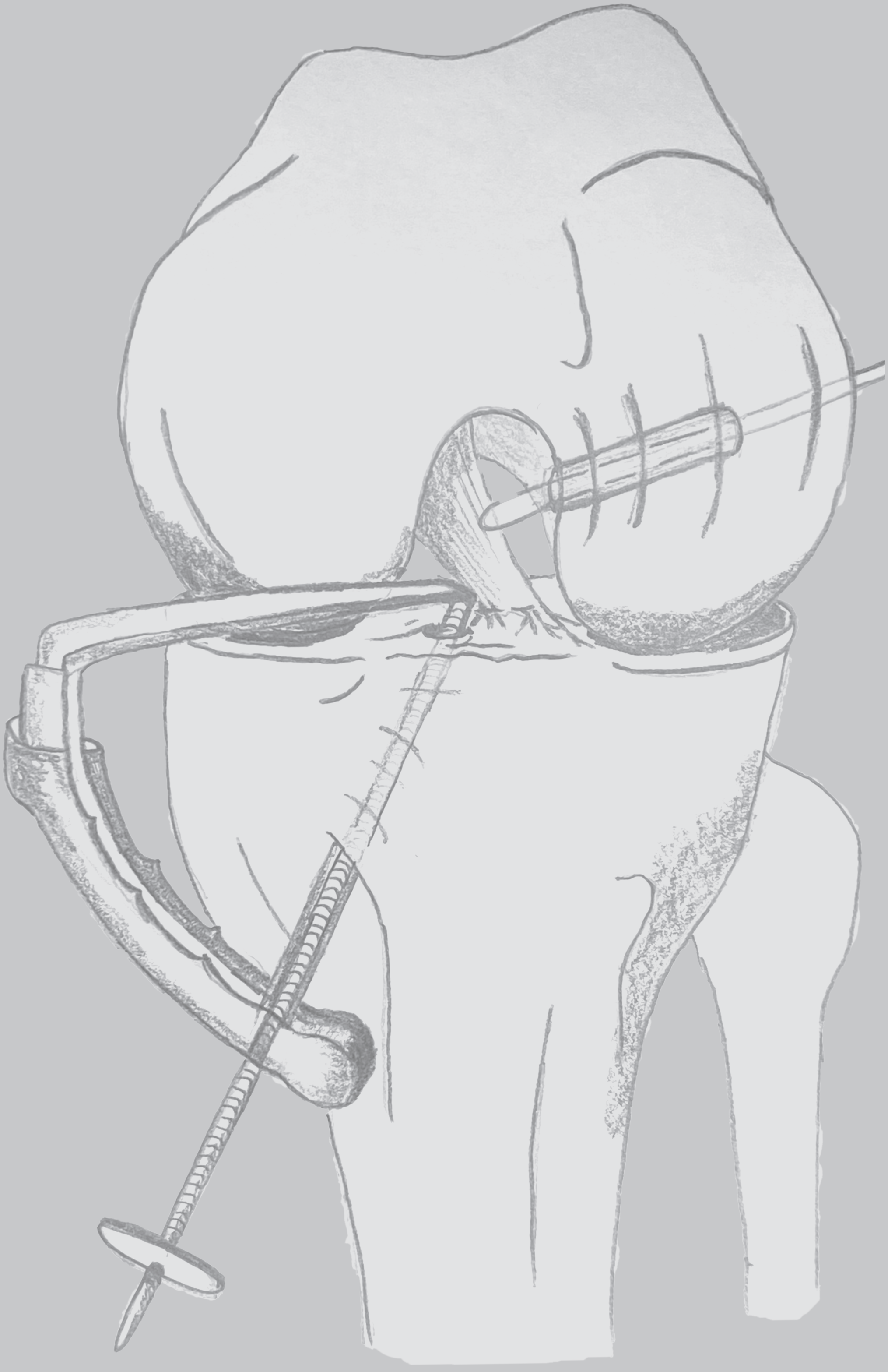
List of abbreviations

ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
ATT	Anterior Tibial Translation
GRF	Ground Reaction Force
Hz	Herz
Nm	Newton-meter
MRI	Magnetic Resonance Imaging
ms	milliseconds
rTR	range of tibial rotation
SD	Standard Deviation
SLHD	Single Leg Hop for Distance
UMCG	University Medical Centre Groningen

Appendix A

Kinematic/Kinetic variable	Pre-operative			Post-operative			
	ACL-intact	ACL-deficient	P-value 1	ACL-intact	ACL-reconstructed	P-value 2	P-value 3
Level Walking							
Max knee flexion, in degrees (SD)	42.7 (7.2)	41.4 (6.6)	0.33	**43.6 (4.5)**	**41.1 (4.9)**	0.30	**0.04***
Max knee extension, in degrees (SD)	**3.5 (2.2)**	**5.5 (3.5)**	**0.02***	4.7 (2.3)	6.0 (2.2)	0.81	0.13
Max knee valgus, in degrees (SD)	4.4 (1.8)	4.4 (1.7)	1.00	5.3 (2.2)	4.7 (1.9)	0.92	0.46
Max knee varus, in degrees (SD)	1.1 (1.2)	0,9 (0.5)	0.75	0.8 (0.9)	1.0 (0.8)	0.47	0.48
Knee flexion moment, in Nm (SD)	0.8 (0.3)	0.9 (0.3)	0.09	0.9 (0.3)	0.8 (0.2)	0.49	0.49
Max ATT, in mm (SD)	6.6 (3.0)	4.6 (4.8)	0.06	6.2 (6.6)	4.4 (6.6)	0.25	0.25
Range of tibial rotation	16.4 (5.6)	13.7 (4.1)	0.21	16.8 (4.6)	14.1 (3.9)	0.38	0.09
Single Leg Hop for Distance							
Max knee flexion, in degrees (SD)	57.5 (9.5)	**53.0 (6.7)**	0.13	61.4 (10.5)	**60.7 (10.4)**	**0.03***	0.75
Max knee extension, in degrees (SD)	19.4 (4.0)	**19.4 (2.7)**	0.98	20.4 (6.3)	**22.8 (3.5)**	**0.03***	0.30
Max knee valgus, in degrees (SD)	9.1 (4.5)	6.3 (3.8)	0.10	9.9 (4.9)	7.2 (1.8)	0.27	0.15
Max knee varus, in degrees (SD)	-0.3 (0.9)	1.5 (3.8)	0.16	0.3 (2.4)	1.1 (1.8)	0.60	0.50
Knee flexion moment, in Nm (SD)	5.2 (0.8)	6.2 (1.4)	.14	5.9 (1.9)	5.2 (1.0)	0.50	0.50
Max ATT, in mm (SD)	13.4 (7.2)	10.1 (5.4)	0.89	12.7 (3.4)	12.2 (8.5)	0.82	0.82
Range of tibial rotation	19.4 (5.5)	16.9 (3.7)	0.21	**22.8 (4.3)**	**17.4 (4.0)**	0.39	**0.01***
Side Jump							
Max knee flexion, in degrees (SD)	49.1 (16.4)	51.8 (7.2)	0.54	56.7 (7.4)	56.1(9.8)	0.15	0.77
Max knee extension, in degrees (SD)	25.2 (5.8)	29.6 (3.7)	0.06	28.3 (7.3)	29.7 (7.8)	0.74	0.44
Max knee valgus, in degrees (SD)	10.3 (5.2)	7.9 (4.9)	0.17	11.3 (6.4)	8.6 (3.0)	0.11	0.19
Max knee varus, in degrees (SD)	-2.0 (3.4)	0.0 (3.7)	0.10	-2.5 (4.0)	-0.3 (2.1)	0.43	0.10
Knee flexion moment, in Nm (SD)	1.9 (0.6)	2.4 (0.9)	.27	2.2 (0.7)	1.7 (0.5)	0.14	0.14
Max ATT, in mm (SD)	7.7 (5.8)	6.7 (5.5)	0.37	7.6 (5.5)	8.9 (7.6)	0.51	0.51
Range of tibial rotation	20.7 (3.6)	**16.6 (5.8)**	0.08	**22.8 (5.3)**	**18.2 (4.7)**	**0.04***	**0.03***

P-value 1 = results of paired t-test comparing means of ACL-deficient and contralateral ACL-intact knees
P-value 2 = results of paired t-test comparing means of ACL-deficient and ACL-reconstructed knees
P-value 3= results of paired t-test comparing means of ACL-reconstructed and contralateral ACL-intact knee
ATT = Anterior Tibial Translation Nm = newton-metre, SD = standard deviation



Chapter 4

More natural knee kinematics are strongly related to better self-reported knee function and psychological readiness to return to sports after ACL reconstruction.

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Submitted

Abstract

Background: It is unclear how rotational and translational lower limb kinematics relate to self-reported knee function and psychological readiness in anterior cruciate ligament reconstructed individuals.

Purpose: The purpose of this study was to evaluate the strength and direction of the correlation between objective lower limb kinematics, range of tibial rotation (rTR) and anterior tibial translation (ATT), and patient reported knee function and psychological readiness to return to sports during low and high demanding functional tasks after an anterior cruciate ligament reconstruction (ACLR).

Study design: Cross-Sectional Study

Methods: 3D motion analyses were conducted in seven subjects, one year after ACLR. The subjects performed a low demanding functional task (level walking) and two high demanding functional tasks (single leg hop and a side jump), to investigate the lower limb kinematics (rTR and ATT) of the reconstructed knee. Pearson's correlation coefficients were calculated to determine the correlation between the amount of tibial rotation and translation and score on the International Knee Documentation Committee (IKDC) and ACL-Return to Sports after Injury (ACL-RSI) questionnaires.

Results: *Large* to *very large* positive correlations were found between rTR and the IKDC and ACL-RSI scores during high demanding tasks. Negative correlations were found between rTR and the IKDC and ACL-RSI scores during a low demanding task. Negative correlations were found between ATT and the IKDC and the ACL-RSI scores during both high and low demanding tasks.

Conclusion: Knee kinematics are strongly correlated to self-reported knee function and psychological readiness after ACL reconstruction. The closer the knee kinematics are to the natural knee kinematics of an intact knee, the better the self-reported knee function and psychological readiness. Measuring rTR during high demanding tasks could potentially expose underlying altered movement strategies and provide more information about the relation between the biomechanics and patient reported outcome measures within the ACLR population.

Key Terms: Anterior cruciate ligament reconstruction, motion capture system, range of tibial rotation, anterior tibial translation, single leg hop for distance, side hop, psychological readiness, self-reported function

Introduction

A rupture of the anterior cruciate ligament (ACL) is the most common ligament injury in athletes and can be season or even career ending for many.[46] ACL reconstruction (ACLR) is indicated in athletes with persistent instability despite non-operative treatment, especially if they wish to return to jumping, cutting, and pivoting sports.[10] After ACLR, more than 90% of the athletes expect to return to their pre-injury level.[11] However, only 55% actually return to competitive sports.[4]Historically the focus of ACLR was restoring anterior tibial translation (ATT), however it is known that the ACLR also plays an important role in limiting the range of tibial rotation (rTR).[15] Despite reconstruction, numerous patients with ACLR report feeling instability in the knee or the knee giving way, especially in dynamic movements such as cutting and pivoting.[29] Instability and stiffness of the knee are known factors in unsuccessful return to sport.[2,13] How this instability manifests itself in the biomechanics of the lower limbs and how it relates to successful return to sport is unclear [32], although, altered biomechanics have been related to increased risk for secondary ACL injury. [7,27,35,36]

Kinesiophobia and fear of giving way are also associated with a decline in the rate of returning to preinjury level of sports.[2,13,33,38] This suggests that psychological factors play a significant role in (un)successful return to sport.[2] Fear of (re)injury is even one of the most cited reasons for patients to not return to sport.[24,43] Studies assessing psychological factors, for example with the ACL-Return to Sports after Injury (ACL-RSI) scale, showed that ACL patients with higher scores on psychological readiness were more likely to successfully return to sport.[14,25,26,40] Moreover, research has shown that patient reported outcome measures (PROMs) can differentiate between individuals with low versus high knee function, as well as those with more versus fewer knee symptoms.[28] Certain PROMs assessing self-reported knee function, like the IKDC questionnaire, have been related to objective outcome measures, such as extensor strength [48], hop distance [1,39,41], postural control [34], and neurophysiological impairments.[8]

Recent findings show that high demanding functional tasks that contain explosive power or the complexity of a landing after a jump, are necessary to investigate rTR.[49] It has been shown that walking gait biomechanics do not correlate with more demanding jump landing outcomes after ACLR.[37] Therefore, high demanding functional tasks may more readily reveal the influence and relation of psychological and biomechanical factors during rehabilitation compared to level walking or other low demanding tasks.

To our knowledge, the existing literature regarding the relationship between rotational and translational lower limb kinematics and patient reported outcome is limited. This knowledge is needed to better understand why some patients do and others do not successfully return to sport.

The primary purpose of this study was to evaluate the strength and direction of the correlation between objective lower limb kinematics (rTR and ATT) and patient reported function as well as psychological readiness to return to sports during level walking, a single-leg hop (SLH) landing, and a side jump one year after ACLR. It was hypothesized that during high demanding functional movements (SLH and side jump) stronger correlations between objective lower limb kinematics and patient reported function and psychological readiness will be seen than during low-to-moderate tasks (level walking).

Methods

Two large hospitals in the Netherlands included the subjects for this multicenter prospective cohort study. The study protocol was reviewed and approved by the Institutional Review Board of the University Medical Center Groningen (registration ID 2015/524, UMCG trial register no. 201501098). The trial was registered in the Dutch Trial Register (NTR: www.trialregister.nl, registration ID NL7686).

Participants

Patients scheduled for ACL reconstruction between June 2016 and June 2018 were screened whether they were eligible to participate in this study.

Inclusion criteria were: 1) Age between 18-35 years old, 2) unilateral ACL rupture, 3) intact contralateral knee on physical examination, 4) no concomitant injury to bone, cartilage, meniscus, or other ligaments on magnetic resonance imaging (MRI). Participants were excluded if any of the following were present: 1) any history of fractures, osteotomy or previous ligament reconstructive surgery in the lower extremities or spine, 2) a neurological condition leading to musculoskeletal disorders, 3) any other musculoskeletal pathology of the lower limbs, 4) the inability to complete the questionnaires in Dutch.

The menisci and anterolateral structures of the knee are known to play a role in the degree of tibial rotation.[23] Accordingly, the degree of tibial rotation can be influenced by the presence or absence of any concomitant knee injury. Therefore only subjects without concomitant knee injury were included.

Surgical procedure

Every subject underwent anatomic, single-bundle ACLR using a semitendinosus/gracilis graft. The tendons were doubled to create a four-strand graft. The femoral tunnel was created inside-out in the anatomical position using the anteromedial portal technique. A suspension type fixation was used for the femoral fixation (Endobutton, Smith&Nephew, London, UK).

The surgical procedures were performed by two orthopedic surgeons experienced in ACLR. Allocation was dependent on the site of inclusion.

Rehabilitation

Rehabilitation was performed according to the Dutch guidelines on ACL injury.[45] ACLR rehabilitators went through several phases in which new exercises and movements were added progressively. This program initially focused on increasing range of motion and to decreasing effusion. First, mainly with isometric exercises and electrostimulation. Subsequently, concentric, and eccentric exercises were implemented using closed and open kinetic chain exercises. In addition to strength training, neuromuscular training was added, and attention was paid to proper movement quality to prevent reinjury.

Motion data collection

Testing and data collection was performed at the motion lab of UMCG's Department of Rehabilitation Medicine. Two 40x60 cm force plates (AMTI; Watertown, MA, USA) were integrated in the floor of a 9m long walkway. An optoelectronic motion capture system (VICON MX, Vicon Motion Systems Ltd., Oxford, UK), with 8 cameras sampling at 100Hz was used. 22 14mm spherical markers were assigned and recorded on the lower extremities according to Hayes and Davis.[9] One researcher was responsible for marker placement during the entire study. After calibration, joint centers were calculated using VICON Nexus software v2.8 (VICON MX, Vicon Motion Systems Ltd., Oxford, UK).

Tests were performed approximately 12 months after ACL reconstruction. Al participants performed three tasks: 1) level walking at a self-selected pace; 2) a single-leg hop for distance (SLH maximum forward jump, jumping and landing on the same leg); and 3) a side jump (maximum sideways jump, jumping from and landing on the same leg). The trials were performed with sports shoes on and hands in free motion. The participants were given 3 practice jumps from which the median distance was obtained to determine the starting distance in front of the force plates. In this way it was ensured that the entire foot lands on the force plate and the participants could familiarize themselves with the task. To determine the starting distance for the side jump, the leg length (greater trochanter tip to lateral malleolus tip) was used. To increase the amount of satisfactory data, three approved trials per task were recorder for each knee. The trials were approved when tasks were performed correctly, i.e. the entire foot landed on the force plate, the landing was stable for at least 3 seconds, and all markers were left in place.

Data processing

Using VICON Nexus software v2.8 and an additional custom MATLAB v9.7 script (The MathWorks Inc., Natick, MA, USA), three-dimensional angular displacements and translations in the knee joint were calculated from the position of the markers. Processing and analysis of the data started at initial contact (defined as vertical ground-reaction force >5% body weight) and continued for 200ms. All data was smoothed using the cross-validated quintic spline. The raw 3D marker position data was filtered using a low-pass frequency convolution filter of 10 Hz with no lag. Software was used to fill any gaps in the data when there was a temporary (maximum gap of ten frames) absence of marker identification. When a trial contained gaps exceeding 2.5ms, smoothing of the data could not be performed, and was therefore rejected.

In order to quantify tibial rotation and anterior tibial translation, two coordinate systems were reconstructed in the tested knee using the customized MATLAB script based of the method of Boeth et al.[6] The parent system was reconstructed in the femoral segment and the child system in the tibial segment. The motion of each coordinate system was consistent with the movement of the respective segment. ATT was quantified in millimeters using the relative movement of the center of rotation of the tibial coordinate system to the center of rotation of the femoral coordinate system in the local tibial coordinate system. rTR was quantified by the angle between the two axes of rotation, as described by Keizer and Otten.[22] Only the data of the reconstructed knee was used in the analysis.

Patient reported outcome measures

To assess self-reported knee function and psychological readiness, the International Knee Documentation Committee (IKDC) questionnaire and the Anterior Cruciate Ligament Return to Sport After Injury (ACL-RSI) scale were used. Both are validated patient reported outcome measures for ACL-injured and reconstructed population. The validated Dutch translations were used.[18,20,42] The IKDC is one of the most used PROMs for ACL-injured population.[17,21] It is designed to measure function, symptoms, and sports activity. A higher score indicates a higher level of knee function and less knee symptoms.[17] The ACL-RSI measures psychological readiness to return to sport after ACL-reconstruction.[47] It is designed to measure emotions, confidence, and risk appraisal.[31,47] A higher score indicates greater psychological readiness for return to sport.[31]

Statistical analysis

The statistical analysis was performed using SPSS (v27; IBM Corp, Armonk, NY, USA). The correlation between the objective lower limb measures (rTR, ATT) and self-reported measures (IKDC, ACL-RSI) was examined by calculating Pearson's correlation coefficients. These coefficients had magnitude thresholds defined as trivial (< 0.1), small (0.1 to < 0.3), moderate (0.3 to < 0.5), large (0.5 to < 0.7), very large (0.7 to < 0.9) based on previous research.[19] All data was checked for normality and significance was set at an alpha level of 0.05.

Results

Patient characteristics, mean rTR, mean ATT, mean IKDC and ACL-RSI scores are shown in table 1. No data was deleted due to missing data and all data was normally distributed.

Large to *very large* positive correlations were found between rTR and the IKDC and ACL-RSI scores during high demanding tasks. Negative correlations were found between rTR and the IKDC and ACL-RSI scores during the low demanding task. Scatterplots displaying rTR on the X-axis and the IKDC and ACL-RSI scores on the Y-axis are shown in Figure 1. Scatterplots displaying ATT on the X-axis and the IKDC and ACL-RSI scores on the Y-axis are shown in Figure 2. *Small*, *moderate* and two *large* negative correlations were found between ATT and the IKDC and ACL-RSI scores. All Pearson correlation coefficients are shown in Appendix

Table 1. Patient characteristics, motion data and patient reported outcomes (n = 7).

Gender (male/female)		**5/2**
Age (years)		24.6 ± 4.3
Height (cm)		185 ± 11
Weight (kg)		82.6 ± 7.4
Body Mass Index (kg/m^2)		24.3 ± 2.2
Time between Injury and surgery (months)		4.7 ± 2.6
Time between surgery and test (months)		11.8 ± 1.9
rTR (deg)	Walking	14.1 ± 3.9
	SLH	17.4 ± 4.0
	Side Jump	18.8 ± 4.7
ATT (mm)	Walking	4.4 ± 6.6
	SLH	12.2 ± 8.5
	Side Jump	8.9 ± 7.6
IKDC		81.2 ± 15.6
ACL-RSI		66.4 ± 24.9

Means ± SD are shown. rTR = range of tibial rotation, ATT = anterior tibial translation, SLH = single leg hop

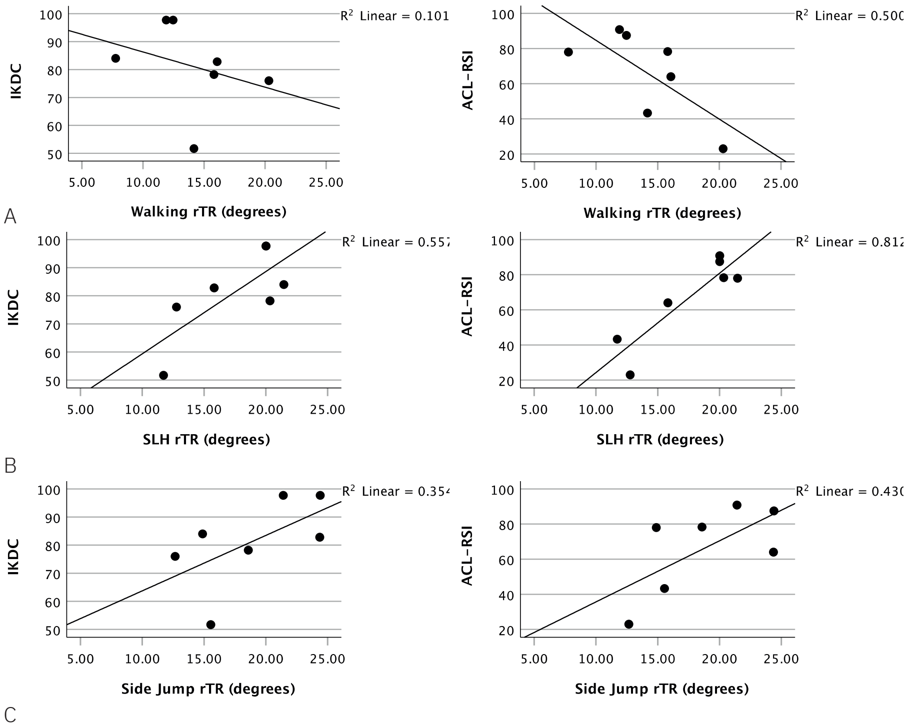

Figure 1. Scatterplots of correlations between range of tibial rotation (rTR) and IKDC or ACL-RSI scores. R^2 = explained variance. a = during level walking, b = during Single Leg Hop, c = during Side Jump

Discussion

This study shows that, one year after ACLR, objective rTR has a strong positive correlation with self-reported knee function and psychological readiness to return to sport during high demand tasks but a negative correlation during a low demanding task. In contrast, the relation between ATT and self-reported knee function and psychological readiness was negative and did not show a discrepancy between low or high demanding tasks.

The correlation between ATT and the self-reported knee function and psychological readiness were negative, indicating that larger ATT is associated with poorer self-reported knee function and psychological readiness. In contrast, the opposite was true for the correlation between rTR and self-reported knee function and psychological readiness. In our previous study, contralateral intact knees show a mean rTR of

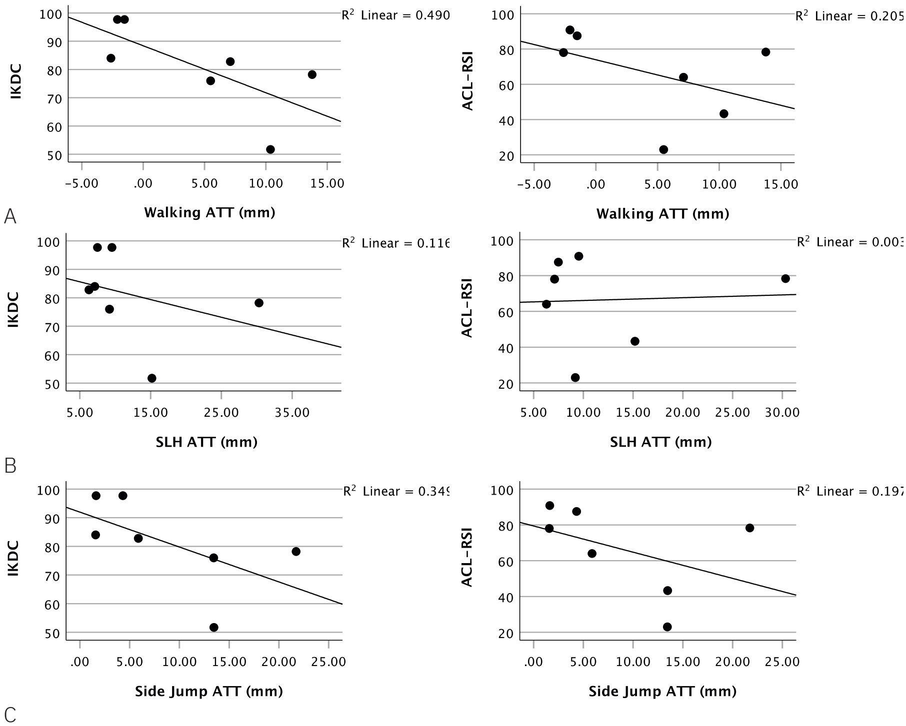

Figure 2. Scatterplots of correlations between anterior tibial translation (ATT) and IKDC or ACL-RSI scores. R2 = explained variance. a = during level walking, b = during Single Leg Hop, c = during Side Jump

approximately 20 degrees during a SLH.[49] This may imply that the greater rTR as shown in the present study may in fact be a manifestation of a more natural movement of the knee, and not a sign of increased rotational laxity. We therefore conclude that more normal knee kinematics after ACLR are correlated to better self-reported knee function and psychological readiness. The aim for ACLR therefore must be to restore pre-injury knee kinematics, rather than strictly pursuing regaining knee stability. This asks for a patient specific approach during ACL reconstruction.

We have observed that less rotation is related to poorer self-reported knee function and less psychological readiness. In the past, over-tensioning of the graft, and thus limiting rTR, has been suggested to reduce knee function.[5] However, this explanation seems unlikely, as during level walking, less rotation does not seem to be related to poorer self-reported knee function. A more convincing argument could be found in altered movement strategies. Previous research has shown that ACLR individuals adopt a “protective” strategy characterized by stiff movements including limiting range of motion, and co-contraction around the knee joint.[30,43,44] Markstrom et al. (2022), showed that ACLR individuals with high fear of re-injury implement this aforementioned protective strategy with higher muscular activity patterns to presumably stabilize the knee joint. This study could not find an association between kinematics and fear of injury; however, they did not include measurements of rTR.

We have observed a discrepancy in the correlation between rTR and the self-reported knee function and psychological readiness between low and high demanding tasks. Rehabilitation (and thus return to sport) is a process in which the goal is to improve step by step. First to regain full range of motion, and subsequently to improve strength and coordination. Eventually, the transition from gym to field training is made, after which it is time to rejoin team training and finally to return to in competition play. During this continuum, the guidance that is offered to the ACLR patient varies and is adjusted in a patient specific manner during every step of the way. Therefore the tests during this process should also be adapted. It has been suggested to adapt return to sport tests to a certain context, specificity, and intensity for each specific phase (and sport).[16]

Level walking can be a method to determine a patient’s starting point at the beginning of the rehabilitation process. As patients progress in their rehabilitation, more sport specific and demanding tasks are necessary. This is in line with previous research showing that it is important to mimic the intensity of sports situations as closely as possible to be able to assess knee function, during rehabilitation.[12] It has been suggested to use reactive, decision-making tests, preferably in a fatigued state.[3] However, there is a risk of injury by testing too intensively too early in the rehabilitation process. On the other hand, tasks requiring little effort (such as level walking) do not seem sufficient to provoke rotational forces on the knee joint. The use of more sport specific and high demanding tasks, such as the SLH and side jump, seems to be more optimal to safely provide a biomechanical and psychological challenge. In contrast to low demanding tasks, they require more balance and musculoskeletal control to perform. This in turn results in a potentially better measure of rTR and thus more readily reveal effects of potentially deployed compensatory movement strategies. Using hop tests may provide more insight in how patients are progressing during their rehabilitation and can provide more knowledge as to why some patients do and other patients do not successfully return to sport.

It has been suggested that during rehabilitation a more holistic approach is necessary, in which physicians must acknowledge that there is a human being attached to the injured knee.[16] Not only biomechanics but also psychological factors are of increasing interest, and it is important that it is better understood how they affect rehabilitation.[16]

Strengths and limitations

This study is to our knowledge, the first to study the relationship between objective measures and self-reported knee function as well as psychological readiness during high demanding tasks (SLH and side jump) in an ACLR population. It provides more insight into how and which objective measures are related to the self-reported knee function and psychological readiness of the ACLR individual.

The small sample size is an issue that must be taken into account. Since concomitant injury (to the menisci and anterolateral structures of the knee) can influence rTR, strict in-and-exclusion criteria were applied.[23,49] This reduced the number of subjects who could participate in the study and may have led to a certain bias.

Conclusion

Knee kinematics during high demand tasks are strongly related to self-reported knee function and psychological readiness. Knee kinematics of an ACLR knee close to normal knee kinematics are related to better self-reported knee function and psychological readiness. A smaller rTR during high demanding tasks is related to poorer self-reported knee function and psychological readiness after ACLR and can be an indication of a protective strategy adopted by the patient. Measuring rTR during high demanding tasks could potentially expose underlying altered movement strategies and provide more information about the relation between the biomechanics and patient reported outcome measures within the ACLR population.

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Appendix 1. Pearson correlation coefficient matrix; range of Tibial Rotation and Anterior Tibial Rotation

		IKDC	ACL-RSI	Level Walking	SLH	Side Jump
	IKDC					
	ACL-RSI	.706				
rTR	Level Walking	-.318	-.707			
rTR	SLH	.746	.901**	-.670		
rTR	Side Jump	.595	.656	-.160	.383	
ATT	Level Walking	-.700	-.453			
ATT	SLH	-.341	.053	.742		
ATT	Side Jump	-.590	-.443	.907**	.849*	

SLH = Single Leg Hop for Distance
rTR = range of Tibial Rotation
ATT = Anterior Tibial Translation
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Chapter 5

The Correlation between Posterior Tibial Slope and dynamic Anterior Tibial Translation and dynamic Range of Tibial Rotation.

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Abstract

Purpose: The amount of passive anterior tibial translation (ATT) is known to be correlated to the amount of posterior tibial slope (PTS) in both anterior cruciate ligament-deficient and reconstructed knees. Slope-altering osteotomies are advised when graft failure after anterior cruciate ligament (ACL) reconstruction occurs in the presence of high PTS. This recommendation is based on studies neglecting the influence of muscle activation. On the other hand, if dynamic range of tibial rotation (rTR) is related to the amount of PTS, a “simple” anterior closing-wedge osteotomy might not be sufficient to control for tibial rotation. The purpose of this study was to evaluate the correlation between the amount of PTS and dynamic ATT and tibial rotation during high demanding activities, both before and after ACL reconstruction. We hypothesized that both ATT and rTR are strongly correlated to the amount of PTS.

Methods: Ten subjects were studied both within three months after ACL injury and one year after ACL reconstruction. Dynamic ATT and dynamic rTR were measured using a motion-capture system during level walking, during a single-leg hop for distance and during a side jump. Both medial and lateral PTS were measured on MRI. A difference between medial and lateral PTS was calculated and referred to as Δ PTS. Spearman’s correlation coefficients were calculated for the correlation between medial PTS, lateral PTS and Δ PTS and ATT and between medial PTS, lateral PTS and Δ PTS and rTR.

Results: Little (if any) to weak correlations were found between medial, lateral and Δ PTS and dynamic ATT both before and after ACL reconstruction. On the other hand, a moderate-to-strong correlation was found between medial PTS, lateral PTS and Δ PTS and dynamic rTR one year after ACL reconstruction.

Conclusion: During high-demand tasks, dynamic ATT is not correlated to PTS. A compensation mechanism may be responsible for the difference between passive and dynamic ATT in terms of the correlation to PTS. A moderate-to-strong correlation between amount of PTS and rTR indicates that such a compensation mechanism may fall short in correcting for rTR. These findings warrant prudence in the use of a pure anterior closing wedge osteotomy in ACL reconstruction.

Level of evidence: Level 2, prospective cohort study

Trial registration: Netherlands Trial Register, Trial 7686. Registered 16 April 2016 - Retrospectively registered

Keywords: Anterior Cruciate Ligament (ACL), ACL reconstruction, tibial rotation, anterior tibial translation, posterior tibial slope.

Introduction

Risk factors for ACL injury are multifactorial and, next to gender-related, genetic, and hormonal factors, include anatomical and biomechanical factors.[14,25] One anatomical factor that has been of interest in recent studies is the amount of posterior tibial slope (PTS). From cadaveric experiments it is known that increased PTS leads to more forward-directed forces on the tibia and increases strain on the ACL.[3] Dejour and Bonnin showed that every increase of 10° in PTS leads to a 6mm increment of passive anterior tibial translation (ATT) in ACL deficiency.[10] More recent studies confirm the correlation between PTS and passive ATT in both ACL-deficient and ACL-intact knees.[8,9,13]

Increased PTS is related to increased risk of primary ACL injury and increased risk of graft failure after ACL reconstruction.[6,30,32] For this reason it has been suggested that, in revision cases, altering the amount of PTS by an anterior closing-wedge osteotomy could reduce strain on the ACL graft and prevent another re-injury.[17] It should be noted that past studies have evaluated passive ATT either using instrumented Lachman or in a cadaveric setting, both of which eliminate muscle tone. The influence of PTS on dynamic ATT is less extensively studied.

As clearly as the relation between PTS and passive ATT is demonstrated, less is known about the relation between PTS and tibial rotation. The ACL is known to restrict ATT, but also plays a role in limiting tibial rotation.[12] Due to the anatomical features of the tibial plateau, axial load transfers into an anteriorly directed force on the tibia.[10] This force increases with PTS.[10] As the medial and lateral tibial plateaus differ in congruency with the femur, as well as in mobility, we argue that the translation in the lateral compartment is more susceptible to changes in PTS. Due to this difference between the medial and the lateral compartment, axial load would not only be transferred into ATT, but also into rotation of the tibia relative to the femur. We hypothesized that this difference (referred to as ΔPTS) might be of more importance than the actual amount of slope itself, with respect to rotation.

If the range of tibial rotation (rTR) is related to the amount of PTS, a “simple” anterior closing-wedge osteotomy might not be sufficient to control for tibial rotation.

The aim of this study was to answer the following research questions:

- Is PTS correlated to dynamic ATT before and after ACL reconstruction?
- Is ΔPTS correlated to rTR before and after ACL reconstruction?

We hypothesized that both ATT and rTR are strongly correlated to the amount of (Δ)PTS.

Methods

To answer the research questions, subjects with acute ACL injury were kinematically assessed using in vivo kinematic motion analysis. Dynamic ATT and rTR were measured during level walking, a single-leg hop for distance (SLHD) and a side jump. This study was set up as a multicentre prospective cohort study. Both University Medical Center Groningen (UMCG) and Martini Hospital (Groningen, the Netherlands) included subjects in the study. The study protocol was reviewed and approved by the institutional review board of the UMCG (ID 2015/524). The study was registered in the Dutch Trial Register (NTR: www.trialgregister.nl, registration ID NL7686). From June 2016 to June 2018 all patients diagnosed with ACL injury in one of the two participating hospitals were screened for eligibility to participate in the study. Inclusion criteria were: (1) age 18-35 years, (2) unilateral ACL injury confirmed by physical examination, (3) less than three months post- injury at time of diagnosis, (4) at least six weeks of conservative therapy, (5) intact contralateral knee on physical examination. Exclusion criteria were: (1) any history of fractures, osteotomy, or previous ligament reconstructive surgery in the lower extremities or spine, (2) neurological conditions leading to musculoskeletal disorders, (3) any other musculoskeletal pathology of the lower limbs (i.e. concomitant ligament or meniscal injuries), (4) inability to complete Dutch-language questionnaires.

Surgical procedure

All subjects underwent anatomic, single-bundle ACL reconstruction using a semitendinosus/gracilis graft. Both tendons were doubled to create a 4-strand graft. For femoral fixation a suspension type fixation was used (Endobutton, Smith&Nephew, London, UK). After pretensioning (60N), tibial fixation was performed by using a PEEK screw and plug (Biosure PK, Smith&Nephew, London, UK).

Data collection

The motion data collection was performed at the motion lab of the UMCG's department of Rehabilitation Medicine. The motion lab consists of a 9m walkway with two 40x60 cm force plates (AMTI; Watertown, MA) embedded in the floor. An 8-camera optoelectronic motion capture system (VICON MX, Vicon Motion Systems Ltd., Oxford, UK) sampling at 100Hz was used. The position of 22 14mm spherical markers, distributed on the lower extremities according to Hayes and Davis, was recorded.[7] After static and dynamic calibration, joint centres were calculated using VICON Nexus software v2.8 (VICON MX, Vicon Motion Systems Ltd., Oxford, UK). For the complete procedure and its sensitivity see Keizer and Otten (2020).[19]

All subjects performed three tasks: (1) level walking at a self-selected pace; (2) a single-leg hop for distance (SLHD, maximum forward jump, jumping from and landing on the same leg); and (3) side jump (maximum sideways jump, jumping from and landing on the same leg). All jump trials were performed with hands in free motion and with sport shoes on. To familiarize subjects with the procedure and to make sure the entire foot would land on the force plate, subjects were asked to perform a dry run of the SLHD consisting of three practice trials. The median of the three practice hops was used to determine the starting distance from the force plates. For the side jump, leg length (greater trochanter tip to lateral malleolus tip) was used as starting distance from the centre of the force plates. Trials were included in the analysis when tasks were performed correctly (i.e. stable landing), the entire foot landed on the force plate, and all markers were left in place. Three correct trials were recorded for each leg. ACL-deficient subjects were tested within three months after injury. Approximately 13 months after the first trial, 12 months after ACL reconstruction, the testing procedure was repeated.

Data processing

The positions of the markers provided data to determine pelvis, femoral, tibial and foot segments. Using VICON Nexus software v2.8 and additional custom MATLAB version 9.7 scripts (The MathWorks Inc., Natick, MA, USA), three dimensional angular displacements and translations in the knee joint were calculated. Data processing and analysis started at initial contact and continued for 200ms. Initial contact was defined as the moment at which the vertical ground-reaction force (GRF) was >5% of the body weight. All data were smoothed using the cross-validated quintic spline. Raw 3D marker position data were filtered by using a low pas frequency convolution filter of 10Hz with zero lag. A maximum gap (temporary absence of marker identification) of 10 frames was accepted to fill in using the software. If a trial contained gaps exceeding 2.5 ms, smoothing of the data could not be performed and trials were discarded. Kinematic variables were quantified and included maximum knee flexion, maximum knee extension, maximum knee valgus, maximum knee varus, maximum anterior tibial translation, range of tibial rotation, and knee flexion moment. Knee flexion moment was calculated from the GRF vector and its lever arm to the center of the knee flexion axis of the stance leg. For quantification of ATT, rTR and knee angles, two coordinate systems were reconstructed in the tested leg using the customized MATLAB script based on the method of Boeth et al.[4] One system was reconstructed in the femoral segment (parent system) and one in the tibial segment (child system). The motion of each coordinate system is consistent with the movement of the respective segment. The ATT was quantified in millimeters using the relative movement of the center of rotation of the tibial coordinate system relative to the center of rotation of the femoral coordinate system in the local tibial coordinate system. The range of tibial rotation was quantified by the angle between the two axes of rotation as outlined by Keizer and Otten.[19] Flexion/extension and varus/valgus angles were obtained using scalar products as in the equations explained by Robertson et al.[26]

Measurement of PTS

As part of usual care, all subjects underwent magnetic resonance imaging (MRI) of the injured knee to exclude concomitant injury. The images were used to calculate medial and lateral PTS using the circle method as described by Hudek et al.[15] A customized MATLAB script (The MathWorks, Inc., Natick, MA, USA) was used to measure both medial and lateral PTS on MRI. Two independent observers measured both medial and lateral PTS on all MRIs twice, with a minimum two-week interval. To determine intra- and interobserver reliability of the PTS measurements, intraclass correlation coefficients (ICC, 2-way random, absolute agreement) were calculated. Values lower than 0.5 were considered indicative of poor reliability, values between 0.5 and 0.75 indicated moderate reliability, between 0.75 and 0.9 good reliability, and greater than 0.90 excellent reliability.[22]

Statistical analysis

Statistical analysis was performed using SSPS (v 23; IBM Corp, Armonk, NY, USA). A general linear model was used to test for differences between the three trials. Means were calculated for each subject over the three trials to obtain one value for ATT and rTR for each movement. A mean value of medial and lateral PTS from both observers and both measurements was used for analysis.

To assess the correlation between PTS and ATT and between PTS and rTR, Spearman's correlation coefficients were calculated. This was performed for medial PTS, lateral PTS and ΔPTS. Correlation coefficients were interpreted according to criteria set by Domholdt et al.: 0.00–0.25 represents little if any correlation; 0.26–0.49 weak correlations; 0.50–0.69 moderate; 0.70–0.89 strong; and 0.90–1.00 very strong correlations.[11] To reduce the effect of multiple testing, statistical tests deemed significant if $P<0.02$.

Results

A total of 394 subjects were diagnosed with ACL injury and screened for eligibility. Fifty-seven subjects matched the inclusion criteria and were invited to participate in the study. Eleven subjects provided informed consent and were included in the study. The data of one subject was not used for analysis due to the subject's inability to perform the jumping tasks at the initial session. Six males and four females (N=10) completed the baseline testing procedures. At follow-up, 12 months after surgery seven subjects remained (N=7), as one subject had sustained a re-rupture (four months after reconstruction, due to a new trauma) and two subjects were lost to follow-up as they moved away from the Groningen region. The first measurements from the subjects lost to follow up were included when comparing ACL-deficient knees to contralateral ACL-intact knees (N=10). Patient characteristics and measured PTS values are presented in Table 1.

Table 1. Patient Characteristics and PTS values

	Mean (SD)
Age	24 (4.4) years
Total body height	184 (10) cm
Total body weight	81.3 (8.9) kg
Body mass index	24.0 (2.1) kg/m^2
Injury-to-surgery interval	4.6 months
Medial PTS	- 6.7 (2.5) degrees
Lateral PTS	- 5.7 (2.0) degrees
Δ PTS	- 1.0 (3.5) degrees

ΔPTS = difference between medial PTS and lateral PTS. PTS = posterior tibial slope, SD = standard deviation

Intraobserver reliability for the medial PTS showed an ICC of 0.82 for observer 1 and 0.83 for observer 2. For the lateral PTS, the ICC for intraobserver reliability was 0.39 for observer 1 and 0.30 for observer 2. Interobserver reliability for the medial PTS demonstrated an ICC of 0.82 and 0.46 for the lateral PTS.

The mean values for rTR and ATT during the different movements are displayed in Table 2 for the contralateral ACL-intact, the ACL-deficient and the ACL-reconstructed knees. Compared to the contralateral ACL-intact knees, both the ACL-deficient and the ACL-reconstructed knees showed no significant difference in terms of ATT and rTR. (see Table 2). As an example, figure 1 shows a graph containing the results of the rTR during SLHD both before and after reconstruction.

Table 2. rTR and ATT during different movements in ACL-deficient, ACL-reconstructed and ACL-intact knees.

Kinematic variable	ACL-deficient		ACL-reconstructed		ACL-intact
Range of tibial rotation (in degrees; mean (SD))					
Level walking	13.7 (4.1)	*(P=0.15,ns)	14.1 (3.9)	†(P=0.12,ns)	17.3 (6.4)
SLHD	16.9 (3.7)	*(P=0.21,ns)	18.4 (3.4)	†(P=0.64,ns)	19.4 (5.5)
Side jump	16.6 (5.8)	*(P=0.08,ns)	18.3 (4.7)	†(P=0.24,ns)	20.7 (3.6)
Anterior tibial translation (in mm; mean (SD))					
Level walking	4.6 (4.8)	*(P=0.13,ns)	4.8 (5.4)	†(P=0.25,ns)	6.6 (3.0)
SLHD	9.3 (5.1)	*(P=0.21,ns)	11.7 (9.2)	†(P=0.60,ns)	13.4 (7.2)
Side jump	6.7 (5.5)	*(P=0.65,ns)	8.8 (7.5)	†(P=0.78,ns)	7.7 (5.8)

* paired t-test results comparing the ACL-deficient knee to the contralateral ACL-intact knee

† paired t-test results comparing the ACL-reconstructed knee to the contralateral ACL-intact knee

ACL = anterior cruciate ligament, SLHD = single-leg hop for distance, SD = standard deviation, mm = millimeter, ns = non-significant result.

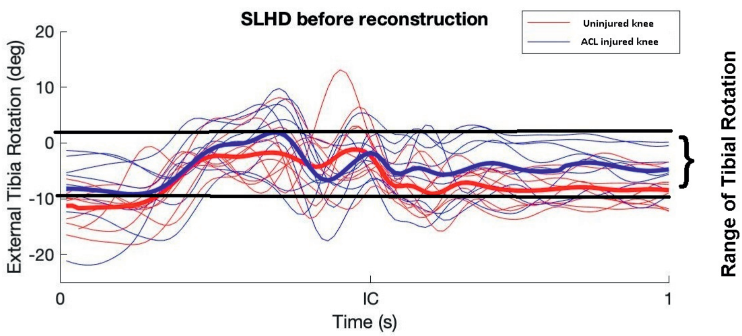

Figure 1. Example of results regarding the range of tibial rotation in both ACL injured knees (red lines) and ACL reconstructed knees (blue lines). The averages are depicted using the bold red and blue line respectively, The solid black lines represent the upper and lower limit of the range of rotation, in this example from the ACL injured knees.

The Spearman's correlation coefficients are displayed in Tables 3 and 4 respectively. Little (if any) to weak correlations were found between medial PTS, lateral PTS and Δ PTS and ATT for ACL-deficient or for ACL-reconstructed knees in all three dynamic tests. Little (if any) to weak correlations were found for ACL-deficient knees between medial PTS, lateral PTS, and ΔPTS and rTR in all three dynamic tests. In ACL-reconstructed knees, these correlations were all moderate-to-strong, except for the correlations between lateral PTS and rTR during level walking and side jump (little (if any) correlation) and medial PTS and rTR during level walking (weak correlation).

It must be noted that the results of the Spearman's correlation test showed non-significant results, as shown in Tables 3 and 4.

Table 3. Spearman's correlation coefficient and significance level for the correlation between ATT and different types of slope.

	Spearman Correlation Coefficient (ρ) (Significance level (P))	
	ACL-deficient	ACL-reconstructed
ATT and medial PTS		
Level walking	ρ = -0.19 (P= 0.60,ns)	ρ = -0.07 (P= 0.88,ns)
SLHD	ρ = -0.13 (P= 0.73,ns)	ρ = -0.14 (P= 0.76,ns)
Side jump	ρ = -0.18 (P= 0.63,ns)	ρ = -0.18 (P= 0.70,ns)
ATT and lateral PTS		
Level walking	ρ = 0.08 (P= 0.83,ns)	ρ = 0.29 (P= 0.54,ns)
SLHD	ρ = 0.44 (P= 0.20,ns)	ρ = -0.11 (P= 0.82,ns)
Side jump	ρ = 0.25 (P= 0.49,ns)	ρ = 0.18 (P= 0.70,ns)
ATT and Δ PTS		
Level walking	ρ = -0.26 (P= 0.47,ns)	ρ = -0.39 (P= 0.38,ns)
SLHD	ρ = -0.47 (P= 0.17,ns)	ρ = -0.04 (P= 0.94,ns)
Side Jump	ρ = -0.46 (P= 0.19,ns)	ρ = -0.43 (P= 0.34,ns)

ACL = anterior cruciate ligament, SLHD = single-leg hop for distance, SD = standard deviation, PTS = posterior tibial slope, ns= non-significant result.

Table 4. Spearman's correlation coefficient and significance level for the correlation between rTR and different types of slope.

	Spearman Correlation Coefficient (ρ) (Significance level (P))	
	ACL-deficient	ACL-reconstructed
Range of tibial rotation and medial PTS		
Level walking	ρ = -0.21(P= 0.56,ns)	ρ = -0.39 (P= 0.38,ns)
SLHD	ρ = 0.48 (P= 0.16,ns)	ρ = 0.64 (P= 0.12,ns)
Side Jump	ρ = 0.44 (P= 0.20,ns)	ρ = 0.69 (P= 0.06,ns)
Range of tibial rotation and lateral PTS		
Level walking	ρ = -0.50 (P= 0.14,ns)	ρ = -0.04 (P= 0.94,ns)
SLHD	ρ = 0.10 (P= 0.78,ns)	ρ = 0.54 (P= 0.22,ns)
Side Jump	ρ = 0.08 (P= 0.83,ns)	ρ = -0.14 (P= 0.74,ns)
Range of tibial rotation and ΔPTS		
Level walking	ρ = 0.21 (P= 0.56,ns)	ρ = -0.50 (P= 0.25,ns)
SLHD	ρ = 0.32 (P= 0.41,ns)	ρ = -0.64 (P= 0.12,ns)
Side Jump	ρ = 0.37 (P= 0.29,ns)	ρ = 0.71 (P= 0.05,ns)

ACL = anterior cruciate ligament, SLHD = single-leg hop for distance, SD= standard deviation, PTS = posterior tibial slope, ns= non-significant result.

Discussion

Our study aimed to examine whether PTS is correlated to either ATT or rTR during high-demand activities. The main finding was little (if any) to weak correlation between dynamic ATT and PTS, both before and after ACL reconstruction. By studying subjects using an in vivo motion-capture system, the dynamic forces of the muscles surrounding the knee joint were enabled, in contrast to what happens when measuring passive ATT. The influence of muscle activity may have led to a weak correlation between PTS and dynamic ATT in our study. Earlier studies show a correlation between PTS and ATT in a passive situation, and particularly that an increase in PTS leads to increased passive ATT.[8-10,23,24,27,28,33,34] This previously observed correlation between PTS and passive ATT might be the sole representation of the mechanical interaction between the femur and the tibial slope, as explained by Dejour and Bonnin.[10] Our study suggests that muscular activity enables subjects to compensate for anatomical factors such as PTS by moderating their muscle activation patterns and kinematics when studied during high-demand activities. Dynamic ATT, as measured in our study, is clinically more relevant than passive ATT, as the clinical feeling of giving way is experienced during high-demand activities.

Muscle forces may be able to reduce dynamic ATT in ACL deficiency and after ACL reconstruction. We indeed found that the measured values for both dynamic rTR and ATT seemed lower in ACL-deficient knees and ACL-reconstructed knees compared to their contralateral intact limbs, although this difference was not significant. This may be explained by reduced quadriceps activity of the injured limb, which increases hamstrings-to-quadriceps ratio (HQ ratio). As shown in a 3D computer model by Shelburne et al., reducing quadriceps force can lower ATT in the presence of ACL deficiency.[29] This theory is referred to as the quadriceps avoidance pattern. Moreover, computer models showed that an increase in hamstrings activity, also leading to an increased HQ ratio, likewise reduces the dynamic ATT.[29,31] Although the theory of altered muscle activation to reduce dynamic ATT is supported by several authors[2,16,21,29], it has been refuted by Keizer et al.[18], who studied healthy subjects with an intact ACL in vivo. In their study, subjects with lax knees on instrumented Lachman displayed less dynamic ATT during SLHD than subjects with lower ATT on instrumented Lachman. Electromyography (EMG) obtained during the SLHD landing showed no clear relation between muscle activity patterns and dynamic ATT, yet less knee flexion was shown by subjects with lax knees. Keizer et al. concluded that landing kinematics may be more relevant than muscle activation in controlling dynamic ATT. Chmielewski et al. found landing kinematics comparable to Keizer et al., i.e. less knee flexion, in subjects with acute ACL injury.[5] In our study these landing kinematics were not seen; no significant difference was observed in maximum knee flexion or knee extension between ACL-intact and ACL-deficient knees.

Several compensation techniques may be successful in reducing dynamic ATT, such as altering landing kinematics or altering muscle activation patterns. A subject's (biomechanical or anatomical) profile may result in preference for a compensation technique, but most likely it is a complex interplay of many factors. A 3D model fed with material properties, geometrical data, and experimental data (kinematics and EMG data) during dynamic tasks may provide more insight into possible compensation techniques to reduce dynamic ATT. Factors such as self-efficacy, psychological readiness, and subjective knee function may also play an important role. As shown in our earlier work (**Chapter 4**) psychological readiness and subjective knee function are related to dynamic rTR in ACL deficiency and after ACL reconstruction.

This study is the first to explore a correlation between PTS and dynamic rTR. As with dynamic ATT, little (if any) to weak correlations between dynamic rTR and PTS were observed in ACL deficiency. More specifically, little (if any) to weak correlations were found between dynamic rTR and ΔPTS in ACL deficiency. In acute ACL injury, similarly to the mechanism involved in reducing ATT, diminished hamstring muscle activity has shown to be related to decreased internal rotation of the tibia in ACL-reconstructed subjects.[1] This emphasizes the possibility of the hamstrings influencing rTR, and in doing so, counteracting the influence of PTS on rTR in acute ACL deficiency. However, one year after ACL reconstruction we have observed moderate-to-strong correlations between rTR and PTS. This may indicate that the previously hypothesized compensation mechanisms fail to compensate for rotatory laxity in the long run. Taking these factors into account, caution should be exercised with highly invasive procedures such as an anterior closing-wedge osteotomy of the tibia. Theoretically, a tibial osteotomy will influence the biomechanical interaction between passive ATT and PTS but neglects the (powerful) influence of muscle activation. Ultimately, the correlation between PTS and ATT may be corrected by muscle activation, but this may not be the case for the correlation between PTS and rTR. Hence the possibilities of an alternative osteotomy technique to correct for tibial rotation, for instance an anteromedial opening wedge, may be explored.

Limitations and future research

This study has several limitations. The narrow inclusion and exclusion criteria were mainly responsible for the small sample size – for instance, subjects with concomitant injury were excluded. Injury to the menisci and anterolateral structures of the knee are known to influence the amount of tibial rotation.[20] By including subjects with concomitant injury, the results could have been biased. Although concomitant injury is a common feature in the general population, we regard our results as an accurate representation of the biomechanics involved in solitary ACL deficiency. The limited sample size is mainly responsible for the non-significant result of the correlation tests. However correlation coefficients are more relevant when interpreting Spearman’s test as opposed to significance levels. Nonetheless the results our study urge the need for future studies with more subjects to confirm the correlations found. Our study did not include electromyography (EMG) measurements to support our theory. In future research it would be interesting to incorporate the use of EMG to evaluate muscle activation patterns during SLHD in ACL deficiency and after ACLR.

The average medial PTS in our population was -6.7° (95% CI -4.9; -8.5), and in the lateral compartment -5.7° (95% CI -4.3; -7.1). It must be noted that interobserver and intraobserver agreement was poorer for lateral PTS compared to medial PTS. Still, our observed PTS values are comparable to previous studies. In a systematic review and meta-analysis by Wordeman et al., average lateral PTS in ACL-injured subjects was between -1.8 (±3.2) and -11.5 (±3.54) degrees.[35] Average medial PTS in ACL-injured subjects was between +1.8 (± 3.5) and -12.1(± 3.3) degrees.[35]

We cannot state whether the aforementioned compensation mechanisms are able to limit ATT in subjects with higher levels of PTS. Dejour et al. report a significant increase of passive ATT with PTS > 12°[8], Li et al. report increased passive ATT with PTS of 10°and Webb et al. report increased risk of ACL injury and graft failure with PTS > 12°.[23,34] Observed PTS did not reach these values in our population. It would be of interest to additionally investigate the relation between PTS and ATT during in vivo motion. The ΔPTS variable is theoretically interesting to explore further with respect to tibial rotation.

Conclusion

In contrast to passive ATT, which is significantly correlated to PTS, little (if any) to weak correlations were found between dynamic ATT and PTS. A compensation mechanism seems to be able to correct for the anatomical influence of PTS on dynamic ATT during high-demand tasks. Moderate-to-strong correlations between PTS and dynamic rTR were found one year after ACL reconstruction. These findings warrant prudence in the use of a pure anterior closing-wedge osteotomy in ACL reconstruction; the effect of an anteromedial opening wedge on dynamic ATT and rTR may be further explored.

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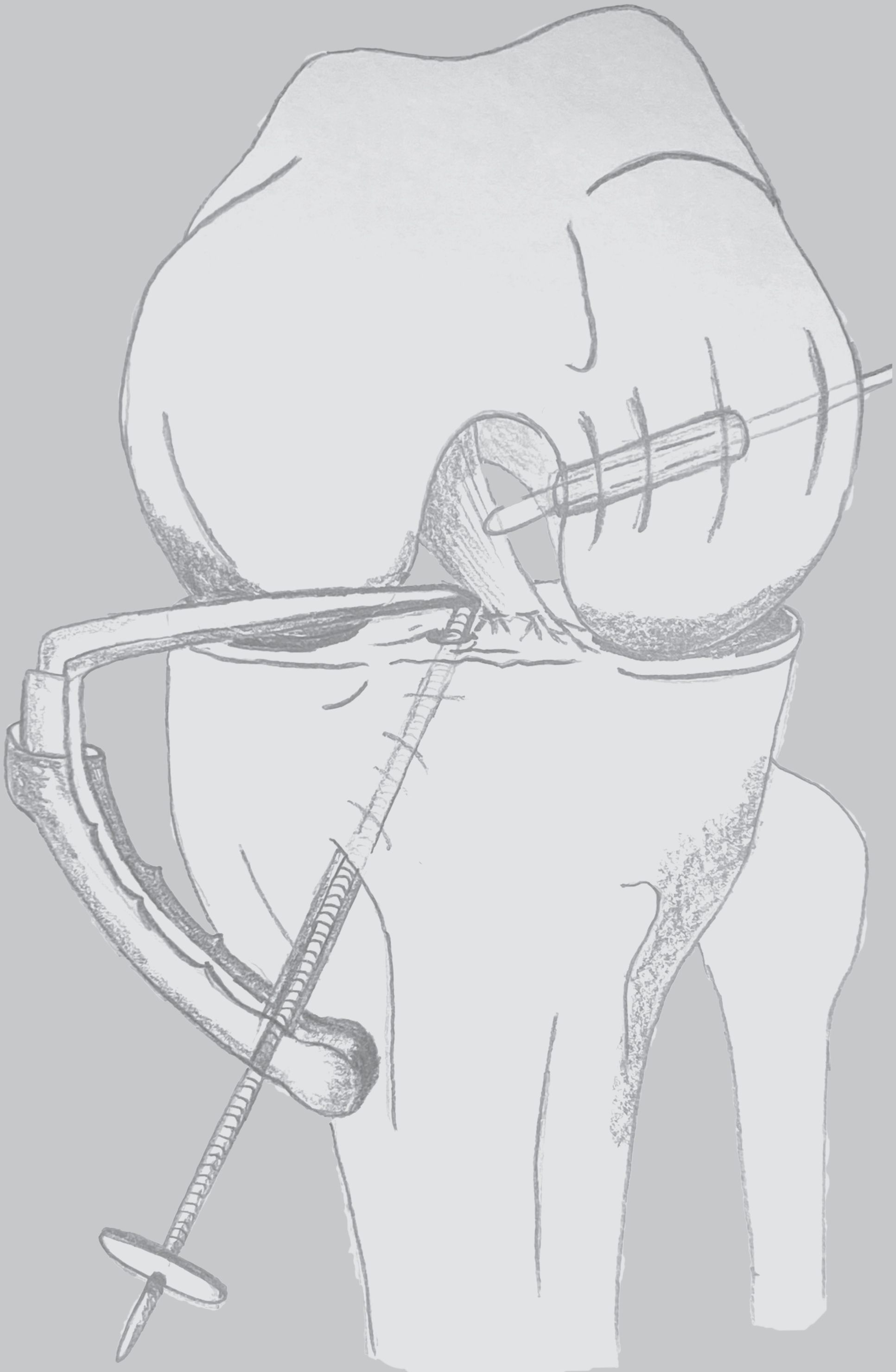
List of abbreviations

ACL	anterior cruciate ligament
ATT	anterior tibial translation
EMG	electromyography
PTS	posterior tibial slope
rTR	range of tibial rotation
SLHD	single-leg hop for distance
SD	standard deviation



Chapter 6

Intra-and interobserver reliability of determining the femoral footprint of the torn anterior cruciate ligament on MRI scans.

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Abstract

Background: Re-injury rates following reconstruction of the anterior cruciate ligament (ACL) are significant; in more than 20% of patients a rupture of the graft occurs. One of the main reasons for graft failure is malposition of the femoral tunnel. The femoral origin of the torn ACL can be hard to visualize during arthroscopy, plus many individual variation in femoral origin anatomy exists, which may lead to this malpositioning. To develop a patient specific guide that may resolve this problem, a preoperative MRI is needed to identify the patient specific femoral origin of the ACL. The issue here is that there may be a difference in the reliability of identification of the femoral footprint of the ACL on MRI between different observers with different backgrounds and level of experience. The purpose of this study was to determine the intra- and interobserver reliability of identifying the femoral footprint of the torn ACL on MRI and to compare this between orthopedic surgeons, residents in orthopedic surgery and MSK radiologists.

Methods: MR images of the knee joint were collected retrospectively from 20 subjects with a confirmed rupture of the ACL. The 2D (coronal, sagittal, transversal) proton-density (PD) images were selected for the segmentation procedure to create 3D models of the femurs. The center of the femoral footprint of the ACL on 20 MRI scans, with visual feedback on 3D models (as reference) was determined twice by eight observers. The intra- and interobserver reliability of determining the center of the femoral footprint on MRI was evaluated. Intraclass correlation coefficients (ICCs) were calculated for the X, Y and Z coordinates separately and for a 3D coordinate.

Results: The mean 3D distance between the first and second assessment (intraobserver reliability) was 3.82 mm. The mean 3D distance between observers (interobserver reliability) was 8.67 mm. ICCs were excellent (>0.95), except for those between the assessments of the two MSK radiologists of the Y and Z coordinates (0.890 and 0.800 respectively). Orthopedic surgeons outscored the residents and radiologists in terms of intra- and interobserver agreement.

Conclusion: Excellent intraobserver reliability was demonstrated (<4mm). However the results of the interobserver reliability manifested remarkably less agreement between observers (>8 mm). An orthopedic background seems to increase both intra- and interobserver reliability. Preoperative planning of the femoral tunnel position in ACL reconstruction remains a surgical decision. Experienced orthopedic surgeons should be consulted when planning for patient specific instrumentation in ACL reconstruction.

Introduction

Several factors are crucial for the success of ACL reconstruction. A surgical factor which is considered to be essential in influencing clinical outcomes is femoral tunnel placement.[5,17] Malposition of the femoral tunnel is a risk factor for re-rupture of the graft.[6] In current surgical techniques, the location of the femoral tunnel is estimated either with a direct measurement beginning on the posterior cortex of the femur or by 'eyeballing' anatomical landmarks through an accessory anteromedial portal. Both techniques are profoundly dependent on the experience and preference of the orthopedic surgeon.

It is not always easy to accurately determine the exact location of the previously ruptured anterior cruciate ligament during ACL reconstruction surgery, even with the help of MR images. Artificial intelligence to aid in determination of this location is yet to be developed. A meta-analysis performed by Piefer et al showed a wide variability in describing the femoral origin of the ACL, on radiologic as well as on arthroscopic landmarks.[13] The need for an individualized guide for optimized femoral tunnel placement seems apparent. When creating a patient specific instrument for ACL reconstruction, preoperatively a decision has to be made regarding the femoral origin of the ACL. Depending on the technique used, this point is either the starting (inside-out) or exit point (outside-in) of the drill. The aim of this study is to determine the intra- and interobserver reliability of identifying the femoral footprint of the torn anterior cruciate ligament on MRI. The influence of background (surgical or imaging) and experience of observers (surgeon or resident) is investigated.

Methods

The research protocol met the requirements to be considered Not Human Subjects Research. This study was a retrospective study in which 20 anonymized MRI scans of subjects with a confirmed rupture of the ACL were analyzed. Scans were selected at random from a cohort of 386 chart numbers corresponding to patients over the age of 16 years, diagnosed with ACL rupture in 2018 at a university hospital. In order to be used in this study, scans had to meet the following inclusion criteria: the scan was of a subject older than sixteen years of age, confirmed by closure of the distal femoral epiphysis, and the rupture of the ACL must have been confirmed by clinical diagnosis and on MRI evaluated by a medical specialist. Scans of subjects with implants, such as screws, rods, plates or knee prosthesis were excluded. Patient information, such as name, gender, age and weight, were undisclosed due to a strict anonymization protocol.

The images were acquired by a 1.5 Tesla MAGNETOM® Aera MRI scanner (Siemens Healthcare GmbH, Erlangen, Germany). The scanning protocol consisted of Proton Density series in the sagittal, coronal and axial planes. Voxel size of 0.4x0.4x3.0 mm was selected (slice thickness 3.0mm) with a 512x512 matrix, a Field of View of 160x160mm, a flip angle of 150^0, a repetition time of 3530 ms and an echo time of 41 ms. All MRI scans were segmented to create a 3D model of the femur. Segmentation of the images was performed using Mimics (v.21, Materialise NV, Leuven, Belgium) as described by Mootanah et al.[11] Manual grey value thresholding and the Livewire tool were used in order to create the masks. Separate masks for cancellous bone, cortical bone and the overlying cartilage on MR images were combined to secure a complete model of the femur.

Furthermore, manual mask adaptations were applied where necessary, such as cropping the mask and mask edges or disconnecting the femur from the tibia if the mask automatically connected them together. All the masks were converted into 3D models. To reduce artifacts from segmentation, the models were smoothed using the following parameters: smoothing factor = 0.8, number of iterations =5 and shrinking was compensated. Final femoral models were saved as a binary Standard Tessellation Language (STL) files. Creation of the 3D model took an estimated 20-30 minutes per case.

After processing, the 2D MR Images and the 3D models were reviewed by three residents in orthopedic surgery (Res), three senior orthopedic surgeons (OS), and two fellowship trained Musculoskeletal (MSK) radiologists. Observers were invited separately at the 3D laboratory of our institute. Each observer was asked to identify the center of the femoral footprint of the ACL of all 20 cases. Observers had access to the anonymized MRI and the 3D model of the femur in Mimics, an example of the screen the observers were exposed to is shown in figure 1. The observers could switch between a high resolution MRI image of either the sagittal, axial or coronal plane.

Using the Mimics software, observers were asked to place a circle of 8 pixels in diameter on a sagittal MRI image of their choice, with the other planes and 3D model as a reference, at the center of the patient specific femoral footprint of the ACL. An example is shown in figure 2. After approximately one week the procedure was repeated by the same observers. All observers were blinded to the results of their first session and those of the other observers. As the observers were not trained in Mimics, a medical student trained in Mimics was present at both sessions for practical questions and to ensure smooth logistics.

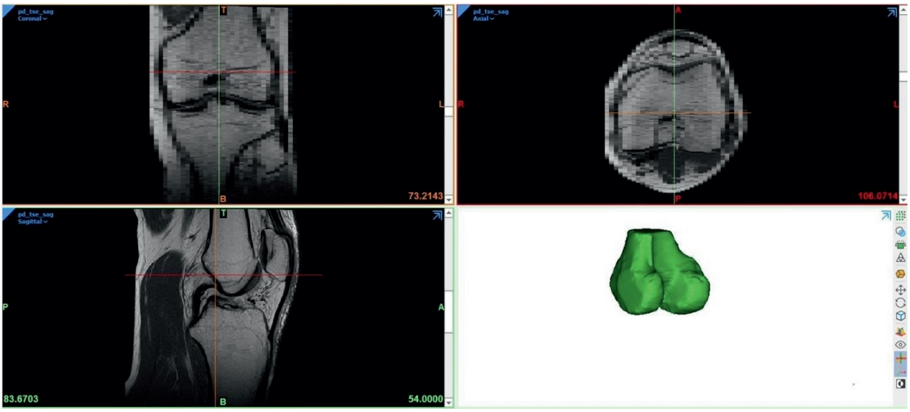

Figure 1. Example of the screen of the observers.

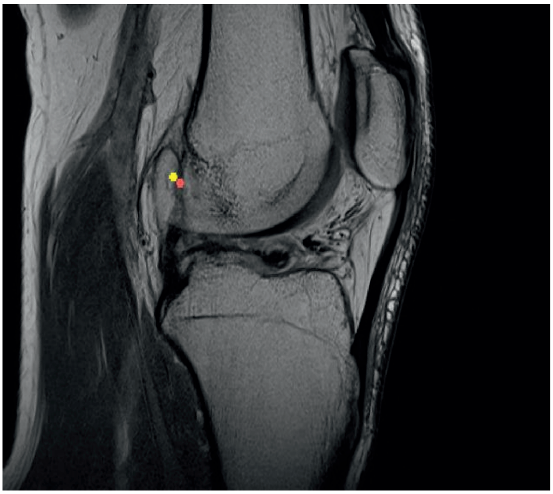

Figure. 2. Example of the intraobserver agreement. Figure showing a sagittal slice of an MRI with two measurements from the same observer with at least one week interval.

Data processing and statistical analysis

The x, y, z coordinates were calculated for each of the marked points using Statistical Package for the Social Sciences version 23 (SPSS, IBM, Armonk, NY, US). The x-axis represents the lateral-to-medial direction, the y-axis the anterior-to-posterior direction and the z-axis the caudal-to-cranial direction. To quantify the intra- and interobserver reliability, the distance between the first and the second assessment and the distance between observers was calculated for each coordinate and the 3D point (i.e. x, y, z and 3D). The total 3D distance between the marked points was calculated using the following formula, where x1, y1 and z1 represents observer 1 or measurement 1 and x2, y2 and z2 represents observer 2 or measurement 2.

$$Dtotal = \sqrt{(x1-x2)^2+(y1-y2)^2+(z1-z2)^2}$$

Intraclass correlation coefficients (ICC 2-way random, absolute agreement) were calculated between the first and second assessment of an observer and between observer groups (Orthopedic Residents, Orthopedic Surgeons and MSK radiologists). Values less than 0.5 were considered to be indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability.[8] Scatter plots using the Bland & Altman method were used to visually assess agreement between raters.[10,16] This was performed for the X, Y, Z and 3D coordinate. The mean difference and the limits of agreement were calculated and depicted in the scatter plots. Statistical analysis were performed in close collaboration with a biostatistician.

Results

The residents in orthopedic surgery were all in their fifth year of their six year residency program. The orthopedic surgeons had an average experience of 11 years (2,7 and 25 years) in ACL reconstructive surgery. The MSK radiologists had an average experience of 5 years in reading MRI scans of the knee (both 5 years).

The 3D-femur models in figure 3 illustrate the observer's scattered marker points.

The absolute mean difference between two measurements regarding the x, y, z and 3D-coordinates as well as the result from the ICC calculations are depicted in table 1. All mean differences per coordinate between the first and second session were below 2.78 mm. The mean 3D distances per group were 3.47 mm, 2.97 and 5.21 mm for the Res, OS and MSK group respectively.

Table 2 shows the interobserver reliability between groups and show excellent ICC values between groups (ICC >0.95). Table 3 shows the interobserver reliability within the groups. Also excellent ICC values were shown within the OS and RES groups (ICC <0.95). The MSK group shows good results. While the agreement regarding the x-coordinate was excellent (ICC >0.95), the agreement regarding the y and z-coordinate were good (ICCs 0.890 and 0.800, respectively). Table 4 shows the mean 3D distances in millimeters between the first and second assessment, as well as the mean difference in 3D distance between the observers per group.

Scatter plots of the Bland & Altman methods are shown in figure 4, figure 5, figure 6 and figure 7 for the X, Y, Z and 3D coordinate respectively. These plots illustrate the absence of a systematic bias between measurements.

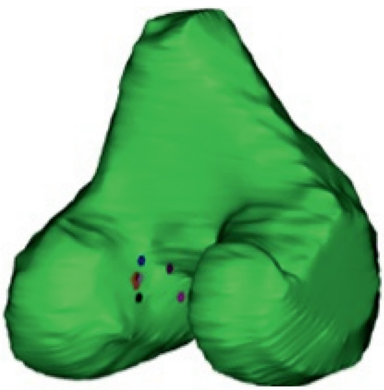

Figure 3. Example of marker points of all observers combined in one case: Orthopedic residents (purple, orange and violet), orthopedic surgeons (red, wine and black) and MSK radiologists (pink and blue).

Table 1. Intraobserver reliability per coordinate and in total: differences between the 1st and 2nd session in mm.

Observer	X coordinate		Y coordinate		Z coordinate		3D Distance
	Mean difference (SD)	ICC	Mean difference (SD)	ICC	Mean difference (SD)	ICC	Mean difference (SD)
Res-1	0.27 (1.77)	1.000	0.00 (2.06)	0.994	1.65 (1.78)	0.987	3.03 (1.95)
Res-2	0.58 (2.40)	0.999	2.12 (2.35)	0.984	1.34 (3.02)	0.979	4.58 (2.29)
Res-3	0.29 (1.60)	1.000	0.13 (2.70)	0.989	1.99 (1.91)	0.986	3.62 (2.00)
OS-1	0.51 (1.20)	1.000	1.28(1.54)	0.994	0.63 (1.97)	0.992	2.74 (1.49)
OS-2	0.13 (1.74)	1.000	1.03 (2.01)	0.993	1.52 (2.37)	0.985	3.55 (1.73)
OS-3	0.31 (2.70)	0.999	1.42 (1.43)	0.993	0.07 (1.33)	0.997	2.63 (2.45)
MSK-1	0.58 (4.11)	0.998	2.26 (3.19)	0.976	2.78 (3.51)	0.961	6.29 (3.41)
MSK-2	0.18 (1.89)	0.999	1.24 (2.19)	0.990	2.05 (3.17)	0.969	4.13 (2.52)
Total	0.35	n.a.	1.15	n.a.	1.50	n.a.	3.82

Res = resident orthopedic surgery, OS = senior orthopedic surgeon, MSK = fellowship trained musculoskeletal radiologist, SD = Standard Deviation, ICC = intraclass correlation coefficient, n.a.= not applicable. The x-axis represents the lateral-to-medial direction, the y-axis the anterior-to-posterior direction and the z-axis the caudal-to-cranial direction.

Table 2. Interobserver reliability between groups per coordinate.

	ICC X coordinate	ICC Y coordinate	ICC Z coordinate
Res vs MSK	0.999	0.970	0.953
Res vs OS	0.999	0.960	0.952
OS vs MSK	1.000	0.982	0.987

Res = resident orthopedic surgery, OS = senior orthopedic surgeon, MSK = fellowship trained musculoskeletal radiologist, ICC = intraclass correlation coefficient. The x-axis represents the lateral-to-medial direction, the y-axis the anterior-to-posterior direction and the z-axis the caudal-to-cranial direction.

Table 3. Interobserver reliability within groups per coordinate.

Group	ICC X-coordinate	ICC Y- coordinate	ICC Z-coordinate
Res	0.999	0.962	0.982
OS	1.000	0.995	0.961
MSK	0.998	0.890	0.800

Res = resident orthopedic surgery, OS = senior orthopedic surgeon, MSK = fellowship trained musculoskeletal radiologist, ICC = intraclass correlation coefficient. The x-axis represents the lateral-to-medial direction, the y-axis the anterior-to-posterior direction and the z-axis the caudal-to-cranial direction.

Table 4. Mean 3D distance difference per group

Group	Mean 3D distance difference between first and second assessment	Mean 3D distance difference between the observers
Res	3.74 mm	6.57 mm
OS	2.97 mm	5.62 mm
MSK	5.21 mm	13.64 mm
All	3.82 mm	8.67 mm

Res = resident orthopedic surgery, OS = senior orthopedic surgeon, MSK = fellowship trained musculoskeletal radiologist,

All = all observers ICC = intraclass correlation coefficient, mm = millimeter

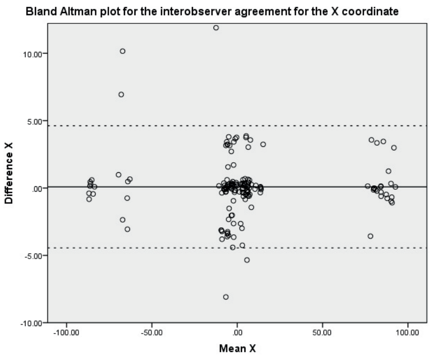

Figure 4. Bland & Altman scatter plot for the X coordinate. Solid black line refers to the mean difference, dashed line illustrates the upper and lower bound of the 95% confidence interval of the difference.

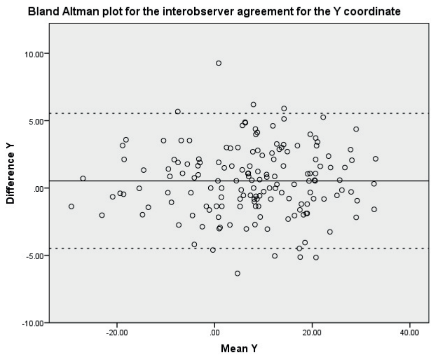

Figure 5. Bland & Altman scatter plot for the Y coordinate Solid black line refers to the mean difference, dashed line illustrates the upper and lower bound of the 95% confidence interval of the difference.

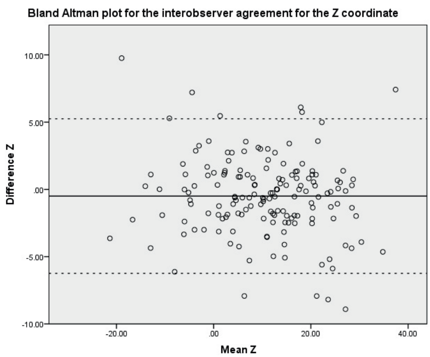

Figure 6. Bland & Altman scatter plot for the Z coordinate. Solid black line refers to the mean difference, dashed line illustrates the upper and lower bound of the 95% confidence interval of the difference.

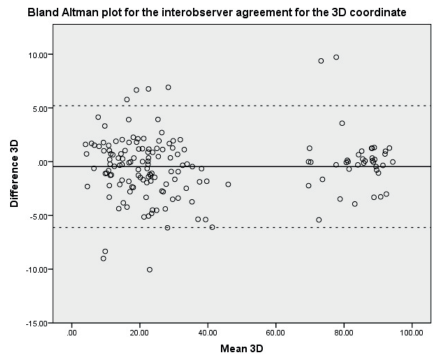

Figure 7. Bland & Altman scatter plot for the 3D coordinate. Solid black line refers to the mean difference, dashed line illustratesthe upper and lower bound of the 95% confidence interval of the difference.

Discussion

To our knowledge, this is the first study to evaluate the intra- and interobserver reliability when determining the femoral ACL attachment site in full-grown ACL deficient subjects on MRI. Excellent intraobserver and interobserver reliability is shown. Orthopedic surgeons with experience in ACL reconstruction were most consistent with a mean difference of

2.97 mm between the first and second assessment. The assessments of the x-coordinate showed an excellent agreement, while those on the y- and z-coordinates showed slightly lower ICC values, but still classify as excellent agreement. This miniscule difference, although not significant, could be explained by the anterior-to-posterior and caudal-to-cranial planes compared to the lateral-to-medial plane. This implies that nearly all observers selected the same sagittal slice to identify the center of the femoral footprint of the ACL. The challenge in identifying the femoral footprint of the ACL is how deep and/or how high the footprint is located on the medial wall of the lateral femoral condyle, hence the anterior-to-posterior and caudal-to-cranial planes (y-coordinate and z-coordinate respectively). This seems to be reflected in the found ICCs.

Our results are in contrast to those of Swami et al, who studied 62 MRI scans in pediatric patients, half of which contained an ACL tear.[19] A mean intraobserver difference of 1.2 mm (± 0.7mm) and a mean interobserver difference of 1.8mm (±1.1mm) were shown. Swami et al asked their observers, which included one radiologist and one medical student, to identify the entire geometry of the footprint of the ACL, out of which a center point was calculated and used for comparison.[19] The geometry of the femoral insertion of the ACL compromises approximately 100mm^2 (50-197mm^2 reported).[9,18,20] In our study, observers were asked to identify the center of the footprint with a small circle of only 8 pixels, replicating a Kirschner wire in the center of the stump of the torn ACL. Identifying a surface from which a center point is calculated may be more forgiving than direct determination of a center point which can explain the difference in results between our study and the results of Swami et al. On the other hand, asking an observer to determine the center of the femoral footprint can be regarded as a more complex task compared to drawing the entire geometry of the femoral footprint of the ACL. When an observer is asked to identify a center of an ellipse, one first has to define the ellipse in his mind. This potentially decreased the reliability as a consequence of the methods used in our study, but still excellent reliability is demonstrated.

Swami studied pediatric patients ranging from 10-17 years of age.[19] Our study only included scans of subject with closed epiphysis of the distal femur, which implies subjects were over 16.6 years of age.[14] The exact age and sex distribution among our subjects could not be retrieved due to a strict anonymization protocol . The presence of open epiphysis can influence the choice of treatment in ACL injury.[12] Whether the age of the subjects influences an observers performance to determine the femoral footprint of the ACL is unknown.

Our findings are comparable to the findings from Rachmat et al who demonstrated a mean intraobserver accuracy of 4.30 mm when identifying the femoral footprint of the ACL on MRI.[15] It has to be noted however that Rachmat et al used one cadaveric specimen with an intact ACL. Our study is thus more representative of the clinically relevant situation. Adding MRI's of subjects with intact ACL's to our database could have introduced a learning effect with the observers. The effect of background and experience may then have been biased. Therefore our study only included MRI with confirmed rupture of the ACL.

In our study orthopedic surgeons were able to determine the same point (femoral footprint) with a mean difference of 2.97 mm between two assessments of 20 scans. A high diversity in the size and shape of the femoral footprint has been reported[9], and this footprint appears to be ribbon shaped with a length of 16mm and a width of 8mm.[9,18] In this light, a mean 3D difference of 2-5 mm can be regarded acceptable.

The orthopedic surgeons showed the highest agreement within their group compared to the other two groups, followed by the orthopedic residents. These findings seem to indicate a lack of "in-field" experience of radiologists compared to the orthopedic surgeons and orthopedic residents. Possibly, witnessing or performing an ACL reconstruction (or knee surgery in general) repeatedly, leads to more consistency in defining the location of the ACL footprint. As residents in orthopedic surgery, not specialized in ACL reconstruction, attained comparable group interobserver reliability compared to the orthopedic surgeons, the effect of general surgical experience seems to be more relevant than experience in ACL reconstruction specifically. This emphasizes that femoral tunnel positioning remains a surgical decision, although it may not always has to be taken in the operating theatre.

The excellent ICC values mainly show that the observers are consistent with locating the same point. It may seem tempting to compare the ACL insertion points as determined by the observers to a predefined point measured from the posterior cortex, for instance as defined by Piefer.[13] This would not be in accordance with the patient specific (instrumentation) concept and would lead to a generalized approach for each patient. No gold standard, such as confirmation by arthrotomy, was used in this study to prove that this point is actually the femoral insertion of the ACL. This is due to the fact that scans of patients with torn ACL's were used and not cadaver samples. The down side of using cadavers is the intactness of the ACL. The ultimate goal of identifying the femoral insertion of the ACL is to give the surgeon the optimal information about where the femoral tunnel should be located. This is, obviously, only necessary in case of a torn ACL. Therefore for clinical purposes, this study was set up to use scans of a cohort of patients resembling the relevant population.

As a consequence, we included subjects who have undergone routing 2D MRI scans of the knee for clinical purposes. It has been shown that 3D MRI improves overall image quality and quantitative contrast ratio[4], although it has not been more accurate in diagnosing ligamentous injuries compared to 2D MRI.[7] It has been demonstrated that there is no advantage in localizing the ACL attachment centers when using 3D MRI over 2D MRI.[20]

In our study manual segmentation of the MRI scans was performed to create a 3D model of the distal femur. Automatic or semi-automatic segmentation techniques have been described in the literature.[1-3] Although the correctness of the 3D model was not evaluated in this study, evaluation of the segmentation technique was done prior to this study. Unpublished data showed an excellent surface comparison when comparing 3D models derived from 2D MRI, 3D MRI and CT.

The fact that orthopedic surgeons reach a high group interobserver agreement may be the effect of a monocenter study. There may be a consensus on femoral tunnel position within a group of direct colleagues. Furthermore, this consensus is transferred to the orthopedic residents during their training. A multicenter and possibly even a multinational study would be needed to determine if this is indeed the case.

Conclusion

The aim of this study was to determine the intra- and interobserver reliability of identifying the femoral footprint of the anterior cruciate ligament on MRI. Excellent intraobserver agreement was demonstrated. The interobserver reliability was less compared to the intraobserver reliability. Orthopedic surgeons had a higher level of intra- and interobserver agreement compared to MSK fellowship trained radiologists and, to a lesser extent, to residents in orthopedic surgery. Employing this feature, experienced orthopedic surgeons are the preferred physicians to preoperatively plan femoral tunnel positioning in patient specific ACL reconstruction. By doing so, femoral tunnel malposition may become less of a problem in ACL reconstruction, increasing return to play rates and decreasing re-rupture rates following ACL reconstruction.

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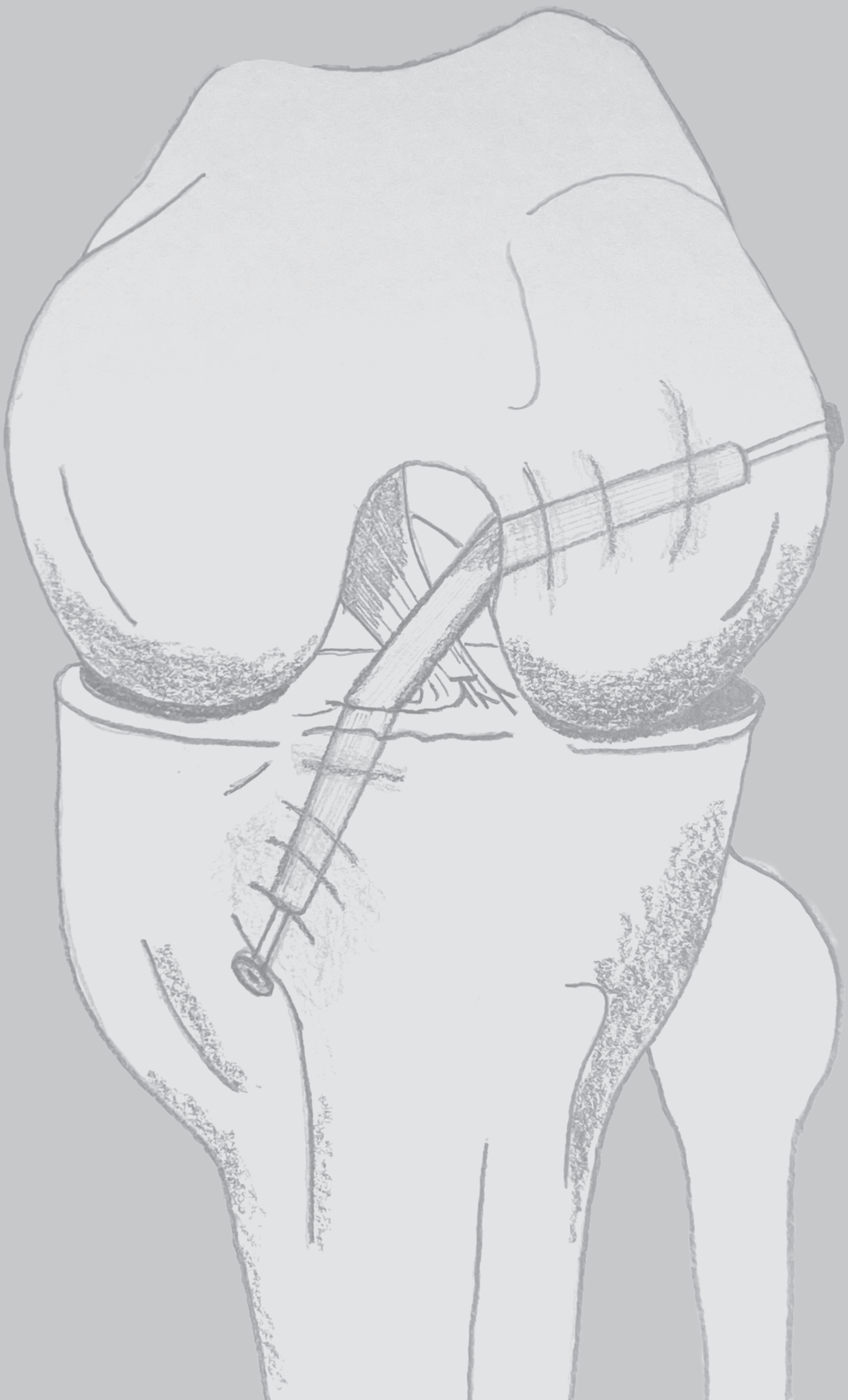

Chapter 7

Patient Specific Instrumentation in ACL Reconstruction:

A proof-of-concept cadaver experiment assessing drilling accuracy when using 3D printed guides.

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Abstract

Introduction: Accurate positioning of the femoral tunnel in ACL reconstruction is of the utmost importance to reduce the risk of graft failure. Limited visibility during arthroscopy and a wide anatomical variance attribute to femoral tunnel malposition using conventional surgical techniques. The purpose of this study was to determine whether a patient specific 3D printed surgical guide allows for in vitro femoral tunnel positioning within 2 mm of the planned tunnel position.

Materials and Methods: A patient specific guide for femoral tunnel positioning in ACL reconstruction was created for four human cadaveric knee specimens based on routine clinical MRI data. Fitting properties were judged by two orthopedic surgeons. MRI scanning was performed both pre- and post-procedure. The planned tunnel endpoint was compared to the actual drilled femoral tunnel.

Results: This patient specific 3D printed guide showed a mean deviation of 5.0 mm from the center of the planned femoral ACL origin.

Conclusion: In search to improve accuracy and consistency of femoral tunnel positioning in ACL reconstruction, the use of a patient specific 3D printed surgical guide is a viable option to explore further. The results are comparable to those of conventional techniques; however, further design improvements are necessary to improve accuracy and enhance reproducibility.

Key terms: patient specific instrument, ACL reconstruction, anatomic, femoral tunnel

Introduction

In young active patients who have suffered a rupture of the anterior cruciate ligament (ACL), ACL reconstruction is used to treat symptomatic knee instability.[17] Anatomical ACL reconstruction aims for a graft to be implanted on the native footprints of the ACL on the femur and tibia. Non-anatomical placement of the graft in ACL may eliminate anterior/posterior laxity, but normal kinematics will not be fully restored.[3,14,23] Also, non-anatomic placement of the ACL graft is associated with an increased risk of graft failure.[11] This graft failure, rupture, or elongation, occurs in up to 14% of primary ACL reconstructions[11] and does not depend on the type of graft used.[9] To reduce graft failure, it is important to address additional posterolateral, posteromedial and collateral laxity,[26] but in up to 24% of patients that undergo ACL revision surgery, surgical inaccuracy is the sole reason for failure.[7] And in up to 54% of patients, this was an additive cause for failure.[7] Malposition of the femoral tunnel was recognized as the most common technical failure (80%).[7] Possible contributing factors are procedure- and patient dependent: During the procedure, limited visibility of the femoral footprint during arthroscopy is a known problem[1,25] and studies show that there is a large individual variation in location and diameter of the femoral footprint of the native ACL.[28] Although femoral and tibial bone tunnels are drilled through surgical guide instruments to optimize positioning, current surgical techniques still depend on the intra-operative identification of landmarks and measurements to determine the femoral footprint of the ACL. The use of anatomical landmarks for ensuring anatomic positioning of the graft however remains associated with a high risk of femoral tunnel malposition, which is related to early to midterm failure of the graft.[7,11] This emphasizes that current surgical techniques using universal aiming devices seem to fall short in creating a constant and reliable result for a femoral tunnel position at the optimal, individual anatomic footprint of the ACL. To provide consistent results, determining the location of the ACL footprint should not be dependent of surgeon's experience or intra-operative visual control, and individual variation should be taken into account.

To individualize anatomical femoral tunnel placement and thus improve graft survival, we developed a novel surgical aiming device to create a femoral tunnel at the individualized anatomic ACL footprint during ACL reconstruction. The use of this patient specific instrumentation in ACL surgery aims for a constant and reliable method to assure a femoral tunnel emerging at the native ACL position. Moreover, patient specific instrumentation can be of aid in complex revision cases with multiple previous bone tunnels and in cases with posttraumatic or torsional deformities of the distal femur.

In this cadaveric study the in vitro accuracy of a patient specific 3D printed surgical guide, to be used for femoral tunnel positioning in an outside-in ACL reconstruction, was determined. The aim of this study was to drill a femoral tunnel in the specimen, emerging within 2 mm of the femoral footprint of the ACL, as determined by planning on preoperative MRI.

Materials and Methods

In this experiment four knee joints of fresh frozen human cadavers were used. The study protocol has been reviewed by the Review Board of the University Medical Center Groningen (UMCG, Groningen, the Netherlands, study number 2015/057) and the committee has confirmed that no ethical approval was required. The cadavers were obtained from the Anatomy department of the UMCG. Knees with previous surgical procedures were excluded. Specimens were separated approximately 30 cm above and below the joint line. After 48 hours of defrosting, the knees were scanned using an MRI scanner.

Image Acquisition.

The specimens were placed supine in a patella forward position and fixed in a common knee coil. A 1.5 Tesla MAGNETOM® Aera MRI scanner (Siemens Healthcare GmbH, Erlangen, Germany) was used to acquire all scans. The used scanning protocol consisted of a routine clinical 2D knee sequence. The protocol consisted of Proton Density (PD) series in the sagittal, coronal, and axial planes. The use of PD series was chosen because of the more pronounced difference between the cartilage and the surrounding structures on these images. Voxel size of 0.4x0.4x3.0mm was selected with a field of view of 160mm, a flip angle of 150^{0}, a repetition time of 3530 ms. and an echo time of 41 ms. The scanning protocol used in this study was similar to the routine clinical protocol for diagnosing ACL injury. This avoids the need for additional scans when this concept is used for clinical purposes in the future. Files were saved for further processing in 16-bit Digital Imaging and Communications in Medicine (DICOM) file formats.

Segmentation Procedure.

Using the Mimics Innovation Suite Software version 21.0 (Materialise, Leuven, Belgium) the images were segmented to obtain accurate 3D models of the knee. The MRI images were semi-automatically segmented with the use of the *livewire* technique as previously described.[29] Using this technique, the software is able to semi-automatically distinguish different gray scales in order to select a region of interest. The region of interest consisted of the femur including the overlying cartilage. Intra-observer reliability for the segmentation method was evaluated using repeated segmentations. The total absolute mean distance between models was 0.20 mm. Although the correctness of the 3D model was not evaluated in this study, evaluation of the segmentation technique was done prior to this study. Unpublished data showed an excellent surface comparison when comparing 3D models derived from 2D MRI compared to CT.

The center of the femoral origin of the ACL was determined on the MRI images and marked by a circle of 2 mm in diameter. This point was referred to as “ACL origin”, see figure 1.

Previous research has shown that the identification of the femoral insertion using this method has a high intra- and interobserver reliability, even in the presence of ACL injury.[29] Intra-observer reliability for this method has been shown to be excellent with an ICC of > 0.98 and excellent interobserver reliability with an ICC of > 0.96.

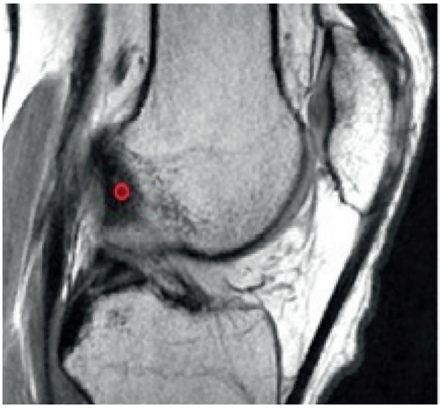

Figure 1. Example of sagittal view of a 3D MRI. The center of the femoral origin of the ACL was determined and marked by a red circle of 2 mm in diameter

In order to control the drilling trajectory and ultimately the femoral tunnel position, the entry point on the lateral side of the lateral femoral condyle was selected based on the work of Kang et al.12 Kang recommended an optimal direction and location for the entry point of the femoral tunnel on the lateral wall of the lateral femoral condyle, taking ACL graft stress, graft bending angle and length of graft into account.12 Based on this recommendation a cone was created, starting from the ACL origin as was determined on the medial wall of the lateral femoral condyle, projecting over the lateral aspect of the lateral condyle. This way, anatomical variation in width of the lateral femoral condyle was accounted for. See figure 2.

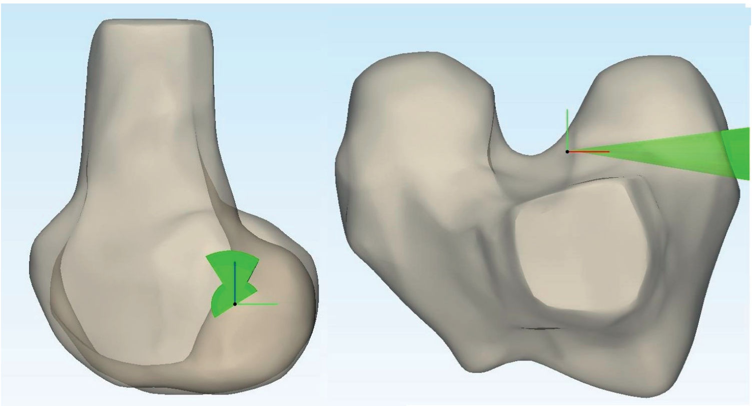

Figure 2. Images displaying a sagittal (left) and cranial (right) view of a 3D model of a distal femur with the cone described by Kang et al. projected in place

Using this technique, a point on the lateral side of the lateral femoral condyle was selected and marked by a circle of 2 mm in diameter. This point was referred to as the “entry point.” The entry point, ACL origin point, and the segmented femur were exported as Standard Tessellation Language (STL) models.

Development of a patient specific guide.

The STL models were processed by an orthopedic engineer to create a patient specific drill guide. A negative mold of the lateral wall of the intercondylar notch was created: a box was fitted in the intercondylar notch and a Boolean operation was performed, subtracting the femoral model from the box. The drill guide was designed as an adaptation to the outside-in GraftLink® technique by Arthrex using the FlipCutter® (Arthrex Inc., Naples, FL, US) as described by Lubowitz.[15] The original femoral aiming guide on the Arthrex instrument was replaced by a 3D printed guide that fits the intercondylar notch, see Figure 3.

The position of the femoral guide in combination with the 3D printed guide was designed to create a drill trajectory between the ‘entry point’ and ‘ACL origin point,’ within “Kang’s cone” see fig 3.

The patient specific guides were printed using a Selective Laser Sintering (SLS) printer with polyamide 12 powder (ISO 13485 certified). Polyamide 12 has an elasticity of 1650 MPa, a tensile strength of 48 MPa and was printed with a layer thickness of 0.1-0.12 mm. The material is suitable for routine steam heat sterilization by the autoclave.

Cadaver Experiment.

Two male and two female cadaveric specimens were used. Average age at time of death was 88 years. Two left knees and two right knees were used. The cadavers were fixed in a custom-made leg holder. Both the femur and tibia were fixed by a clamp connected to a hinge which allowed for flexion/extension and internal/external rotation of the knee. Skin and subcutaneous tissue were dissected off. The extensor mechanism including the patella, Hoffa’s fat pad and the anterior capsule was removed. After resection of the ACL, the patient specific hooks were introduced in the notch and

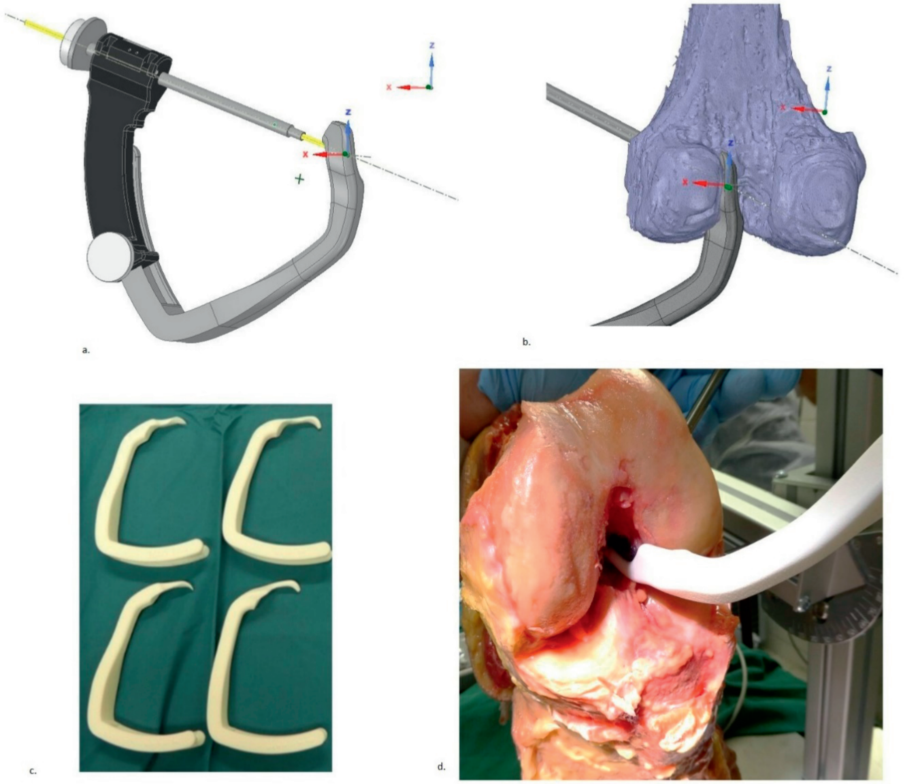

Figure 3. The patient specific 3D printed femoral aiming guide. (a) The drill trajectory aims for the pre-determined ACL origin (b) the aiming device fits the medial wall of the lateral femoral condyle anatomically (detailed view). (c) inventory kit with four 3D printed PSI aiming guides. (d) Example of the 3D printed aiming guide in situ

were judged for its fit, see Figure 3 (right bottom). The guides were judged upon the type of fit by two orthopedic surgeons with experience in ACL reconstruction. The type of fit was rated by each orthopedic surgeon on a 5 point Likert scale, 1 meaning a very poor fit and 5 meaning a very good fit. The orthopedic surgeons judged the type of fit independent of each other.

Next a femoral tunnel was drilled using the guide when accurate positioning based on tactile and visual feedback was confirmed.

After the experiment, the same MRI protocol was performed as before which allowed for comparison of the actual drill trajectory with the planned drill trajectory. Both the pre- and post-procedural scans were segmented as described before. The post-procedural drill trajectories were easily identified and segmented as cylinders on all post-procedural scans (See Figure 4). The position of these cylinders was compared to the pre-procedural planned drill trajectories. Measurements were performed in Mimics. Distances from cylinder edge to cylinder edge were recorded in mm using a digital ruler. Because of the oblique drilling trajectory, the center of the cylinder was hard to determine, therefore we chose for edge-to-edge measurements and added the diameter of the RetroDrill (3.5mm) to this measurement. All measurements were performed by one trained observer. The measurements were repeated by the same observer more than 2 weeks later to determine the intra-observer reliability of the measurements. The intraclass correlation coefficient (ICC 2-way random, absolute agreement) was calculated between the first and second assessment. A value less than 0.5 was considered to be indicative of poor reliability, value between 0.5 and 0.75 indicates moderate reliability, a value between 0.75 and 0.9 indicates good reliability, and a value greater than 0.90 indicates excellent reliability.

Results

The introduced hooks provided a very good fit in the intercondylar notch as shown in table 1. The two orthopedic surgeons reported similar results as shown in table 1.

Table 1. Overview of the fitting properties of the patient specific guides as judged by the two orthopedic surgeons. Fitting properties were rated on a 5 point Likert scale (1= very poor, 2= poor, 3= moderate, 4= good, 5 = very good)

Observer	Cadaver 1	Cadaver 2	Cadaver 3	Cadaver 4
Orthopedic Surgeon 1	Good	Very Good	Very Good	Very Good
Orthopedic Surgeon 2	Good	Very Good	Very Good	Very Good

Using the 3D printed guide hooks resulted in a mean difference of 5.0 mm (SD 1.0 mm range 3.8-6.7mm) between the planned and actual drilled trajectory. For an example, see Figure 4. In Figure 4, the planned drill trajectory is displayed as the dark-gray cylinder. The actual drilled tunnel is displayed in red.

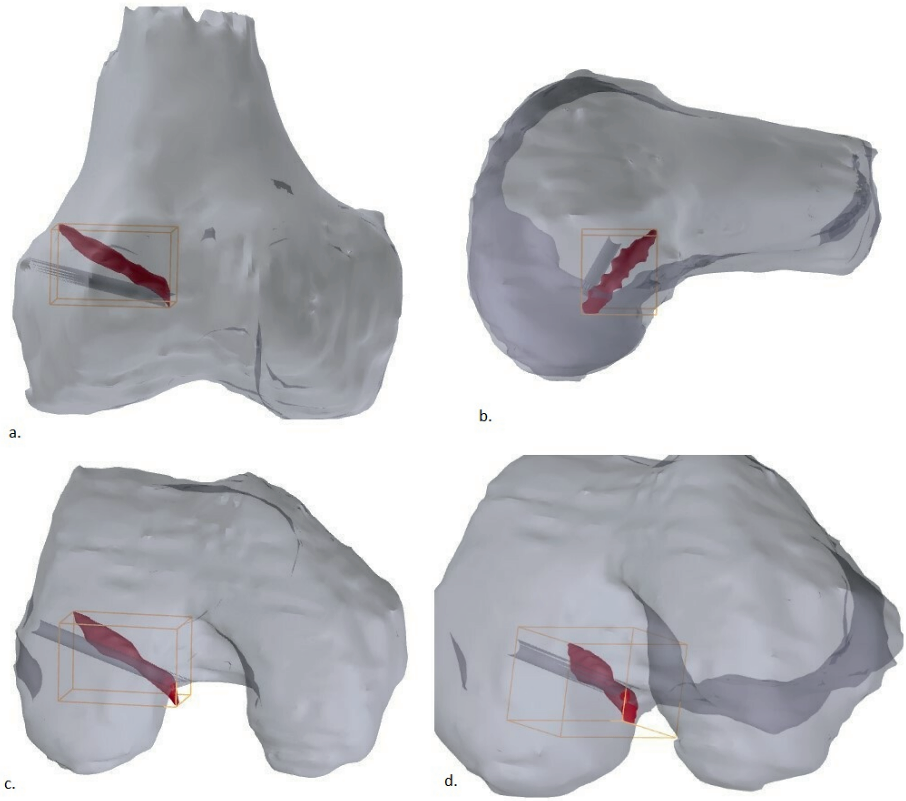

Figure 4. Example of comparison planned and drilled tunnels. Drilled tunnel is displayed in red. Planned tunnel in dark-gray. (a) Anterior Posterior view. (b) sagittal view. (c) Caudo-cranial view. (d) notch view.

The intraclass correlation coefficient for intra-observer reliability regarding the distance measurements between the planned and achieved tunnel position was calculated to be excellent: 0.956 for average measures (95% confidence interval 0.558-0.997, p=0.01).

Discussion

The main finding of our study is that with our patient-specific targeting device a deviation of 5.0 mm exists compared to the planned tunnel. While the technique and development seem promising, this is outside our intended target of < 2mm.

The accuracy of the segmentation process could be a large contributory factor to the inaccuracy of the current construct. In this study, we have segmented the MRI images semi-automatically. Even though we have observed that repeated segmentation of the same images leads to a minimal change in the total absolute difference in the model, minor impurities of the model may cause the final aiming device to fit incorrect. Nevertheless, we noticed that the fit was very good. A recent review has demonstrated the potential of automated segmentation based on deep learning.[5] As this technique develops over time, segmentation may be more accurate and less time consuming.

In addition, the construct using polyamide 12 could attribute to lower accuracy of the aiming device, since polyamide 12 contains a certain degree of flexibility. This can lead to a bending of the system. This can be solved by using more rigid materials. Titanium is available for 3D printing, but this is a costly affair. More obvious is the use of 316L stainless steel as it is used for many surgical instruments. 316L stainless steel can be machined by a robotic milling cutter to create the patient specific part for the targeting device.

The use of polyamide-12 however, is a cheap option. We have not performed a cost-effectiveness analysis in this study. In this study the total cost for a 3D virtual surgical plan and 3D printed guides were approximately 700-1000 euro per case, with approximately 100-300 euro for the 3D printed guides.

We have to conclude that so far, the total deviation has been too large, and we need further improvements to ensure that partially anatomic placement of the ACL graft will not occur.

Up to now only one other study has been published regarding the potential of a 3D printed patient specific targeting device for the creation of the femoral tunnel. Rankin et al have reported on a patient specific template that can be used to mark the insertion of the ACL in the notch with a chondropick.[22] Rankin et al did not describe the accuracy of their system.

In total hip and knee arthroplasty, the use of 3D-printed patient-specific instruments (PSI) has shown added value in the form of high accuracy.[8,21] However, no demonstrable improvement in patient reported outcome, and surgery time or transfusion rate has been shown when using PSI compared to standard total knee arthroplasty.[13] As exact anatomic reconstruction within a 2mm range of the native ACL footprint already has shown to have a significant relation with graft failure, the accurateness provided using PSI in ACL reconstruction may have more noticeable effects.

The accuracy of femoral tunnel placement has been studied extensively before. An empirical optimal point for femoral tunnel position has been determined based on cadaver studies at a point at 28% on the proximal-to-distal axis and 35% on the perpendicular axis.[2] It has been shown that when surgeons rely on anatomical landmarks alone, a mean deviation of 12.5 mm occurs with respect to this empirical optimal point.[10] This emphasizes that current, widespread used surgical techniques fail to recreate the native ACL. The use of intra-operative fluoroscopy can improve accuracy, but still a mean deviation of 9.8 mm remains. Other reports show that an experienced surgeon can obtain a deviation of 4.2 mm of the femoral origin when using arthroscopy alone, which can improve to 2.7 mm when using intra-operative navigation.[20] Additive value in ACL reconstruction in terms of accuracy of femoral tunnel placement was shown using computer assisted surgery (CAS).[4,16,20] The use of CAS during ACL reconstruction has been shown to lead to a deviation of planned tunnels of approximately 2 mm, in which 1 mm is attributed to the overall robotic system and 1 mm to intra-operative movement of the patient. Disadvantages of CAS include the learning curve and time consumption during surgery. With our newly developed PSI system we strive for comparable results in terms of accuracy, while at the same time using a simpler and more practical construct. The main difference between a CAS/Fluoroscopy based approach and a PSI concept is that PSI strives for an individual anatomic approach rather than a one size fits all approach which leads back to an empirical determined point averaged over multiple cadaveric studies.[2,10] It is therefore that our selected point cannot be compared to this empirical optimal point, as we never aimed for the empirical optimal point.

The shortcoming of the current surgical techniques is resembled by the high prevalence of femoral tunnel malposition. It has been recognized before that a one size fits all approach is not the way to go in ACL reconstruction.[18] Using the current available techniques that rely on the intra-operative identification of anatomical landmarks and ACL remnants, an accurate, true anatomic femoral tunnel position is not easily achieved. With the use of PSI we aim to provide a patient specific true anatomic ACL reconstruction that does not rely on the experience of the surgeon. When both the femoral and tibial tunnel are positioned at the native origin and insertion sites, the graft can resemble the native ACL more closely.

From a practical point of view, we have chosen to aim for the center of the femoral footprint of the ACL which was regarded as the midpoint between the anteromedial (AM) and posterolateral (PL) bundle of the ACL. The advantage of the PSI design as described here, is that the surgeon has ultimate control over the entire femoral tunnel position. This means that a point toward the AM bundle can be selected as well. Also, control over tunnel position can be of great benefit in the case of revision surgery. In this way, tunnel collision can be prevented through accurate preoperative planning of the tunnel. The selected point in this experiment is not representative for clinical use as mid-bundle techniques potentially have a higher graft re-rupture rate.[22] The aim of our study was limited to determining the accuracy of the patient specific aiming guide; in other words, can we achieve a planned tunnel position. The scope of this study did not involve the amount of coverage of the ACL footprint. However we hypothesize that recreation of native anatomy will improve outcome after ACL reconstruction. The footprint of the ACL has been shown to vary in size from $60mm^2$ to $130mm^2$, of which about half of it being reserved for each bundle.[18] An average hamstrings graft of 8mm in diameter can cover an area of about $50mm^2$ ($A = \pi r^2$) which increases to about $80mm^2$ when a 10 mm graft is harvested. More recent studies by Smigelski have shown that the ACL may in fact be more ribbon shaped[27] and ACL reconstruction techniques have been proposed to reconstruct the ACL using a ribbon shaped graft.[6] On the other hand, some authors advocate the reconstruction of the isometric, direct fibers of the ACL using the I.D.E.A.L. technique.[19] Ideally, if we strive for patient specific ACL reconstruction, the native ACL should be reconstruction in all its shape and dimensions. A recent study has shown that anthropometric data can be used to predict the graft dimensions, by which means an appropriate graft can be selected preoperatively.[24] That way true anatomic ACL reconstruction may become within reach.

Finally, we would like to emphasize that the guides in the present study have been used in a situation that replicates open surgery. This allowed for visual feedback in addition to tactile feedback in search for the optimal fit. Therefore, the results of the current study cannot be translated one-on-one to an experiment in an arthroscopic setting. The next step is to develop a guide that can be used arthroscopically. This would ask for a slimmer design which special attention to allow for easy introduction through the portal. By further improving the design, the authors hope to further improve the accuracy of the patient specific guide.

In this proof-of-concept study the use of 3D printed patient specific instrument for anatomic ACL reconstruction has been shown feasible. An accuracy of 5 mm is demonstrated on cadavers. Currently, this is not sufficient for the instrument to be used in a human population. Further improvement in the design and materials is needed before this concept can be introduced in an in vivo setting.

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List of abbreviations

3D	Three dimensional
ACL	Anterior Cruciate Ligament
AM	Anteromedial
AMP	Anteromedial Portal
CAS	Computer Assisted Surgery
DICOM	Digital Imaging and Communications in Medicine
ICC	Intraclass Correlation Coefficient
mm	millimetre
MPa	Megapascal (Pressure Unit)
MRI	Magnetic Resonance Imaging
OI	Outside-in
PD	Proton Density
PL	Posterolateral
PSI	Patient Specific Instruments
SD	Standard Deviation
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
UMCG	University Medical Center Groningen

Chapter 8

Feasibility of a newly developed rehabilitation programme after ACL reconstruction: Knee Rehabilitation on Skates.

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Submitted

Abstract

Objective: The main study objective was to determine whether the KROS rehabilitation protocol is feasible.

Design: Feasibility study

Setting: During the KROS rehabilitation, subjects were prepared for their skate training by implementing skate specific exercises. Once the strength of the ACL reconstructed leg reached at least 80% of the non-involved leg, skate training was initiated

Participants: 15 participants were recruited for rehabilitation after ACL reconstruction according to the KROS rehabilitation protocol.

Main Outcome Measures: Feasibility was defined as less than 30% loss of compliance, an overall participant reported rating > 6/10 on NRS scale at the end of rehabilitation and no serious adverse events related to the rehabilitation.

Results: Due to COVID-19 and the associated closure of the ice stadium, only 5 subjects were able to complete the KROS rehabilitation protocol. Overall loss of compliance was 20%. The KROS rehabilitation protocol was rewarded with a 6.8/10 overall on the NRS scale. No adverse events were recorded.

Conclusions: The incorporation of speed skating in a rehabilitation protocol after ACL reconstruction is feasible and may enhance compliance during training. Future research is needed to determine whether objective outcomes as strength and functional capabilities are at least non-inferior to current common practice.

Introduction

Rupture of the ACL is a common injury, occurring primarily in young athletes participating in pivoting sports like soccer, football, handball and field hockey.[2] The incidence of ACL rupture is estimated at 81:100.000.[9] As described in the Dutch guideline on ACL injury, surgery is indicated in patients with persistent instability after six to 12 weeks of conservative therapy.[17] Especially in young athletes the treatment of choice is an ACL reconstruction (ACLR).

Objective outcome of ACL reconstruction can be divided in technical success (re-rupture rate, residual instability) and functional success. Functional success is often measured using a hop test battery including the one legged forward hop test, side jump and single leg balance test. Based on these tests a limb symmetry index (LSI) can be calculated by comparing the involved leg to the contra-lateral intact leg. A functional LSI of 85-95%, nine months after ACL reconstruction has been postulated to be a successful result.[12] A successfully performed functional test is highly related to return to sports.[22]

In the population of young athletes, return to sports has become the most relevant outcome after ACLR. Return to sports after ACLR is commonly allowed once a LSI of 90% has been achieved. This mostly takes up nine to twelve months after surgery and consists of lots of hours in the gym, training on quadriceps and hamstrings strength. A review of literature has shown that a mere 55% of athletes are able to return to a competitive form of sports after an ACLR.[3] Surgical technique or choice of graft has been shown not to influence the rates of return to sports, but it has been shown that compliance to ACL rehabilitation protocols has a positive influence.[5,10]

Main factors influencing compliance to rehabilitation have been shown to be mood, pain and stress.[5] As the majority of patients tearing their ACL participate in pivoting sports, predominantly soccer, current rehabilitation programmes focus on return to pivoting sports.[2] Before actual field training can commence, lots of hours are spent in the gym to regain knee strength. Incorporating another activity, like speed skating, early in the rehabilitation after ACL reconstruction can pose a challenge for young athletes and make the rehabilitation phase more fun, potentially increasing compliance during rehabilitation.

It has been recognised that research regarding rehabilitation after ACL reconstruction needs to address 'what works for which context, for whom, and when some criteria are relevant'.[11] This implies that we need to tailor rehabilitation after ACL reconstruction to the specific patient. In order to do so, we need alternatives for the current rehabilitation programme, and the incorporation of ice speed skating in a rehabilitation programme may be such an alternative. Also, rehabilitation after ACL reconstruction needs to include sensory and cognitive stimulation adjuvant to motor tasks[11], which is combined in ice speed skating. Ice speed skating focusses on improving balance, core stability and strength, and so athletic abilities overall may be increased.

The aim of this study was to develop a safe, fun and feasible rehabilitation programme incorporating ice skating as an alternative for the current rehabilitation programme after ACL reconstruction.

Methods

A rehabilitation protocol incorporating ice skating after ACL reconstruction was developed by discussion within an expert group. Two physical therapist, three orthopaedic surgeons and two human movement scientist took part in the discussions.

Theoretical framework for the KROS programme

Potential risk factors for ACL injury include ligament dominance, quadriceps dominance, leg dominance and trunk dominance.[15] Ligament dominance is a biomechanical condition in which muscles do not absorb ground reaction forces sufficiently, so the joints and ligament have to absorb high amounts of force over a brief period of time, making ligaments more susceptible for rupture. Quadriceps dominance highly relates to ligament dominance. Untrained use of the posterior kinetic chain (i.e. the gluteal, hamstring and calf muscles) leads to less shock absorbance by decreased use of knee flexion. In quadriceps dominance athletes preferentially use the quadriceps instead of posterior kinetic chain to control the limb and therefore enhance ligament dominance. Moreover, overtightening of the quadriceps muscle leads to more anterior forces on the proximal tibia. This leads to more stress on the ACL which functions as a restraint to anterior translation of the tibia.[15]

A rehabilitation protocol focusing on the posterior kinetic chain might enhance performance after ACL reconstruction and lead to earlier return to sports.

Trunk dominance or core dysfunction is defined as the inability to precisely control the trunk in the three dimensional space. During all activities the ground reaction force is aimed at the centre of mass, which is located in the trunk segment of the body. In case of an unstable trunk, the trunk is often moved laterally during single leg stance. This leads to a lateral shift of the ground reaction force through the knee and thus producing a valgus alignment. A valgus position of the knee is known to produce a higher stress level on the ACL and therefore making it more susceptible for injury.[15] Core stability training may decrease lateralization of the trunk and in doing so, protect the ACL. All these factors are described more often in female athletes than in males.

The skating position (both in inline and in ice speed skating) requires a high amount of trunk balance and prolonged squatting. A prolonged squatting position requires the presence of an adequate posterior kinetic chain. The forward stride in skating combines hip extension, abduction and external rotation, knee extension and foot plantar flexion. From this theoretical overlap between ACL rehabilitation and the skating motion we developed the idea to combine the two and incorporate speed skating in the rehabilitation after ACLR.

Because of the possibility of major balance disturbances and even falling during skate training, adequate preparation before starting the skate training was deemed essential. Therefore certain objective criteria have been postulated which had to be obtained before the start of the skate training. By preparing the subjects and setting criteria of objective muscle strength we hypothesized that the chances of falling and balance disturbances are no higher than during regular rehabilitation.

In order to commence skating practice a subject had to meet the following criteria:

- Minimal to no effusion in the knee joint
- Able to perform 20 minutes of running without signs of effusion in the knee joint
- Strength LSI > 80% regarding hamstring and quadriceps power

Treatment of subjects
Compliant with current guideline of rehabilitation after ACL reconstruction, rehabilitation was divided in three phases as is shown in table 1.

Skating
Only after meeting the aforementioned criteria, a subject was allowed to start skating training.

The first skating training consisted of 20-30 minutes pure skating time. Main focus was on the control of the skating motion and on symmetrical performance in skating. In the initial phase, the ‘cross over’ in the corners of the track were avoided. When subjects felt comfortable, the cross over manoeuvre was allowed.

While increasing the intensity in skating, extra attention was paid to potential aggravation of pain and effusion of the knee. This had to be minimal in regards to both effusion and pain. A pain score on the Numeric Pain Rating Scale (NPRS) of up to 3-4/10 and minimal increase in effusion which reduces after 1-2 days, were leading in considering the progression in intensity of skating.

At the beginning of each training a short evaluation of the past days was initiated by the treating physiotherapist. Subjects were asked for delayed physical responses in regards to the previous training day. In addition, at the end of each training subjects were asked to shortly evaluate the training.

Study Procedure

Participants were recruited consecutively at the Tjongerschans hospital in Heerenveen, the Netherlands. Eligible participants were > 18 years of age and had suffered unilateral ACL injury requiring ACL reconstruction as defined by the Dutch guideline on ACL injury. Exclusion criteria were; additional surgical procedures altering the postoperative rehabilitation protocol (e.g. meniscal repair), a history of fractures in the lower extremities or spine, previous osteotomy procedures in the lower extremities, previous musculoskeletal surgery in the lower extremities, neurological conditions leading to musculoskeletal disorders, and the inability to complete Dutch questionnaires. As soon as an eligible patient was scheduled for an ACL reconstruction by the treating surgeon, the patient received the study information and was asked to participate. During the inclusion period, the mean interval between consultation and surgery was aimed to be 6 to 8 weeks.

Inclusion started in May 2019 and ended upon enrolment of the 15th participant in November 2020.

Baseline was defined as the moment of inclusion. Follow up measurements were performed 3, 6, 9 and 12 months after ACL reconstruction.

Feasibility

Feasibility was determined as:

- Less than 30% loss of compliance.
- Overall patient reported rating > 6/10 on NRS scale at the end of rehabilitation
- No serious adverse events, related to the rehabilitation, as defined by the Central Committee on Research Involving Human Subjects.[1]

Table 1. Schematic display of the KROS protocol.

Mobility	Strength	Activity and participation level
Phase 1 **Takes place at the physiotherapist office.** **Focus on regaining a normal range of motion with limited effusion.**		
- Passive mobilizations of the patellofemoral joint. - Focus on regaining range of motion (ROM), mainly full extension (active and passive). - Aim for full extension within 2-4 weeks. - Motor reactivation of the m. quadriceps (possibly with electrical stimulation), with isometric exercises, enhancing to concentric and eccentric exercises.	- m. Quadriceps strength training in closed chain in ROM 0-60°, starting from week 4 in open chain in ROM 90-45°; starting from week 5 ROM every week with 10° increase. - Concentric and eccentric training the hamstrings, gluteal and calf muscles. - Step up and skate step. Start in the sagittal plane, enhancing to transition in the frontal plane.	- Neuromuscular training focusing on quality of exercises. - Exercise gait and cycling.
Phase 2 **Took place at the physiotherapist office and at the ice rink.** **Focus on getting subjects ready for training on skates.**		
Mobility	**Strength**	**Activity and participation level**
- Maintain full ROM	- Training of the m. quadriceps: • in open chain from week 6 in ROM 90-20 °, week 7 in ROM 90-10 °, in week 8 in ROM 90-0 °. • in closed chain starting from week 8 to ROM 0-90 ° - Step up and skate step into deeper knee angles and if possible on a less stable surface (e.g. Skate step on an exercise mat and a step up on a box with a soft top). - Intensify strengthening exercises for hamstrings, gluteal and calf muscles (less repetitions, higher resistance)	- Expand of neuromuscular training with focusing on correct implementation. - Start with outdoor cycling - Cyclic forms of exercise, especially aerobic. If available, start exercising on a step trainer. The push off is aimed oblique posterior. - Start from week 10-12 with jogging - Agility training - Return to work (if applicable)

Phase 3
Took place at the ice rink. Focus on return to play.

Criteria for transition to phase 3:
- **qualitative correct implementation of the neuromuscular exercises in phase 2**
- **Minimal to no effusion.**
- **Able to run for 20 minutes without increase in effusion.**
- **Strength limb symmetry index > 80% for hamstring-and quadriceps power.**
- **Functional limb symmetry index > 80%**
- **report to medical specialist**

Mobility	Strength	Activity and participation level
- Maintain full ROM.	- Intensify strengthening exercises for quadriceps, hamstrings, gluteal and calf muscles. - (sport) specific strengthening exercises.	- Expand neuromuscular training with qualitative correct implementation. - Expanding jogging/biking to sport specific tax. - Expand and intensify agility training. - Return to training at own sports club.

Compliance

Compliance was defined as the presence during scheduled training sessions after ACL reconstruction. The treating physiotherapist was involved in the study and was instructed to register the presence of each participant in the patients logbook. Also, At the beginning of each training a short evaluation of the past days was initiated by the treating physiotherapist. Participants were asked for delayed physical responses in regards to the previous training day. In addition at the end of each training participants were asked to shortly evaluate the training on a 3 point scale (good-neutral-bad).

Questionnaires

Subjects were asked to complete a study specific questionnaire regarding the KROS rehabilitation programme 12 months after ACL reconstruction. This questionnaire asked subjects to evaluate the KROS rehabilitation for 0 to 10 on fun, physical aspects, emotional aspects, compliance and return to sports.

At baseline, and 3,6,9 and 12 months after ACLR, all subjects completed the Dutch translation of the 2000 International Knee Documentation

Committee Subjective Knee Form (IKDC form)[14], the Dutch language version of the ACL Return to Sports after Injury questionnaire (ACL-RSI) [19], and the Knee-Self Efficacy Scale (K-SES).[20]

The IKDC questionnaire measures subjective knee functioning and is scaled from 0-100. A higher score indicates better subjective knee function. The ACL-RSI measures the psychological readiness to return to sports. The outcome is scaled from 0-100 in which higher scores indicate better psychological readiness to return to sports. The KSES questionnaires measures knee self-efficacy, i.e. a person's belief in their own ability to complete a particular task. Scores are reported from 0-10, in which higher scores indicate better knee self-efficacy.

At baseline and 12 months after ACL reconstruction the Tegner Activity Scale[8] was completed by the treating physiotherapist to determine the sport activity level of the participants.

Strength LSI

At 3,6,9 and 12 months after ACL reconstruction, isometric Quadriceps (Q) and Hamstring (H) strength was measured in Nm/kg using a handheld dynamometer as described by Hansen et al.[13] All subjects performed three measurements of both hamstrings and quadriceps strength. To calculate the Q/H ratio the average quadriceps strength was divided by the average hamstring strength. A normal H/Q ratio is considered to be 50% to 80% as averaged through the full range of knee motion, with a higher ratio at faster speeds.[18] The strength limb symmetry index (LSI) was also calculated. The operative limb strength average was divided by the non-operative limb strength average, and multiplied by 100 (percentage).

Functional LSI

At 6, 9 and 12 months after ACL reconstruction, subjects performed a single leg hop for distance, a side jump, a single leg balance test and a Y balance test. To calculate limb asymmetry index values, the operative limb average was divided by the non-operative limb average, and multiplied by 100 (percentage). An average limb symmetry index of the above described three types of test was calculated.

Statistical analysis

Statistical analysis was performed using SPSS (v 28; IBM Corp, Armonk, NY, USA). Descriptive statistics (means, SD, range) were applied for baseline characteristics, loss of compliance and overall patient reported rating of the rehabilitation programme. QQ plots were conducted for all variables and no signs of non-normality were shown. To compare means of strength and functional outcomes between the KROS group and the groups that received regular rehabilitation, independent sample t-tests were used (two-sided, equal variances assumed). Statistical tests deemed significant if $P < 0.05$.

Results

In total 15 participants were recruited. Due to interference of the COVID pandemic during the period of this study, only five subjects were able to follow the ice skate part of the KROS programme. This group of subjects was referred to as the "KROS group". The other ten subjects were rehabilitated according to the routine ACL rehabilitation protocol: the "Regular Rehabilitation Group". Baseline characteristics of both groups are presented in table 2. As seen in table 2 there are distinct differences between the two groups. The KROS group consisted of more male participants, which is also reflected by the biometric parameters length and weight. The ACL-RSI, IKDC and KSES-scores were lower in the KROS group at baseline, but this was not significantly different from the regular rehabilitation group.

Overall, three participants decided to discontinue their participation in the study, one in the KROS group, two in the regular rehabilitation group. Reasons varied but were mainly related to personal circumstances. All other participants were present during all scheduled training sessions or rescheduled their training session in case of absence. This led to a total loss of compliance of 20% in both groups.

The KROS rehabilitation programme was rated with a 6.8 on a scale from 0 to 10. No serious adverse events were recorded during this study.

Table 2. Baseline characteristics

	KROS group N=5	Regular rehabilitation group N=10
Male/Female	4/1	5/5
Age (years)*	27 (5)	30 (12.5)
Length (cm)*	183 (7.1)	178 (9.2)
Weight (kg)*	82.4 (13.0)	73.1 (8.1)
BMI (kg/m^2)*	24.4 (2.7)	23.0 (1.8)
Dominant/non dominant leg involved	3/2	3/7
Injury to surgery interval (months)	6.7 range 4-12	12.3 range 3-37
Tegner score at baseline	4 (2.5) range 0-7	5 (2.4) range 1-9
ACL-RSI score at baseline	27.6 (20) range 3-48	44 (18) range 18-68
IKDC score at baseline	48 (8.2) range 38-59	58 (14.4) range 31-78
KSES score at baseline	5 (1.8) range 3-7	6 (2.6) range 2-9
Withdrawal from study participation	1	2

*values displayed as mean (SD)

Figure 1-3 show bar charts of the outcome of the ACL-RSI, KSES and IKDC questionnaires of the KROS and regular rehabilitation group at the different measurement points.

A comparison of means showed no significant difference between the KROS group and the regular rehabilitation group at 12 months regarding the ACL-RSI scores, KSES scores, isometric quadriceps strength, Isometric hamstrings strength, H/Q ratio, strength LSI, functional LSI, Single Leg Hop for Distance outcome, Side Hop outcome, Single Leg Balance outcome and the Y-Balance outcome.

In figure 4 and 5 it is shown that over the course of the KROS programme, the quadriceps strength keeps improving, whereas the hamstrings strength dips around month 9. As demonstrated in figure 6 and 7 both the strength and functional limb symmetry indexes are near normal in both groups from 6 months after ACL reconstruction.

Results from the strength and functional tests and results from the questionnaires for all subjects that participated in the KROS programme over the different timepoints are depicted in appendix A. In appendix B the same results are shown for the regular rehabilitation group. In appendix C the individual results of the KROS participants are shown with regard to the ACL-RSI scores, IKDC scores, KSES scores, isometric quadriceps strength and isometric hamstrings strength.

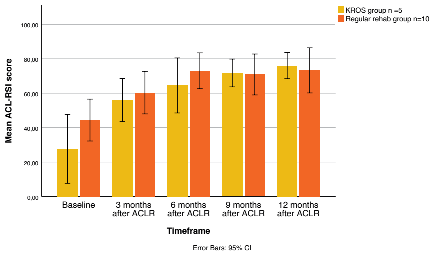

Figure 1. Bar chart illustrating the mean ACL-RSI score from baseline to 12 months after ACL reconstruction.

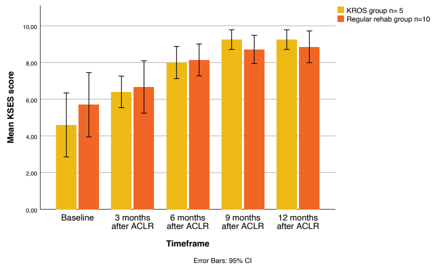

Figure 2. Bar chart illustrating the mean KSES score from baseline to 12 months after ACL reconstruction.

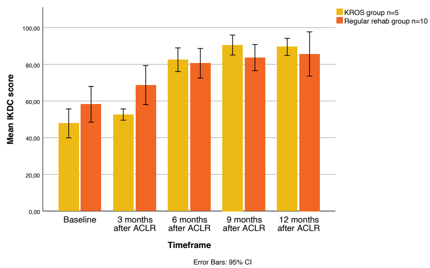

Figure 3. Bar chart illustrating the mean IKDC score from baseline to 12 months after ACL reconstruction.

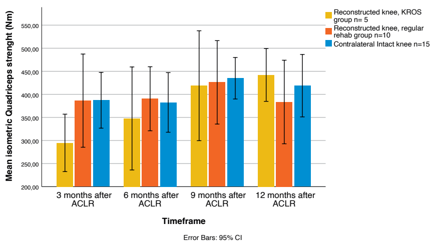

Figure 4. Bar chart illustrating the mean isometric quadriceps strength from 3 to 12 months after ACL reconstruction in different subgroups.

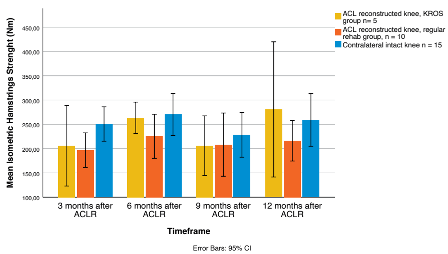

Figure 5. Bar chart illustrating the mean isometric hamstrings strength from 3 to 12 months after ACL reconstruction in different subgroups.

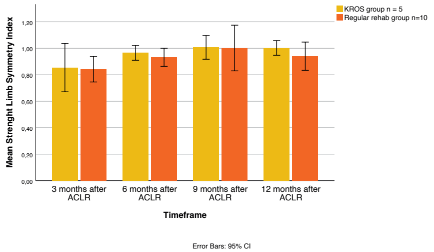

Figure 6. Bar chart illustrating the mean limb symmetry index for strength from 3 to 12 months after ACL reconstruction in different subgroups.

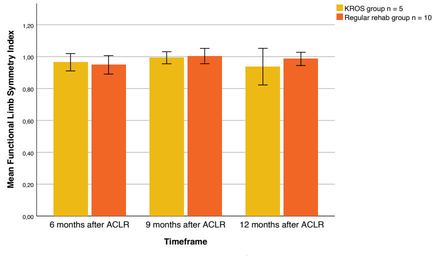

Figure 7. Bar chart illustrating the mean limb symmetry index for functional from tasks 3 to 12 months after ACL reconstruction in different subgroups.

Discussion

The main objective of this study was to determine the feasibility of a newly developed rehabilitation programme for patients after ACL reconstruction with ice skating as part of the programme. Based on our results we can conclude that the KROS programme seems feasible and safe and is rated positively by the participants.

It has been demonstrated that compliance to rehabilitation protocols positively influences return to sports rates.[5,7] With our newly developed KROS rehabilitation programme we have shown a compliance rate of 80%.

A previous report by della Villa showed that 44 of 79 patients were ‘non-compliant’ or ‘somewhat compliant’ during rehabilitation after ACL reconstruction.[7] This highlights that current rehabilitation programmes fail to achieve good compliance rate for a large group of patients. In our study, before inclusion, patients were offered the choice to participate in our study or to follow the regular rehabilitation programme. We demonstrate that when patients are offered such a choice, high compliance rates are achieved. This may be a way to improve compliance during ACL rehabilitation and by doing so, we may be able to improve outcome after ACL reconstruction. We therefore advocate that the topic of rehabilitation after ACL reconstruction needs to be addressed already before surgery and stimulate surgeons to involve the patient in the design of her/his specific rehabilitation programme.

The continued provision of challenges during the rehabilitation programme has proven to be important for recovery after ACL reconstruction.[16] This process of periodization comes into its own during the KROS protocol. With the KROS programme, sensory and cognitive stimulation and motor learning is promoted. Another possible advantage could be the fact that patients get in touch with a different kind of sport with a lower risk of ACL injury. If patients decide to stick to skating, re-injury of their reconstructed ACL might be prevented. If patients decide to stop skating, they may have developed into a more all-round athlete who, for instance, can play football at an increased level.

To our knowledge there is only one other report that comprehensively describes on-ice training after ACL reconstruction. Capin et al[6] described general guiding principles for the return on ice after ACL reconstruction. Most of our KROS programme was based on the work of Capin et al. They included a case description of 1 patient including quadriceps strength, hoptests battery and a limb symmetry index. They reported a quadriceps strength index of 88% at 7 months after surgery, 97% after 8.5 months after surgery and 94% 11 months after surgery. We have observed similar results with a mean quadriceps strength index in the KROS group of 108% after both 6 and 9 months after surgery and 101% 12 months after surgery. Capin asked his patient to complete the Knee Outcome Score (KOS) ADL subscale at 7.5, 8.5 and 11 months after surgery. Patient reported outcome improved from 80% at 7.5 months to 93% at 11 months after surgery.[6] We have used a different questionnaire to test subjective knee symptoms during daily activities. Our participants reported a mean score of 81 points on the IKDC-questionnaire at 6 months after surgery, which improved to 87 at 12 months after surgery.

In the KROS group, the mean outcome is comparable to previous studies reporting on outcome after ACL rehabilitation. In our study, the mean ACL-RSI score in the KROS group was 76 (SD 7) which is higher than reported by Webster in a large cohort of 635 patients that followed routine ACL rehabilitation.[22] Is has to be noted that in the cohort of Webster et al, only 25% of patients had returned to a competitive form of sports. A recent review of literature that assessed knee self-efficacy in ACL injured patients has shown a mean KSES score at 7-12 months after surgery from 7.5 [95% CI 6.8–8.2]. We have seen excellent outcome scores on the KSES score in our KROS group [9.3 at 12 months]. The major increment in subjective knee symptoms, psychological readiness to return to sports and knee self-efficacy was seen from baseline to 6 months after surgery.

Webster et al also tested a large cohort for a functional limb symmetry using the single hop for distance and the crossover hop 12 months after surgery which led to a LSI of 94 and 96% respectively.[21] In our population we have seen comparable results with a functional LSI of 94% in the KROS group. In terms of quadriceps strength a LSI 101% (SD 9) was observed in the KROS group. Arundele et al. reported a quadriceps strength LSI of 101% (SD 14) in 40 patients 12 months after surgery,[4] which is again comparable to our results.

We observed that over time, the quadriceps strength in the KROS group increased well. Hamstring strength seemed to dip around month 9, but this was also seen in the regular rehabilitation group. This supports the fact that return to sports after 9 months is too early. It could be, that after these 'disappointing' results after 9 months compared to the measurement after 6 months, participants have become extra motivated to work on the quadriceps and hamstring strength. We had no influence on, nor restricted, any training done in addition to the specified ice skating programme. This may have led to some bias in the results.

Overall we have observed no differences in development of strength or performance on hop tests during the course of the rehabilitation between the KROS group and the regular rehabilitation group. Even though this was not the main purpose of the study and baseline characteristics differ between the two groups, this pilot study shows that it seems that the KROS protocol is not inferior to the gold standard. A non-inferiority study is needed to confirm our preliminary data. For now, these results underline the feasibility of the KROS rehabilitation programme.

Limitations and future perspectives

During the course of this study, the world had been affected by the covid pandemic. In the Netherlands, this has led to a lockdown, which has also led to the closing of facilities where large groups of people can come together. The Thialf ice rink was also among the facilities that were closed. To this end, only 5 of the 15 participants were actually able to rehabilitate according to the KROS protocol. Nevertheless, in these few subjects we have seen excellent results in terms of compliance, satisfaction and safety. Future studies are needed to confirm our results in a larger population.

Due to the design of the study, there may be a selection bias present. Only patients who are actually interested in rehabilitation on skates have participated in the study. However, the underlying goal has not been to offer the KROS programme to all patients, but rather to look for an alternative for the current standard rehabilitation. Tailoring the rehabilitation after anterior cruciate ligament reconstruction is of great importance. One size does not fit all, patient-specific rehabilitation is the path we will have to take to improve compliance, and with that improve outcome, after ACL injury.

Conclusion

Rehabilitation on skates after ACL reconstruction is feasible and safe, shows high compliance and seems to lead to excellent objective and patient reported outcomes. Future research is needed in a large group of patients to determine whether objective outcomes like strength and functional capabilities are at least non-inferior to current common practice.

Acknowledgements

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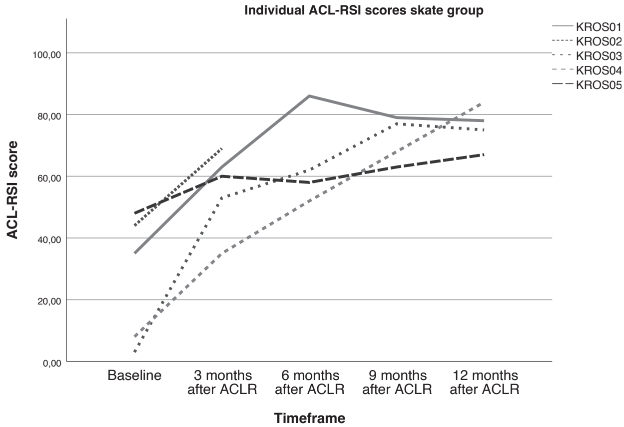
Appendix A. Mean results for the KROS group, n= 5

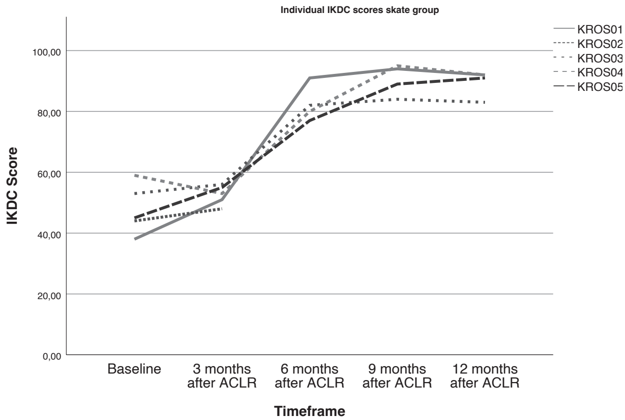
		Baseline	3 months after ACLR	6 months after ACLR	9 months after ACLR	12 months after ACLR
Questionnaires						
ACLR-RSI questionnaire		28 (21)	56 (13)	65 (15)	72 (8)	76 (7)
IKDC questionnaire		48 (8)	53 (3)	83 (6)	91 (5)	90 (4)
KSES questionnaire		4.6 (1.8)	6.4 (0.9)	8.0 (0.8)	9.3 (0.5)	9.3 (0.5)
Strength						
Isokinetic Hamstring strength (Nm/kg)	ACLR		206 (86)	264 (30)	206 (50)	281 (130)
	Intact		251 (77)	307 (52)	241 (64)	279 (106)
Isokinetic Quadriceps strength (Nm/kg)	ACLR		295 (65)	348 (104)	499 (69)	442 (53)
	Intact		332 (76)	330 (133)	464 (95)	443 (97)
Hamstrings/Quadriceps ratio	ACLR		70% (26)	79% (19)	41% (5)	62% (25)
	Intact		81% (33)	104% (44)	51% (4)	63% (23)
Quadriceps strength limb symmetry index			91% (22)	108% (11)	108% (8)	101% (9)
Hamstrings strength limb symmetry index			83% (21)	87% (10)	86% (3)	99% (17)
Combined strength Limb Symmetry Index			85% (19)	97% (5)	101% (7)	100% (5)
Functional						
Single Leg Hop for Distance (cm)	ACLR			159 (33)	167 (32)	188 (24)
	Intact			146 (37)	173 (24)	190 (21)
Side Hop (number of correct hops)	ACLR			52 (13)	57 (22)	59 (14)
	Intact			55 (13)	58 (22)	60 (11)
Single Leg Balance (number of floor supports)	ACLR			1.1 (1.3)	0.3 (0.0)	0.5 (0.2)
	Intact			1.9 (1.4)	0.4 (0.2)	0.3 (0.3)
Y balance Anterior (cm)	ACLR			76 (18)	68 (4)	70 (5)
	Intact			79 (15)	68 (2)	72 (5)
Y balance Posteromedial (cm)	ACLR			110 (11)	110 (7)	118 (15)
	Intact			115 (16)	108 (5)	117 (13)
Y balance Posterolateral (cm)	ACLR			109 (10)	68 (4)	115 (18)
	Intact			105 (13)	68 (2)	115 (16)
Functional limb symmetry index				97% (5)	99% (3)	94% (11)

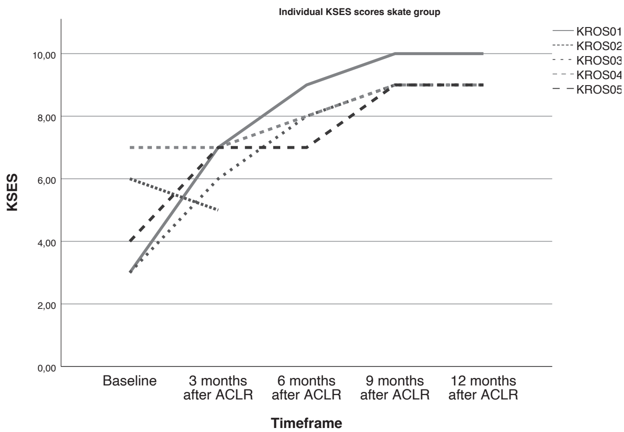
Appendix B. Mean results for the Regular rehabilitation group n = 10

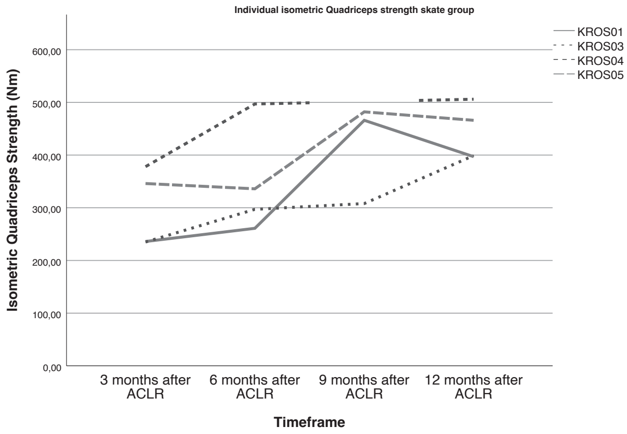
		Baseline	3 months after ACLR	6 months after ACLR	9 months after ACLR	12 months after ACLR
Questionnaires						
ACLR-RSI questionnaire		44 (18)	60 (17)	73 (13)	71 (16)	73 (17)
IKDC questionnaire		58 (14)	69 (15)	81 (10)	84 (9)	86 (16)
KSES questionnaire		5.7 (2.6)	6.7 (2.0)	8.1 (1.1)	8.7 (1.0)	8.9 (1.1)
Strength						
Isokinetic Hamstring strength (Nm/kg)	ACLR		197 (41)	225 (56)	208 (68)	216 (43)
	Intact		250 (35)	250 (69)	221 (65)	243 (48)
Isokinetic Quadriceps strength (Nm/kg)	ACLR		433 (85)	413 (70)	426 (94)	383 (94)
	Intact		386 (115)	390 (85)	417 (25)	399 (99)
Hamstrings/Quadriceps ratio	ACLR		53% (12)	59% (14)	51% (17)	60% (25)
	Intact		60% (14)	61% (14)	53% (14)	64% (23)
Quadriceps strength limb symmetry index			92% (16)	97% (13)	102% (23)	97% (9)
Hamstrings strength limb symmetry index			79% (9)	90% (6)	92% (7)	94% (17)
Combined strength Limb Symmetry Index			84% (11)	93% (8)	100% (18)	94% (11)
Functional						
Single Leg Hop for Distance (cm)	ACLR			174 (36)	188 (25)	178 (24)
	Intact			188 (29)	200 (28)	182 (20)
Side Hop (number of correct hops)	ACLR			55 (10)	61 (8)	58 (9)
	Intact			57 (9)	61 (8)	60 (8)
Single Leg Balance (number of floor supports)	ACLR			0.9 (2.2)	0.3 (0.6)	0.9 (1.9)
	Intact			0.6 (1.5)	0.5 (0.9)	0.8 (1.6)
Y balance Anterior (cm)	ACLR			69 (7)	70 (4)	68 (5)
	Intact			71 (11)	72 (5)	70 (6)
Y balance Posteromedial (cm)	ACLR			105 (12)	112 (12)	114 (7)
	Intact			134 (64)	106 (22)	111 (10)
Y balance Posterolateral (cm)	ACLR			112 (9)	70 (4)	115 (9)
	Intact			112 (14)	72 (4)	119 (7)
Functional limb symmetry index				95% (7)	100% (5)	99% (4)

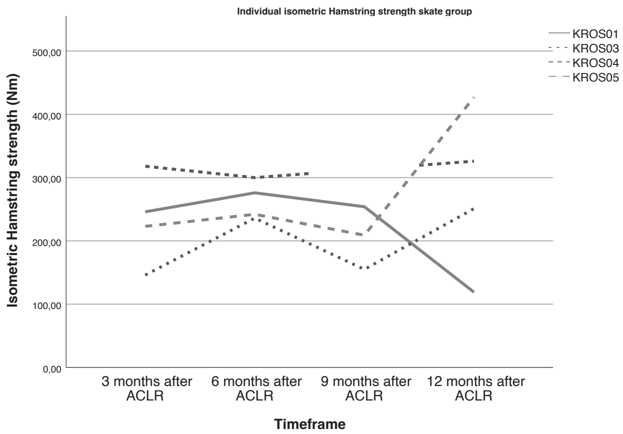
Appendix C. Line graphs representing the individual results of the KROS participant for the ACL-RSI score, IKDC-scores, KSES-scores, isometric Quadriceps strength and isometric hamstrings strength.



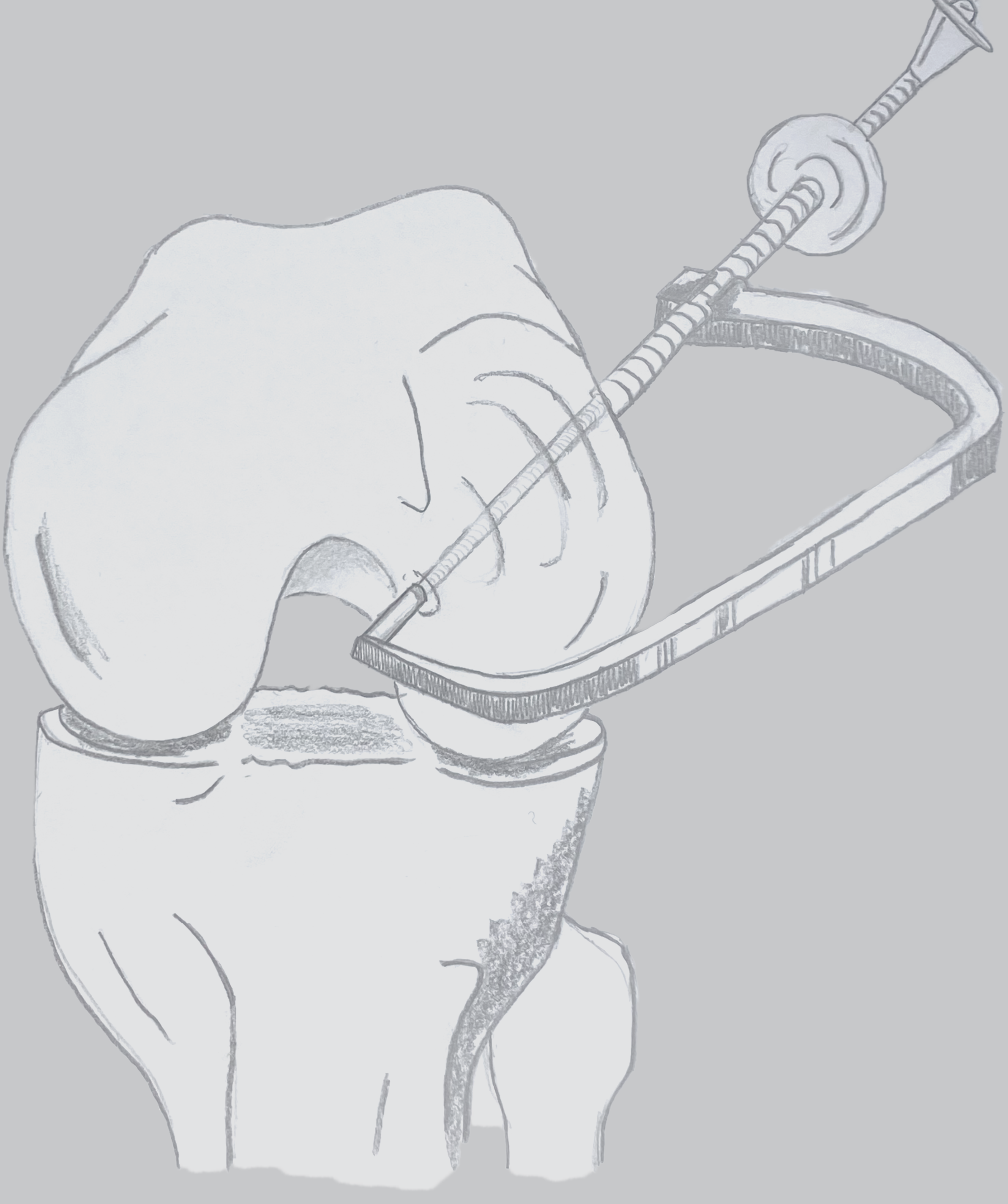





Individual isometric Quadriceps strength skate group
KROS01
KROS03
KROS04
KROS05
Isometric Quadriceps Strength (Nm)
600,00
500,00
400,00
300,00
200,00
100,00
0,00
3 months after ACLR
6 months after ACLR
9 months after ACLR
12 months after ACLR
Timeframe


Individual isometric Hamstring strength skate group
KROS01
KROS03
KROS04
KROS05
Isometric Hamstring strength (Nm)
500,00
400,00
300,00
200,00
100,00
0,00
3 months after ACLR
6 months after ACLR
9 months after ACLR
12 months after ACLR
Timeframe

8



Chapter 9

General Discussion

Improving Functional and Biomechanical Outcome after ACL reconstruction

Despite the rise in the number of ACL reconstructions being performed worldwide, return to sports rates are still poor. For instance, it is estimated that 175,000 ACL reconstructions are performed in the US annually.[5] With only 55% of patients returning to sports,[1] the estimation is that 70,000 patients will quit competitive sports annually in the US alone. As return to sports is a complex concept, the general aim of this thesis is to improve functional and biomechanical outcome after ACL reconstruction, by generating a better understanding of these factors that are known to influence return to sports rates. In this General Discussion, the results of these studies are summarised and implications for clinical practice and future research are presented.

Summary of the main findings

The aim of the first part of the thesis was to study the influence of the ACL on the range of tibial rotation and to study the association between range of tibial rotation in sport-related activities on one hand and subjective knee function, psychological readiness and slope of the tibial plateau on the other. Persistent rotational laxity could be a key factor in poor return-to-sports rates.

In **Chapter 2** we reviewed the literature for studies investigating the purely mechanical influence of an ACL graft on the range of tibial rotation. Several studies conducted in anaesthetised patients show that the passive range of tibial rotation in ACL-deficient subjects is higher than that of intact knees, and that the passive range of tibial rotation decreases by 17-32% (average 25%) after ACL reconstruction.[6,37,38] It should be noted that the methodological quality of the included studies was low and the level of the evidence was low-to-very-low due to heterogeneity in the design of these studies. The findings are nonetheless generally accepted, as they match the biomechanical role of the ACL and underline that ACL reconstruction can control the passive rotational movement of the tibia.

In **Chapter 3** we showed that, in contrast with the result of passive testing as reported in **Chapter 2**, within three months of ACL injury the dynamic range of tibial rotation is not increased. In fact, the range of tibial rotation that we measured was even smaller in ACL-injured knees compared to contralateral intact knees, albeit not significantly. When performing the same tests again one year after ACL reconstruction, we found that the range of tibial rotation approached that of the contralateral intact knee, but was still smaller in ACL-reconstructed knees than in intact knees. This study supports the theory that dynamic range of tibial rotation is essentially different from passive range of tibial rotation.

In **Chapter 4** we showed that the dynamic range of tibial rotation has a strong positive correlation with self-reported knee function and psychological readiness to return to sports in high-demand functional tasks. We observed that the more closely knee kinematics resemble those of a normal knee, the better the subjective knee function scores and the better the reported psychological readiness to return to sports. Another important finding that we demonstrated in this chapter is that dynamic anterior tibial translation has a low correlation with psychological readiness to return to sports. This supports the hypothesis that not control of translation but control of rotation could be the most important factor influencing actual or subjective function after ACL rupture and reconstruction.

In **Chapter 5** we found a moderate-to-strong correlation between amount of posterior tibial slope and dynamic range of tibial rotation. In a dynamic setting, we found only a low correlation between anterior tibial translation and posterior tibial slope. This implies that in a dynamic setting, muscular activity can compensate for the anterior translation of the tibia but effectively falls short in compensating for its rotational movement.. We concluded that bone morphology can contribute to altered knee kinematics after ACL reconstruction. Hence this is another factor that we need to take into account in the process of individualising ACL reconstruction.

The second part of this thesis focuses on this individualising process and aimed to develop a patient-specific guide to ensure a femoral tunnel position in the native footprint of the ACL, plus determine the feasibility of an alternative rehabilitation protocol after ACL reconstruction.

In **Chapter 6** we demonstrated that identification of the femoral footprint of a torn ACL on MRI has a high intraobserver and interobserver reliability. Although the differences were small, it was also demonstrated that orthopaedic surgeons are more consistent in the exact identification of the femoral footprint of the ACL than radiologists. It has been evidenced that identification of an intact ACL is possible on MRI.[35,36] Now we have demonstrated that it is also feasible to identify the femoral footprint of a torn ACL.

Based on the results of the research in **Chapter 6** we were able to create and use a patient-specific guide for a patient-specific reconstruction of the ACL. Based on a routine clinical MRI of a patient, a 3D model of the femur was created and a femoral tunnel position was planned. Next, a patient-specific guide was designed that fits the intercondylar notch to ensure the femoral tunnel position. **Chapter 7** shows the in vitro results of the newly developed guide. Although we need further improvement in the design to increase accuracy, the concept of a patient-specific guide seems promising.

In **Chapter 8** we present a novel rehabilitation protocol – Knee Rehabilitation on Skates (KROS) – to be used in patients after ACL reconstruction. Compliance with rehabilitation is a precondition for better return to sports rates after ACL reconstruction.[2] The current Dutch guideline on rehabilitation after ACL reconstruction mainly focuses on strength exercises, but allows room for interpretation.[40] In order to prevent potential dullness and monotony of rehabilitation after ACL reconstruction, it is important to compose an individualised rehabilitation programme that meets the patient's needs and wishes, within evidence-based boundaries. With the development of the KROS protocol we strove to offer an alternative for patients who do not necessarily participate in pivoting sports. Even though the COVID pandemic affected this study, the results of this pilot study are promising. This study has shown that it is feasible to introduce ice speed skating in the rehabilitation after ACL reconstruction, which may provide a good alternative rehabilitation modality to enhance compliance among some patients.

Understanding the effects of ACL injury

Rupture of the ACL leads to an onset of several events that include biological, mechanical, neuromuscular and psychological factors. The biological aspect is demonstrated by several cascades which involve the release of inflammatory markers (CRP and lubricin) at the time of injury.[5] While the level of the inflammatory markers drop over the course of the first four weeks, serum proteins that indicate increased cartilage metabolism (proteoglycans) actually seem to increase over the same period, which may indicate an adaption of the cartilage biosynthesis in the presence of mechanical instability.

Over 50% of patients with a traumatic hemarthrosis have an ACL rupture,[26] so one might say that hemarthrosis is pathognomonic for the presence of ACL rupture. Even though that might be a bold statement, the presence of a hemarthrosis may initiate the cascade mentioned above. On the other hand, hemarthrosis also leads to stiffening of the knee capsule.[27] This stiffening can be regarded as a protective strategy to oppose the mechanical instability caused by the rupture of the ACL.

Also, the ACL contains mechanoreceptors and proprioceptive receptors.[31] Transection of the ACL leads to altered afferent neurological pathways to the central nervous system. It is shown that sensory nerves located in the knee capsule play an important role in preventing the acutely unstable knee from rapid breakdown, probably by influencing protective muscular reflexes.[25] It is suggested that after ACL injury the central nervous system relies more on visual feedback and spatial awareness, as the biomechanical feedback is disturbed.[30] Those parts of the brain responsible for visual processing (posterior inferior temporal gyrus), motor control (pre-supplementary motor area), and pain and sensory control (somatosensory area) are more active in patients after ACL injury.[19] This indicates that the central nervous system is shifting to alternative pathways to regain knee stability.

Adding to the biological, mechanical and neurogenic consequences, ACL injury has a major impact on psychological wellbeing.[42] In **Chapter 8** we showed that ACL-injured patients have low knee self-efficacy, poor psychological readiness to return to sports and low subjective knee function. This is recognised by many others too. A review of literature by Bullock et al. demonstrated high levels of kinesiophobia, low knee self-efficacy and high levels of fear avoidance in ACL-injured patients.[3] The results presented in this thesis emphasise that it is not just the knee we have to take into account – a more holistic approach may be needed to treat ACL-injured patients.

In the treatment of ACL-injured patients it is essential to understand the above-mentioned pathways, and physicians need to be aware that ACL reconstruction is only a small part of the puzzle to enhance return to sports. As demonstrated by this thesis, the currently available reconstruction techniques seem unable to recreate a pre-injury state in many patients. With the available reconstruction techniques, the influence of biological, neuromuscular and psychological factors may be just if not as important as the actual surgical reconstruction itself to achieve pre-injury level of knee function.

The power of dynamic testing

Dynamic rotation is a different construct than passive rotation because in the dynamic setting muscle tension, neuromuscular interaction and psychological aspects influence the range of tibial rotation. Therefore, in our view measuring rotation in a dynamic setting is more clinically relevant than measuring rotation in a passive setting. To understand why patients are unable to return to sports, it is essential to evaluate patients in sport-specific circumstances.

Several tasks have been used in the past to evaluate knee kinematics after ACL reconstruction, for example a 60° cut,[37] stepping off stairs[32] and jumping from platforms.[6] Knee flexion torques are often unreported, but some earlier studies report values varying from 0.2 to 2 Nm/kg.[24,34,37] In this thesis we showed that while using a forward hop and a side jump, the knee flexion torque is up to 6 Nm/kg. This amount of force may be better able to expose potential underlying compensatory mechanisms. Also, it exposes the subject not only to a physical but also a mental challenge. There is clearly a strong correlation between psychological readiness to return to sports and knee kinematics, as demonstrated in **Chapter 4**. We have evidenced that the use of hop tests is of great value when studying knee kinematics after ACL reconstruction. Moreover, combining knee kinematics with hop tests performance can provide even more insight into the status of the individual patient. While cutting and jumping from a stable platform of 40 cm has theoretical advantages of high repeatability, we have shown that performing dynamic hop tests is a safe and reliable way to expose subjects to high amounts of rotational and other forces on the knee. These hop tests are widely used to support the decision for patients to commence return to sports, as explosive power, balance and agility are combined when performing these tests.[14,33]

A downside of the use of hop tests for kinematic analysis of the knee joint could be that they are conducted in a laboratory setting. With the development of augmented reality and the improvements on video performance, future research can focus on actual sport-specific situations. This is important as distraction, double-tasking, anxiety and arousal are factors known to influence athletes' muscle activity and coordination.[19] This may very well be a reason why many athletes do not return to sports, despite proper training in the 'safe' clinical setting, and even field training. The step towards competitive sports requires not only physical but also psychological readiness. The simple recreation of a string is insufficient to achieve something as complex as return to sports.

Rotational laxity one year after ACLR

Based on the findings from the first part of this thesis, we have no evidence that persistent rotational laxity in high-demand activities is present one year after ACL reconstruction. It is therefore unlikely for persistent rotational laxity at this timepoint to be hampering return to sports after ACLR. Instead, patients are able to control or compensate for rotational laxity, potentially using neuromuscular adaptations and alterations in landing techniques[20] in which also psychological factors play an important role. It seems that one year after ACL reconstruction patients still exhibit compensatory patterns. Given that over 91% of patients expect to return to sports within one year of ACL reconstruction,[11] measuring range of tibial rotation at that moment should be considered a sensible and valuable adjunct to ACL rehabilitation, as this may reveal persistent compensatory muscle activity. As time passes, some subjects may display more rotational laxity as a consequence of depletion of the compensatory mechanisms. It is plausible that within one year of reconstruction, patients use compensatory muscle activation patterns to stabilise the knee, but that those compensatory mechanisms fail to protect the graft in the long term. This is supported by the new (and recently popularised) insight that lateral extra-articular tenodesis as an adjunct to ACL reconstruction can reduce the incidence of a positive pivot shift after ACL reconstruction and foremostly can reduce the graft failure rate.[14]

The finding that one year after ACL reconstruction compensatory mechanisms are still present, supports the theory that ACL reconstruction and rehabilitation are individual processes that are not time-driven but rather need to be guided by individual patient characteristics and rates of progression. This is relevant as patients need to be counselled preoperatively to ensure that expectations are realistic. Recreational athletes may mirror themselves against professional athletes who generate a lot of media attention, and may recover more quickly thanks to high-intensity, professional guidance and money-driven goals. It needs to be emphasised in preoperative counselling that this may not be realistic for the average recreational athlete, which still covers the majority of patients.

The findings of this thesis support the theory that we need to aim for an individualised approach in which the most biomechanically accurate reconstruction is created, combined with an individualised rehabilitation protocol with attention for neuromodulation strategies. Based on the knowledge gained in the first part of this thesis we conclude that we must improve the surgical treatment of ACL-injured patients in order to better recreate native knee kinematics and restore the 'biology, neurology and psychology of the knee'. The necessity to match the patient's pre-injury state in the best possible way is pertinent from a surgical perspective.

Individualising ACL Reconstruction

Even though it is recognised that one size does not fit all,[23] current surgical techniques still seem to fall short in providing a reproducible, anatomic result. This is reflected by the altered knee kinematics as shown in this thesis. Apparently, even when using an 'anatomic' ACL reconstruction, native knee kinematics are poorly restored.[13] This may be because during ACL reconstructive surgery it is hard for the surgeon to identify the exact position of the femoral footprint of the ACL, resulting in an estimated best-guess for the location of the femoral tunnel. The ensuing non-anatomic ACL graft placement leads to altered knee biomechanics and poor subjective knee function. We must strive for anatomic ACL reconstruction to restore native knee biomechanics, taking the demonstrated individual variations into account.[28]

With increasing understanding of the anatomy and biology of the ACL,[22] true anatomic ACL reconstruction comes within reach.[23] A patient-specific guide can help attain this result. Also, hypothetically speaking a true anatomic ACL reconstruction can induce positive feedback to the central nervous system, which in turn can promote pre-injury neuromuscular functioning.

In recent years attention has shifted back to ACL repair due to the success of arthroscopic suturing techniques. For these techniques it is at least as important to recognise the femoral footprint of the ACL, since a femoral tunnel is created to secure the sutures. A possible advantage is the short interval between ACL injury and repair, which is preferentially within 3-4 weeks post-injury.[17,39] This may assist visualisation of the femoral footprint. Another theoretical benefit of ACL repair is preservation of the native ACL fibres, including proprioceptive function.[39,43] This may help regain biomechanical feedback to the central nervous system. The same is strived for using ACL remnant-preserving reconstruction.[7] In both techniques it remains vital to guarantee an anatomic reconstruction – with or without use of a patient-specific guide – to ensure native biomechanics of the knee. While these techniques evolve over time, recognising the importance of neurogenic feedback is important. Unfortunately, despite promising short-term results, the non-inferiority of ACL repair versus ACL reconstruction in the midterm remains questionable so far.[17]

Efforts that have been made to enhance accuracy in the drilling of the femoral tunnel include the use of intraoperative fluoroscopy and computer-assisted surgery (CAS). Both techniques strive to enhance accuracy in terms of achieving a planned femoral tunnel. Conflicting results are reported in CAS for femoral tunnel placement.[9] Neither fluoroscopy nor CAS take the footprint of the native ACL into account. These techniques aim for a mean average position of the ACL – the empirical optimal point. This point can be better referred to as a 'suboptimal point', as there is wide variability in the size and location of the footprint of the ACL.[28] This may lead to a partial anatomic or non-anatomic reconstruction in a number of patients. Identifying the exact location of the footprint of the native ACL should be done in order to aim for the correct femoral tunnel position.

A future question that needs to be addressed is the amount of coverage of the ACL footprint during reconstruction. This footprint is shown to vary in size from 60 mm^2 to 130 mm^2, about half of it being reserved for each bundle.[23] An average hamstrings graft of 8 mm in diameter can cover an area of about 50 mm^2 ($A = \pi r^2$), which increases to about 80 mm^2 when a 10-mm graft is harvested. It is shown that full dimensions of the femoral footprint of the ACL can be accurately determined on MRI.[35,36] Bearing this in mind, we can preoperatively assess the diameter of the graft needed and position the femoral tunnel anatomically. To restore a native situation, all we should wish for then is a tissue-engineered ACL that resembles the native ACL in all its dimensions and properties, including mechanoreceptors.

When using patient-specific instrumentation for ACL reconstruction some challenges remain though. As described above, identification of the femoral footprint of the ACL needs to be developed further. Up to now we have only aimed for a single selected point with a diameter of 2 mm, which for practical purposes was in the centre of the ACL. Ideally, this identification process should be automated. In the near future it may be possible to determine the femoral footprint of the native ACL using artificial intelligence and machine learning. The same could be true for segmentation of the femur. When the 3D model of the femur increases in accuracy, the guide will likely increase in accuracy too.

The technique we used to develop the patient-specific guide is not unique but had never been applied in ACL reconstruction surgery. The Boolean subtraction method has been used in several fields of medicine, including orthopaedics – for example when planning patient-specific guides for osteotomies, in both orthopaedic and maxillary procedures. 3D laboratories are quickly emerging throughout the Netherlands, in academic as well as large teaching hospitals. This may boost the use of patient-specific guides in orthopaedic procedures, including ACL reconstruction. This demands a sound scientific foundation to justify the all-round use of these guides.

We have now developed an arthroscopic instrument that can be used in arthroscopic ACL reconstructions. To increase its accuracy, this instrument is made of stainless steel. Arthroscopic ACL reconstructions have been performed on four human cadavers, where we showed that the accuracy of the device has improved to 2 mm. This is sufficient for purposes of a pilot study we started aiming to assess the in vivo accuracy of this patient specific-surgical guide for the creation of a femoral tunnel in ACL reconstruction.

Step by step, we aim to achieve a more individualised ACL reconstruction technique.

Individualising rehabilitation after ACL reconstruction

Rehabilitation after ACL reconstruction is a continuum towards return to sports, where periodisation, neuromuscular training and psychological support are essential.[8] The care for ACL-injured subjects needs to be individualised in order to improve return-to-sport rates.[15] This thesis has explored new possibilities that can be used to offer a more individualised approach to ACL reconstruction and rehabilitation.

Something that may appeal to many athletes is that with the KROS protocol the main focus lies on the outcome of the movement instead of the movement itself. Literally moving your body forward can make a psychological difference when comparing it to performing a leg press at the gym. By incorporating speed skating to ACL rehabilitation, more fun and higher compliance may be achieved. This study shows that it is feasible to look for alternative modes of rehabilitation outside the gold standard for rehabilitation after ACL reconstruction. This opens up the path towards individualised ACL rehabilitation, not only in terms of speed, frequency and intensity of exercises but also type of sports integrated within the rehabilitation programme.

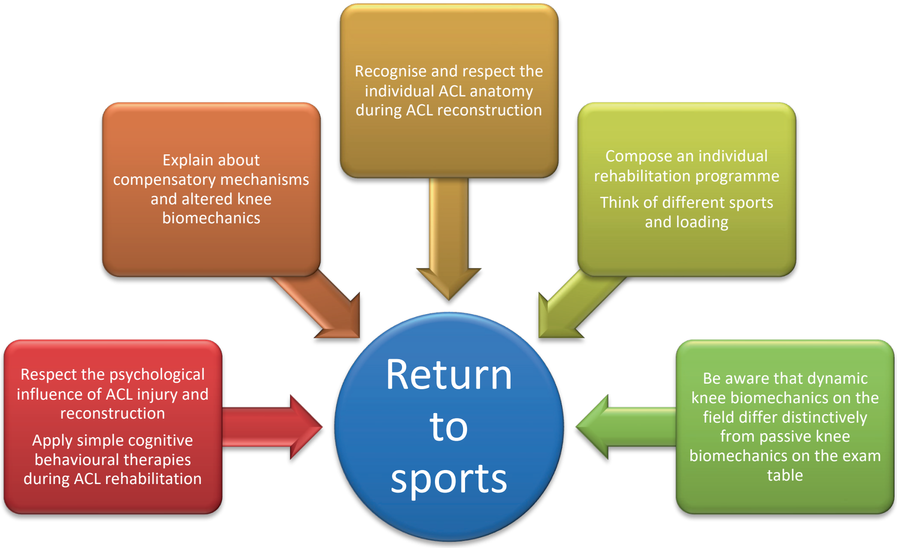
It has been suggested that a more holistic approach is needed towards ACL rehabilitation.[15] It would therefore be useful to involve patients in designing their rehabilitation programme, within evidence-based boundaries. With further development of the KROS programme, patients can be offered a choice for their rehabilitation after ACL reconstruction. This sense of ownership and co-responsibility is important for patients.[10,12]

A periodised rehabilitation programme aims to optimise the principle of overload.[18] Hypothetically, by posing the challenge of ice skating the central nervous system is also overloaded and thus trained. It is important to include neurocognitive training over the course of the rehabilitation. As described in the section *understanding the effects of ACL injury*, the central nervous systems switches to alternative pathways at the moment of ACL injury. After ACL reconstruction, the central nervous system has to be trained just as much as the muscle strength of the leg. By introducing ice speed skating to rehabilitation after ACL reconstruction, the central nervous system is provided with new stimuli and motor learning may be stimulated. It has already been postulated that a focus on perturbation training, adding visual and auditive stimuli, distraction and multitasking can be helpful during the rehabilitation process to promote motor learning and potentially prevent secondary injury.[16,19] All these factors can be combined in ice speed skating.

With the KROS protocol, periodisation is applied not only physically but also mentally. This may enhance knee self-efficacy. We have seen that fear of reinjury, kinesiophobia, knee self-efficacy and psychological readiness to return to sports are important factors in return to sports.[3] These factors are potentially modifiable,[4,42] and some patients may benefit from cognitive behavioural therapy over the course of their rehabilitation process. Using questionnaires like the ACL-Return to Sports after Injury, Tampa Scale for Kinesiophobia and Knee Self Efficacy Score, patients in need of cognitive behavioural therapy can be identified.

It is important that practitioners pay attention to the psychosocial aspects of an ACL injury. This type of psychological counselling is still not reimbursed by basic insurance in the Netherlands. Treatment of psychological problems – in the absence of a psychological disorder according to the DSM-5 – is not covered by medical insurance. And although orthopaedic surgeons may not have – or allow themselves – the time to provide concrete psychological treatment for patients in need, they should not neglect their role in enhancing the psychological wellbeing of their patients.[29] It does not take long to let a patient know that psychological struggles frequently occur during rehabilitation after ACL injury, and acknowledgement of these feelings is reported to be important for patients.[29] 'Simple' cognitive behavioural interventions can be initiated by the treating physical therapist, such as realistic goal-setting, small success experiences, group rehabilitation, time projection, self-desensitisation and disputing catastrophic thoughts.[21] Also, it has been suggested by Burland et al. that cognitive behavioural therapies could be used to improve fear-related emotions, motivation and self-efficacy. This can be achieved by using imagery, mindfulness, guided relaxation and breathing techniques.[4] But practitioners must be aware that postinjury depression is reported in 5-21% of patients and appropriate referral in such cases is imperative.[21]

At this stage, the added value of psychological interventions seems apparent yet needs further research. This thesis contributes to the growing evidence that psychological factors play an important role after ACL injury, not only in return to sports but also in return to previous levels of daily activities and work-related activities.



Clinical implications: a modern patient journey

- In the preoperative consultations it is important to emphasise that full recovery after anterior cruciate ligament surgery takes longer than a year. One year after ACL reconstruction, compensatory patterns and altered knee biomechanics will still be present in sport-related activities. These altered biomechanics in the knee are related to reduced subjective knee function.
- Orthopaedic surgeons must be aware that dynamic knee biomechanics on the field differ distinctively from passive knee biomechanics on the exam table. It is essential to evaluate patients in sport-specific circumstances.
- It is important to recognise and respect the individual ACL anatomy when performing an ACL reconstruction. In current practice, preoperative MRI images and remnant preservation can be helpful, but patient-specific instrumentation could be the way to go for the future.
- Involving patients in composing their individual rehabilitation programme according to their personal sports track record and

interests is one way to enhance participation. It is important for the physician to realise that it is also feasible to search off the beaten track in terms of type of sports used in rehabilitation. In preoperative consultations it is therefore important to address not only a patient's expectations and rehabilitation goals, but also the preferred method of rehabilitation and what types of sports exercises are to be incorporated.

Future perspectives

The results of this thesis give food for thought for the future treatment of ACL-injured patients. There is a long road ahead before we can ultimately reach better return-to-sports rates after ACL reconstruction.

It needs to be addressed that most of our work was based on small sample studies or pilot studies. In order to confirm our findings, larger studies are needed. Unfortunately, the acquisition, processing and analysis of kinematic data is complex and time-consuming. This hampers routine use of knee kinematic data in clinical practice. As we can see with the use of hop test batteries and muscle strength testing, since their incorporation began in routine follow-up for ACL-reconstructed patients, the data have grown enormously. By implementing these tests in usual care, large cohorts of more than 2500 patients can be analysed, as reported by Webster.[41] Nonetheless, objectively assessed kinematic data are key to evaluating the biomechanical success of a true anatomic ACL reconstruction.

The development of virtual/augmented reality and artificial intelligence can aid in the future for a better understanding of the role of knee kinematics in return to sports. Virtual or augmented reality can more realistically imitate sport-specific situations and can include the visual and auditive stimuli/ distractions that can better prepare a patient for return to sports. One of the challenges in the type of research that uses in vivo motion analysis is determining when and over what period of time the measurement is running. During hop testing, there is a distinct impact (initial contact) that can be registered with a force plate. For example, in the studies of this thesis we decided to measure from initial contact up to 200 ms afterwards. Ideally, one would like to see what happens during a game of soccer, for example, with all the movements that go with it. Sport-specific situations include acceleration, deceleration, pivoting, jumping and landing. All of these factors are interesting to evaluate, but also difficult to time when recording data. This would involve going from a 2-second measurement to a 10-minute measurement. That is not realistic with the current techniques, but perhaps in the future artificial intelligence can assist in the processing and analysis of knee kinematics. If this can be automated, more data can be collected towards improving knowledge about knee kinematics in sports.

For future purposes, with the use of the data gathered in this thesis a finite element model may be created to evaluate the effect of both neuromuscular influence and bone morphology on dynamic range of tibial rotation and anterior tibial translation. Up to now, altering the posterior tibial slope is mostly reserved for revision cases, but using a finite element model maybe a cut-off point can be calculated to guide clinicians in the decision process of slope-altering osteotomies.

There is a need to further investigate the association between knee kinematics and modifiable factors like psychological readiness to return to sports. Now that we have established the strong association between knee kinematics and psychological readiness to return to sports (**Chapter 4**), it would be of interest to investigate whether there is a causal relationship between the two. If we can identify patients with abnormal knee kinematics and randomise them between cognitive behavioural therapy and routine rehabilitation, we can determine whether the biomechanical outcome can be improved. If not, it may be the case that poor psychological readiness to return to sports is a consequence of poor biomechanics.

The patient-specific ACL reconstruction technique needs fine-tuning. A pilot study in patients using a further developed variant of the aiming device as described in **Chapter 7** is planned for the near future. First we need to prove the concept of the patient-specific instrument – can we achieve our planned tunnel position using the instrument? The next step would be a non-inferiority study to compare patient-specific instrumented ACL reconstruction to the current gold standard in terms of clinical outcomes (like objective knee laxity, subjective knee function and hop test battery outcome) and whether it leads to more natural knee kinematics. Another topic of future research is whether patient-specific ACL reconstruction can in fact lead to better return-to-sports rates. Also, a future topic that needs to be addressed is whether the added costs of patient-specific instrumentation outweigh potential long-term benefits such as reduced re-injuries and development of osteoarthritis.

All in all, ACL reconstruction is only one item in the toolbox when treating a patient with ACL injury aiming to return to sports. It should be recognised that a one-size-fits-all approach is no longer appropriate in the treatment of ACL injured patients, but rather a patient-specific approach is needed along all five R's of the ACL: from rupture, rotation, reconstruction and rehabilitation towards return to sports.

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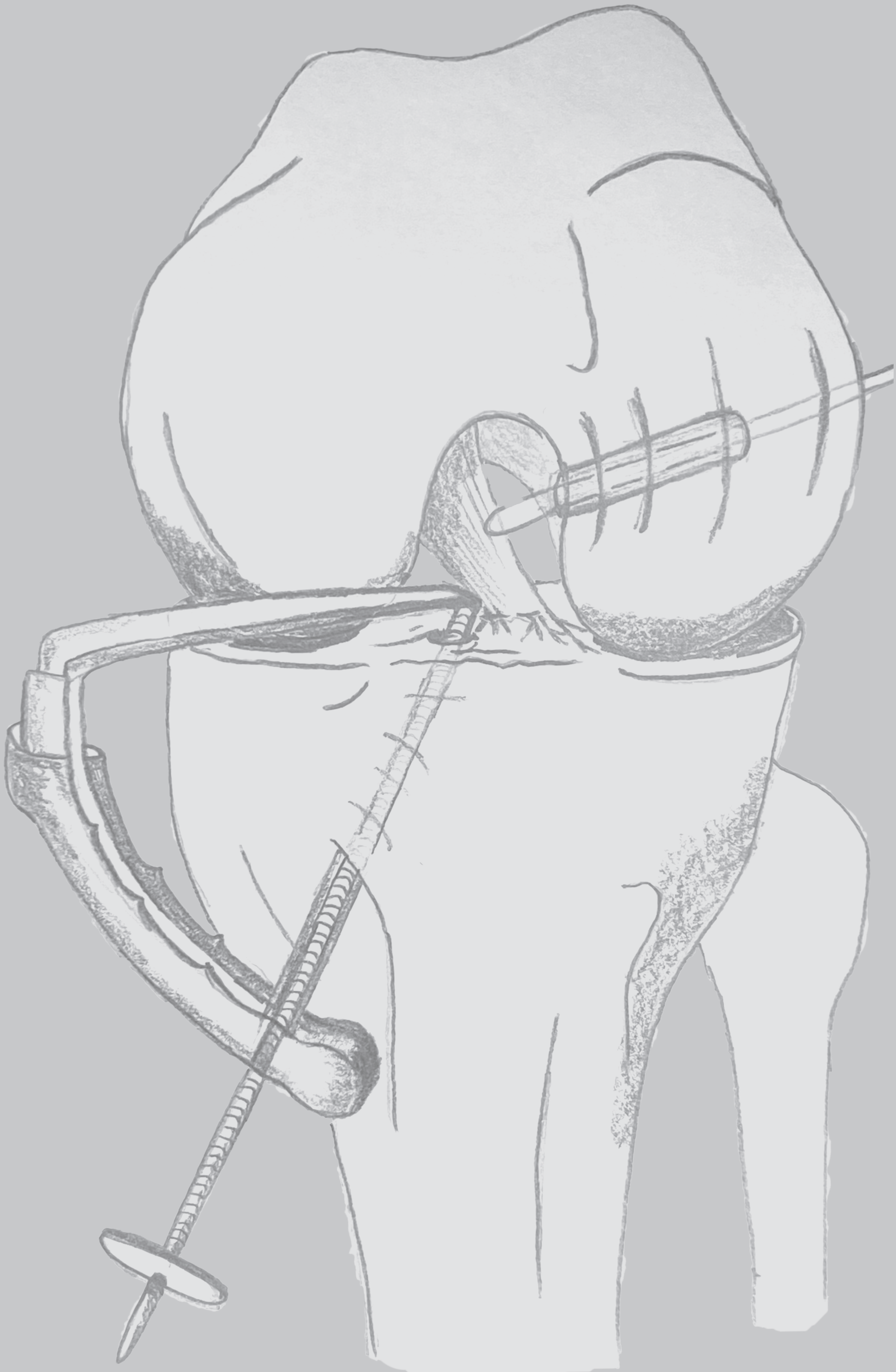


Chapter 10

Summary

Summary

ACL injury is a devastating injury for many young athletes, leading to prolonged absence or even cessation of sports activities. ACL reconstruction aims to restore knee kinematics and to return knee function to the pre-injury level. An important outcome for successful ACL reconstruction is return to sports. Despite the increasing numbers of ACL reconstructions being performed around the globe, return to sports rates are poor. We hypothesised that persistent rotational laxity during sports activity could be a reason why athletes cannot return to their pre-injury level of sports.

In **Chapter 2** the results of a systematic review are described to assess the role of an ACL graft on range of tibial rotation. Most of the studies included used computer-assisted surgery (CAS) to assess range of tibial rotation before and after surgery. In an anaesthetised patient, a reduction of 17-32% of range of tibial rotation is achieved after ACL reconstruction. Included studies were mostly non-randomised and of low quality. Based on this review, we proposed a new measuring protocol that contains measurements at 0, 30 and 60 degrees flexion and a maximum of 5 Nm rotational force, in order to enhance comparability between studies.

In **Chapter 3** we report on a prospective cohort study to determine the range of tibial rotation within three months of ACL injury, and again one year after ACL reconstruction. It was hypothesised that, in line with the results from **Chapter 2,** after ACL injury the range of tibial rotation would increase compared to the contralateral intact knee. In search for a reason why athletes are unable to return to sports, we hypothesised that one year after ACL reconstruction increased range of tibial rotation would still be present during high-demand tasks, in comparison to the contralateral intact knee.

Interestingly, this study showed that both within three months after ACL injury and one year after ACL reconstruction the range of tibial rotation was not increased during high-demand tasks. Both findings are indicative of a compensatory mechanism or protective strategy that is deployed by subjects. The underlying mechanism could not be determined based on the results of this study.

In **Chapter 4** we analysed the correlation between knee kinematics and subjective knee function and psychological readiness to return to sports. Range of tibial rotation and anterior tibial translation were measured during both low- and high-demand tasks one year after ACL reconstruction. Subjects were asked to complete the International Knee Documentation Committee (IKDC) and the Anterior Cruciate Ligament- Return to Sports after Injury (ACL-RSI) questionnaires to assess self-reported knee function and psychological readiness to return to sports, respectively. This study showed that range of tibial rotation has a strong positive correlation with self-reported knee function and psychological readiness to return to sports in high-demand tasks but a negative correlation in low-demand tasks. In contrast, the association between anterior tibial translation and self-reported knee function and psychological readiness was negative and did not show a discrepancy between low- or high-demand tasks. The mean range of tibial rotation was smaller than previously reported for high-demand tasks, which may imply that the ‘greater’ range of tibial rotation, which is correlated to better subjective knee function and better psychological readiness to return to sports, may in fact be a manifestation of a more natural movement of the knee and not a sign of increased rotational laxity. We therefore conclude that more normal knee kinematics after ACLR correlate with better self-reported knee function and psychological readiness.

In **Chapter 5** we analysed the correlation between the steepness of the tibial plateau, also known as posterior tibial slope, and the range of tibial rotation and anterior tibial translation. Studies based on passive testing show a strong correlation between anterior tibial translation and amount of posterior tibial slope. It is unknown whether this correlation is also present in high-demand tasks, in which muscle activity becomes a relevant factor. The correlation between range of tibial rotation and amount of posterior tibial slope was unknown. We hypothesised that the difference between the slope of the medial and lateral plateaus might be of more importance than the actual amount of slope itself, in terms of rotation. Dynamic range of tibial rotation and dynamic anterior tibial translation were measured during high-demand tasks both before and after ACL reconstruction. The amount of posterior tibial slope was measured on MRI. Posterior tibial slope was measured in the medial and lateral compartments using Hudek’s circle method. A difference between the medial and lateral posterior tibial slopes was calculated. The main finding was little (if any) to weak correlations between dynamic anterior tibial translation and amount of posterior tibial slope, both before and after ACL reconstruction. As with dynamic translation, little (if any) to weak correlations between dynamic range of tibial rotation and posterior tibial slope were observed with ACL deficiency. However, one year after ACL reconstruction we observed moderate-to-strong correlations between range of tibial rotation and posterior tibial slope. This study suggests that muscular activity enables subjects to compensate for anatomical factors such as posterior tibial slope by moderating their muscle activation patterns and kinematics when studied during high-demand activities. These compensatory mechanisms fail to make up for rotatory laxity one year after ACL reconstruction.

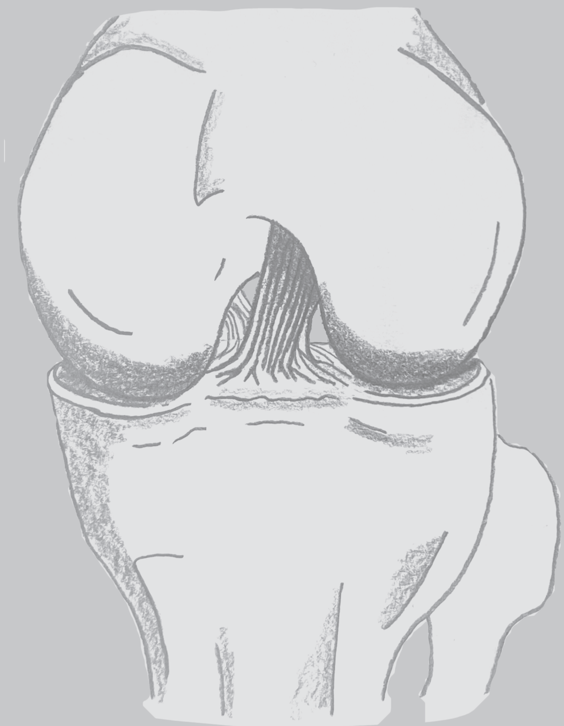
Chapter 6 describes our first steps towards the development of a patient-specific surgical guide for the creation of a femoral tunnel in the anatomic footprint of the ACL. This study answers the question of whether we can reliably identify the footprint of a torn ACL on MRI. Orthopaedic surgeons and residents and musculoskeletal-trained radiologists were asked to identify the femoral footprint of the ACL on MRI. Twenty MRIs were evaluated twice, at intervals of at least one week. We demonstrated excellent intraobserver and interobserver reliability. The interobserver reliability was less than the intraobserver reliability. Orthopaedic surgeons had a higher level of intraobserver and interobserver agreement compared to musculoskeletal-trained radiologists and, to a lesser extent, to orthopaedic residents. Employing this feature, experienced orthopaedic surgeons are the preferred physicians to preoperatively plan femoral tunnel positioning in patient-specific ACL reconstruction.

In **Chapter 7** the first in vitro results of the newly developed patient-specific surgical guide for the creation of a femoral tunnel in ACL reconstruction are demonstrated. The design ratio and manufacturing process are highlighted and the results of a cadaveric study are presented. In an open procedure, using a polyamide-12 3D printed guide a mean deviation of 5 mm from the planned tunnel position was achieved. While the technique and development seem promising, this was outside our intended target of < 2 mm. Further improvement in the design and materials are needed before this concept can be introduced in an in vivo setting.

Chapter 8 describes a feasibility study on our newly developed rehabilitation protocol for patients after ACL reconstruction. In the search to offer patients a patient-centred alternative to rehabilitate after ACL reconstruction, we developed the Knee Rehabilitation on Skates (KROS) protocol. The skating position requires a high amount of trunk balance and prolonged squatting, enhancing the posterior kinetic chain. Despite the influence of COVID on this study, we have shown that further exploration of the KROS protocol is feasible and that, despite the small sample size, functional and strength limb symmetry is not different than that of subjects who followed the routine rehabilitation protocol. Athletes who prefer to be challenged and are looking for a fun aspect to rehabilitation may be interested in this alternative rehabilitation protocol.

Chapter 9 highlights the results of the studies and presents implications for individualisation of ACL reconstruction. Special attention is turned towards biological, mechanical, neurogenic and psychological aspects that influence return to sports. To understand why patients do not return to sports, it is essential to evaluate patients in sport-specific circumstances, and hop test batteries are very useful in this respect. It is advised to emphasise in the preoperative consultations that even one year after ACL reconstruction altered knee kinematics still show, which indicates that rehabilitation requires more than one year. During ACL reconstruction it is important to recognise and respect the individual ACL anatomy. In current practice preoperative MRI images and remnant preservation can be useful, but patient-specific instrumentation could be the way to go for the future. Individualising the care for ACL-injured patients is not limited to the surgical procedure: individualising ACL rehabilitation can be a way to enhance participation and compliance. It is therefore important to address the topic of rehabilitation and discuss patient expectations and goals in the preoperative consultations. All in all, ACL reconstruction is only one item in the toolbox when treating a patient with ACL injury aiming to return to sports. It should be recognised that a one-size-fits-all approach is no longer appropriate in the treatment of ACL-injured patients, but rather a patient-centred approach is needed along all five R's of the ACL: from **r**upture, **r**otation, **r**econstruction and **r**ehabilitation towards **r**eturn to sports.

Nederlandse Samenvatting



Samenvatting

Een voorste kruisbandruptuur is een dramatische blessure voor veel jonge atleten die leidt tot een langdurige afwezigheid of zelfs het stoppen met sporten. Een voorste kruisband (VKB) reconstructie heeft als doel om de kinematica van de knie te herstellen en de kniefunctie en het activiteitenniveau van vóór het letsel te herstellen. Een belangrijke maatstaf voor een succesvolle VKB reconstructie is het al dan niet terugkeren naar sportactiviteiten. Ondanks het toenemende aantal VKB reconstructies dat wereldwijd wordt uitgevoerd, is het percentage patiënten dat terug kan keren naar sportactiviteiten laag. Wij vermoeden dat persisterende rotatie instabiliteit tijdens sportactiviteiten een van de redenen kan zijn waarom atleten niet terug kunnen keren naar hun oude niveau van sportactiviteiten. Het doel van dit proefschrift is het bestuderen van verschillende aspecten die betrokken zijn bij terugkeer naar sport na VKB-reconstructie. Daarnaast bestuderen we of het haalbaar is om een VKB-reconstructie en de VKB-revalidatie meer patiënt specifiek te maken.

In **Hoofdstuk 2** presenteren we de resultaten van een systematische review naar het effect van de VKB graft op de mate van tibiale rotatie. De meeste van de beoordeelde studies gebruikte computer geassisteerde chirurgie (CAS) om de mate van tibiale rotatie vóór en na de VKB reconstructie te beoordelen. Na de VKB reconstructie is er 17-32% minder tibiale rotatiemogelijkheid dan vóór de operatie. Dit is getest bij patiënten onder anesthesie. De beoordeelde studies waren meestal niet-gerandomiseerd en van lage methodologische kwaliteit. Op basis van deze review hebben we een nieuw en gestandaardiseerd meetprotocol voorgesteld dat metingen bevat bij 0, 30 en 60 graden flexie en een maximum van 5 Nm rotatiekracht om de vergelijkbaarheid tussen studies te vergroten.

In **Hoofdstuk 3** bespreken we een prospectieve cohortstudie die uitgevoerd werd om de mate van tibiale rotatie te bepalen op twee tijdstippen: binnen drie maanden na een VKB ruptuur en één jaar na VKB reconstructie. Er werd verondersteld dat, in lijn met het resultaat van **Hoofdstuk 2**, we één jaar na een VKB reconstructie een toegenomen mate van tibiale rotatie ten opzichte van het gezonde been zouden observeren tijdens sportactiviteiten. Dit onderzoek toonde aan dat in de eerste drie maanden na een VKB ruptuur tijdens sportactiviteiten de mate van tibiale rotatie niet toenam. Ook was één jaar na de VKB reconstructie de mate van tibiale rotatie niet toegenomen tijdens sportactiviteiten in vergelijking met de contralaterale knie. Beide bevindingen doen vermoeden dat een compensatiemechanisme dan wel een beschermende strategie door proefpersonen wordt ingezet. Het onderliggende mechanisme van deze strategieën kon niet worden bepaald op basis van de resultaten van deze studie.

In **Hoofdstuk 4** hebben we de correlatie tussen enerzijds kinematica van de knie en anderzijds subjectieve kniefunctie en psychologische gereedheid om terug te keren naar de sport geanalyseerd. De mate van tibiale rotatie en anterieure translatie van de tibia werden één jaar na een voorste kruisbandreconstructie gemeten zowel tijdens lopen als tijdens sprongtesten. De deelnemers werden gevraagd om de International Knee Documentation Committee (IKDC) vragenlijst en de Anterior Cruciate Ligament-Return to Sports after Injury (ACL-RSI) vragenlijst in te vullen om respectievelijk subjectieve kniefunctie en psychologische gereedheid om terug te keren naar de sport te beoordelen. Dit onderzoek toonde aan dat de mate van tibiale rotatie tijdens de sprongtesten een sterke positieve correlatie heeft met subjectieve kniefunctie en psychologische gereedheid om terug te keren naar sport. We zagen dat hoe groter de mate van tibiale rotatie was, hoe beter de subjectieve kniefunctie en psychologische gereedheid om terug te keren naar sporten was. Tijdens het lopen werd echter een negatieve correlatie aangetoond. De correlatie tussen anterieure tibiale translatie en subjectieve kniefunctie en psychologische gereedheid was negatief en deze vertoonde geen discrepantie tussen lopen of springen. De gemiddelde mate van tibiale rotatie was kleiner dan eerder gerapporteerd in gezonde knieën tijdens springactiviteiten, hetgeen zou kunnen impliceren dat de ‘grotere’ mate van rotatie in feite een uiting kan zijn van een meer natuurlijkere beweging van de knie en niet een teken van toegenomen rotatielaxiteit. We concluderen daarom dat meer normale kniekinematica na een voorste kruisbandreconstructie gecorreleerd is aan betere subjectieve kniefunctie en psychologische gereedheid om terug te keren naar sport.

In **Hoofdstuk 5** hebben we de relatie geanalyseerd tussen de steilheid van het tibiaplateau, bekend als de *tibial slope,* en de mate van rotatie en anterieure translatie van de tibia tijdens sprongtesten. Eerdere studies hebben aangetoond dat er een sterke correlatie bestaat tussen passieve anterieure translatie en de mate van tibial slope. Het was onbekend of deze correlatie ook aanwezig is tijdens sprongtesten, waarbij spieractiviteit een relevante factor wordt. De correlatie tussen de mate van tibiale rotatie en de mate van tibial slope was onbekend. We vermoedden dat het verschil tussen de slope van het mediale en laterale plateau van meer belang zou kunnen zijn dan de mate van tibial slope zelf met betrekking tot rotatie. De dynamische mate van rotatie en de dynamische anterieure translatie werden gemeten tijdens sprongtesten, zowel vóór als na een voorste kruisbandreconstructie. De tibial slope werd gemeten op MRI in het mediale en laterale compartiment met behulp van de cirkelmethode volgens Hudek. Het verschil tussen de mediale en laterale tibial slope werd berekend. De belangrijkste bevinding was een geringe (of geen) tot zwakke correlatie tussen dynamische anterieure tibiale translatie en de mate van tibial slope, zowel voor als na de VKB-reconstructie. Hetzelfde gold voor de correlatie tussen de mate van tibiale rotatie en de mate van tibial slope, gemeten bij patiënten met een VKB ruptuur. Een jaar na VKB-reconstructie hebben we echter een matige tot sterke correlatie waargenomen tussen de mate van tibiale rotatie en de mate van tibial slope.

De uitkomsten van deze studie suggereren dat anterieure translatie kan worden gecompenseerd door spieractiviteit tijdens dynamische sprongtesten. Ook rotatie kan in de acute fase na de VKB ruptuur worden gecompenseerd, maar dat dit compensatiemechanisme faalt om de rotatielaxiteit een jaar na de voorste kruisbandreconstructie nog te kunnen compenseren.

Hoofdstuk 6 beschrijft de eerste stappen op weg naar de ontwikkeling van een patiënt specifiek chirurgisch richtapparaat voor het boren van een femorale tunnel die uitkomt op de anatomische insertie van de VKB. De eerste vraag was of we de insertie van de gescheurde voorste kruisband betrouwbaar kunnen identificeren op MRI. Orthopedisch chirurgen, AIOS orthopedie en musculoskeletaal getrainde radiologen werden gevraagd om de femorale insertie van de VKB op MRI te identificeren. 20 MRI's werden tweemaal geëvalueerd, met een interval van minimaal een week. We hebben een uitstekende intra- en interobserver betrouwbaarheid aangetoond. De interobserver betrouwbaarheid was lager dan de intraobserver betrouwbaarheid. Orthopedisch chirurgen hadden een betere intra- en interobserver overeenstemming dan de radiologen en, in mindere mate, dan de AIOS orthopedie. Ervaren orthopedisch chirurgen zijn de aangewezen personen om preoperatief de positionering van de femurtunnel te plannen bij een patiënt specifieke VKB-reconstructie.

In **Hoofdstuk 7** worden de eerste in vitro resultaten beschreven van het nieuw ontwikkelde patiënt specifieke richtapparaat voor het boren van de femorale tunnel bij een VKB-reconstructie. De ratio achter het ontwerp en het fabricageproces worden beschreven en de resultaten van een kadaveronderzoek worden gepresenteerd. In een open procedure, met behulp van een polyamide-12 3D-geprint richtapparaat, werd een gemiddelde afwijking van 5 mm van de geplande tunnelpositie bereikt. Hoewel de techniek en ontwikkeling veelbelovend lijken, viel dit buiten ons beoogde doel van < 2 mm. Verdere verbetering van het ontwerp en de materialen zijn nodig voordat dit concept in een in vivo setting kan worden geïntroduceerd.

Hoofdstuk 8 beschrijft een studie naar de haalbaarheid van een door ons nieuw ontwikkelde revalidatieprotocol voor patiënten na een VKB-reconstructie. Om patiënten een patiëntgericht alternatief te bieden voor revalidatie na VKB-reconstructie, hebben we het Knee Rehabilitation on Skates (KROS)-protocol ontwikkeld. Hierin wordt vroeg in de revalidatie gebruik gemaakt van schaatsen. De schaatspositie vereist een hoge mate van rompbalans en langdurig hurken, waardoor de posterieure keten wordt versterkt (bil, hamstrings, kuitspieren). Ondanks de invloed van COVID op deze studie, hebben we aangetoond dat het haalbaar is om het KROS-protocol te implementeren tijdens de revalidatie na een voorste kruisbandreconstructie. Daarnaast bleek dat, zij het in een kleine groep, de functionele en kracht-symmetrie van de benen van de proefpersonen die het KROS protocol volgende niet verschilt van die van de proefpersonen die het normale revalidatieprotocol volgden. Sporters die graag uitgedaagd worden en op zoek zijn naar een leuk aspect tijdens de revalidatie, kunnen geïnteresseerd zijn in dit alternatieve revalidatieprotocol.

In **Hoofdstuk 9** worden de resultaten van de onderzoeken belicht en worden de implicaties voor een geïndividualiseerde VKB reconstructie beschreven. Speciale aandacht wordt besteed aan biologische, mechanische, neurogene en psychologische aspecten die de terugkeer naar sport beïnvloeden. Om te begrijpen waarom patiënten niet meer terugkeren naar sport, is het essentieel om patiënten in sport specifieke omstandigheden te onderzoeken. Hoptestbatterijen zijn hierbij zeer nuttig. Het wordt geadviseerd om tijdens het preoperatieve consult te benadrukken dat zelfs één jaar na de VKB-reconstructie er nog steeds een abnormale kniekinematica zichtbaar is, wat erop wijst dat de revalidatie meer dan één jaar vergt. Tijdens een VKB-reconstructie is het belangrijk om de individuele anatomie te herkennen en te respecteren. In de huidige praktijk kunnen de preoperatieve MRI-beelden en het behouden van de VKB restanten behulpzaam zijn, maar voor de toekomst zou patiënt specifieke instrumentatie een uitkomst kunnen bieden. Het individualiseren van de zorg voor patiënten met een gescheurde voorste kruisband beperkt zich niet tot de chirurgische ingreep; het individualiseren van VKB-revalidatie kan tevens een manier zijn om de participatie en therapietrouw te vergroten. Tijdens het preoperatieve consult is het daarom belangrijk om het onderwerp revalidatie aan de orde te stellen en de verwachtingen en doelen van de patiënt te bespreken. Al met al is een VKB-reconstructie slechts één item in de gereedschapskist bij de behandeling van een patiënt met een gescheurde voorste kruisband met als doel weer te gaan sporten.

We moeten onderkennen dat een *one size fits all*-benadering niet langer geschikt is voor de behandeling van patiënten met een kruisbandletsel maar dat er eerder een patiënt specifieke behandeling nodig is langs alle 5 de R'en van de VKB: van **r**uptuur, **r**otatie, **r**econstructie en **r**evalidatie op naar ***r**eturn to sports.*

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M.J.M. Zee, P.A.J. Pijpker, J.Kraeima, A. Viddeleer, R.L. Diercks. Patient specific instrumentation in ACL reconstruction: a proof-of-concept cadaver experiment assessing drilling accuracy when using 3D printed guides. Archives of Orthopaedic and Trauma Surgery. 2023; Sep 29

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Oral presentation

8th Dutch Biomedical Engineering Conference 2021
Patient specific instrumentation in ACL reconstruction. A novel technique using 3D printed guides.

Oral presentation

International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine, ISAKOS 2021: Global
Patient specific instrumentation in ACL reconstruction. A novel technique using 3D printed guides.

E-poster

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(Dr MM Faas, Prof X Xu, Prof X Huo)

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About the Author

Mark Johannes Maria Zee was born on Sunday August 31st 1986 in Bodegraven, the Netherlands. Aged 7 he moved with his parents and his older sister to Bergen op Zoom where he spent most of his childhood. In 2004 he graduated from high school (Roncalli Scholengemeenschap) and moved to Groningen to start medical school. During his Bachelor of Medicine he became interested in Orthopaedic Surgery and started his Master of Medicine with his research internship at the department of Orthopaedic Surgery at the UMCG, under supervision of prof. dr. Diercks. After completing his rotations in the Deventer Hospital, the Yodogawa Christian Hospital (Osaka, Japan) and the Martini Hospital in Groningen he graduated Medical School in 2010.

His first clinical experience as a resident was at the Orthopaedic Center Eastern Netherland (OCON) in Hengelo and the Medical Spectrum Twente in Enschede. In 2013 he started his Orthopaedic training under supervision of prof. dr. Bulstra in the North-Eastern region of the Netherlands. During his residency in the UMCG (2014-2016) he started with the first steps in research which would eventually lead to a PhD trajectory under supervision of prof. dr. Diercks. After completing his residency program in the Martini Hospital he graduated as an orthopaedic surgeon in 2019, and started a fellowship in knee arthroplasty under supervision of dr. van Loon in the Rijnstate Hospital in Arnhem. In 2020 he worked as a chef de Clinique in the Rijnstate Hospital and in 2021 he transferred to the Noord West Ziekenhuis groep (Alkmaar and Den Helder) to work as a chef de Clinique.

In 2022 he started working at the Bergman Clinics in Naarden as a consultant knee surgeon where he still works to this date.

Mark is happily married to Eefje and a proud father of Thijmen (2017) and Floortje (2019).

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