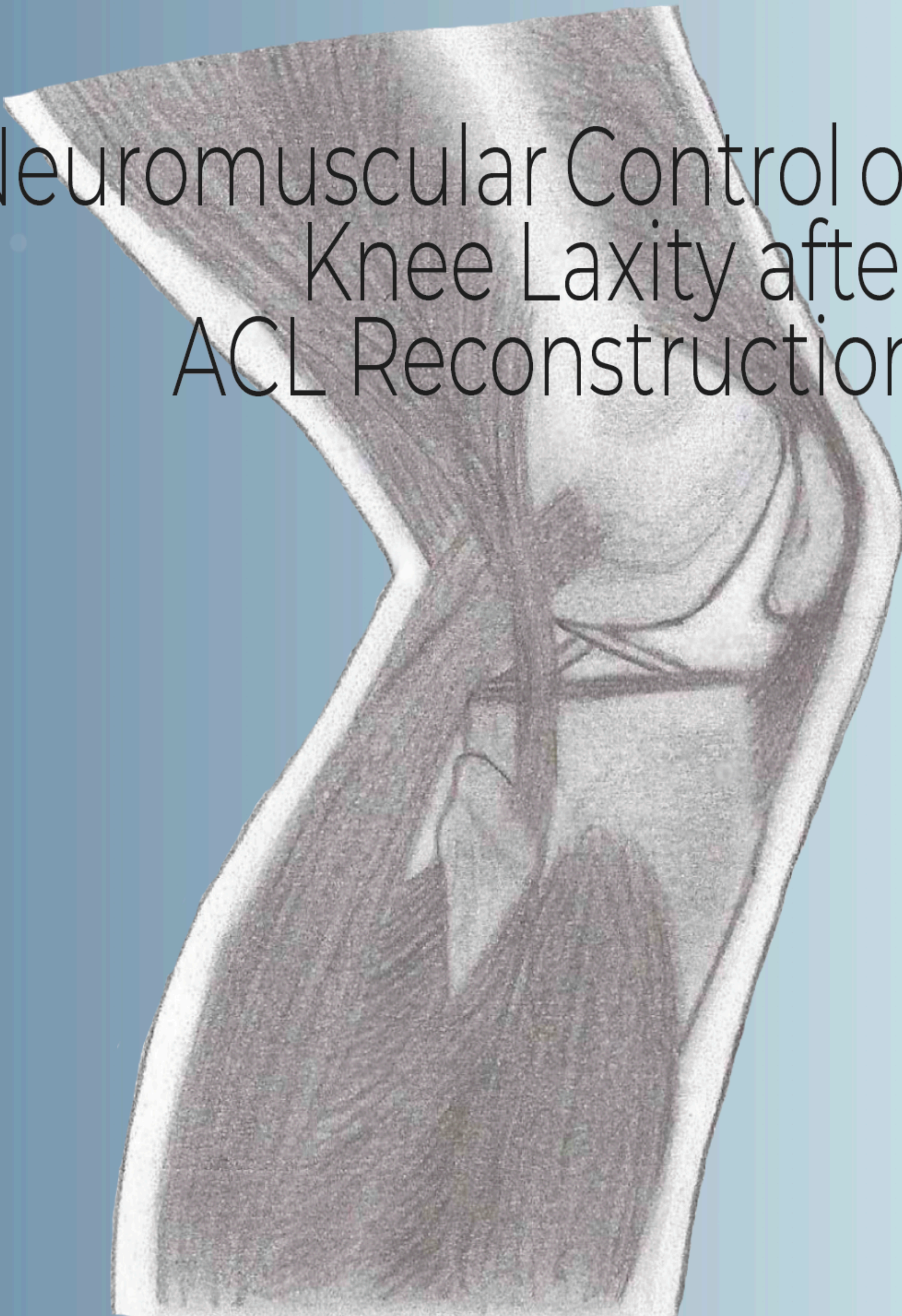
Neuromuscular Control of Knee Laxity after ACL Reconstruction



M.N.J. Keizer

Neuromuscular Control of Knee Laxity after an Anterior Cruciate Ligament Reconstruction

Michèle Keizer

The experiments described in this thesis have been conducted at the Center of Rehabilitation in at the University Medical Center Groningen, University of Groningen, the Netherlands in cooperation with the Center of Human Movement Sciences at the University Medical Center Groningen and the Martini Hospital of Groningen, the Netherlands.

The projects were financially supported by a grant of the University Medical Center Groningen (UMCG).

The Ph.D. training was facilitated by the research institute School of Health Research (SHARE), part of the Graduate School of Medical Sciences.

Paranymphs: P.M.T. Keizer
M.H.A. Keizer

Layout: M.N.J. Keizer

Cover: E.J. Keijzer

Drawings: M.N.J. Keizer

Printed by: Ridderprint | www.ridderprint.nl

Neuromuscular Control of Knee Laxity after an Anterior Cruciate Ligament Reconstruction

Proefschrift

ter verkrijging van de graad van doctoraat aan de
Rijksuniversiteit Groningen
op gezag van de
rector magnificus, Prof. dr. C. Wijmenga
en volgens besluit van het College voor Promoties.

De openbare verdediging zal plaatsvinden op

woensdag 3 februari 2021 om 12:45 uur

door

Michèle Nicole Jackeline Keizer

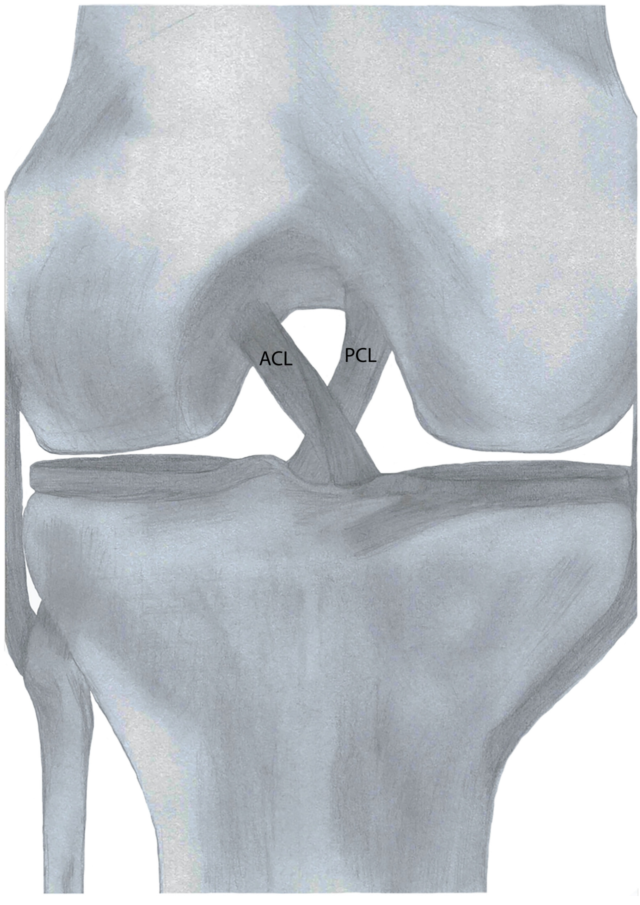
geboren op 28 december 1993
te Haren

Promotores
Prof. dr. E. Otten
Dr. J.M. Hijmans

Co-promotor
Dr. R.W. Brouwer

Beoordelingscommissie
Prof. dr. J.H.P. Houdijk
Prof. dr. ir. H.F.J.M. Koopman
Prof. dr. G.M.M.J. Kerkhoffs

Contents


ACL
PCL

Chapter 1

General Introduction

Background

The knee

The knee exists of three compartments: the medial, lateral and patellofemoral compartment. The medial and lateral condyle of the femur rest on the medial and lateral tibia plateau. The angles of the tibia plateaus, medial and lateral (defined as the angle of this plateau relative to the plane orthogonal to the longitudinal axis of the tibia in the sagittal plane) differ between persons. The tibia, femur and patella are protected by articular cartilage. There are two menisci in the knee: the medial and the lateral meniscus [17]. Those structures reduce the peak contact stress on the tibia and femur during movements. The menisci also guide rotations and contribute to stabilizing translations of the tibia relative to the femur [17]. To provide stability of the knee (a decrease of knee laxity, i.e. tibiofemoral translations), the tibia and femur are connected by ligaments: the extra-articular medial collateral ligament (MCL) and lateral collateral ligament (LCL) and the intra-articular posterior cruciate ligament (PCL) and anterior cruciate ligament (ACL) [17]. The MCL is attached to the medial surface of the shaft of the tibia and to the medial epicondyle of the femur. The LCL is attached anterior to the lateral aspect of the fibula head and the lateral epicondyle of the femur. These two ligaments prevent anterior, posterior, medial and lateral tibia translations relative to the femur and also limit valgus and varus angles [17]. The PCL, one of the two main intra-articular ligaments, is attached to the medial surface of the intercondylar notch and the posterior side of the proximal tibia in the fovea centralis. The PCL prevents posterior tibia translation [17]. The ACL (Figure 1) is the other main intra-articular ligament and is attached medially to the anterior intercondylar tubercle of the tibia and a small part is attached to the anterior of the lateral meniscus [21]. At the femoral side, the ACL is attached to the posterior part of the medial aspect of the lateral femoral condyle [21].

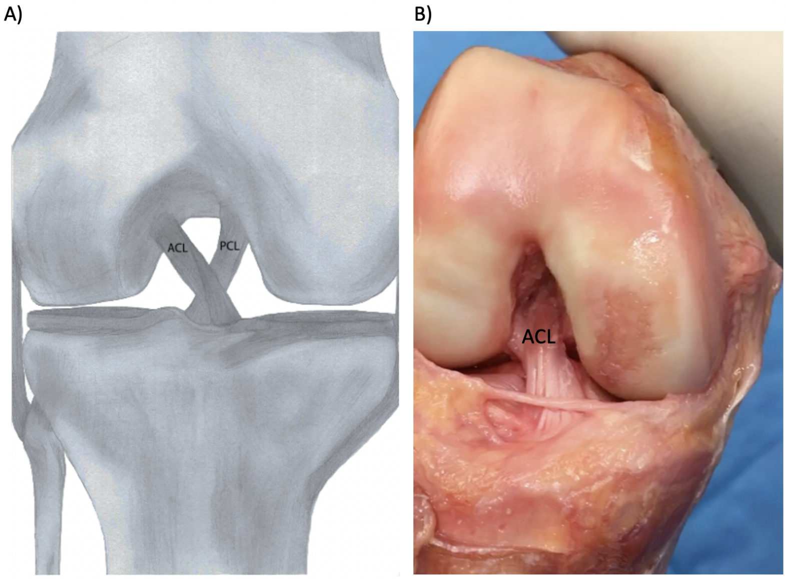


Fig. 1 A: the anterior cruciate ligament and posterior cruciate ligament. B: a cadaver knee in a flexion angle of approximately 90 degrees.

The ACL consists of three bundles: the smaller anteromedial (AM) bundle, the intermediate bundle (IM) and the larger posterolateral (PL) bundle. In literature, the intermediate bundle is often disregarded as it is not clear where this bundle is attached. The AM and PL bundle become taut at different knee flexion angles [31]. The AM becomes taut when the knee is flexed at 90 degrees and the PL becomes taut at full extension [31]. The ACL prevents both anterior tibia translation relative to the femur (ATT) and internal tibial rotation [14, 35]. In cadaveric knees, the ACL provides approximately 80% to 90% of the force restraining ATT [7]. The ultimate force that the ACL can handle, tested in cadaveric knees, when the force is applied to the whole ACL is approximately 1725N [31].

Surrounding the knee, three main muscle groups are situated: the quadriceps, the hamstrings and the gastrocnemius muscles [33]. The quadriceps group consist of the rectus femoris, vastus lateralis, vastus intermedius and vastus medialis and provides an extension moment around the knee. Moreover, the quadriceps group is a dynamic antagonist to an intact ACL [17]. The hamstrings consist of the biceps femoris, semitendinosus and semimembranosus muscles and provide a flexion moment around the knee. The gracilis muscle, an adductor of the hip, also crosses the knee and aids in the flexion of the knee. The hamstrings group and gracilis muscle are antagonists to an intact PCL [17]. The gastrocnemius consists of two muscles: the medial and lateral gastrocnemius and, besides being a planter flexion of the foot, also contributes in knee flexion.

ACL injury

Annually around 0.2-4 percent of the athletes injure their ACL [34]. ACL injuries most commonly occur during sports that involve sudden stops or changes in direction, jumping and landing [12] such as in soccer, basketball and downhill skiing [25, 12]. Mostly the ACL injury occurs during deceleration without contact with another player in combination with a valgus angle and external rotation [35]. Other common injury mechanisms are hyperextension with torsion, a valgus angle due to an external force or hyperflexion [35].

An ACL injury results in increased ATT at the same anterior force on the tibia. A lack of constraint in ATT can lead to instability of the knee. Moreover, an ACL injury commonly results in alterations of muscle activation patterns, kinematics and kinetics [24, 29, 39, 42]. These alterations, especially the instability of the knee, can result in the inability to perform sports. Moreover, an increase in ATT is associated with in increased risk of cartilage damage [24].

ACL reconstruction

In order to improve stability of the knee and to reduce probability of cartilage damage, an ACL reconstruction (ACLR) is commonly indicated as treatment, especially when aiming to return to sports [22]. In the Netherlands it is estimated that around 6000 ACLR's are performed each year [35]. The first extra-articular procedures to treat ACL injuries were reported by Bennett in 1926 and Cotton, Morrison, Bosworth and Bosworth in the mid 1930s [35]. Campbell described the first intra-articular procedure to reconstruct the ACL using a patellar tendon [45]. Since then, the technique of the ACLR has improved considerably: for example, from an open surgery to an arthroscopy, the anatomical placement of the ACL, the fixation technique, and from single bundle to double bundle reconstructions. In Figure 3 an MRI of a knee after an ACLR using a patellar tendon is shown.

During an ACLR the torn ACL is removed and replaced with a piece of a tendon from the patient (autograft) or from a donor (allograft), mostly being a bone-patella tendon-bone autograft, a semitendinosus and gracilis autograft, a quadriceps autograft, or an allograft of these tendons. Considerable research is done on the results after the type of graft used (for example: [8, 13, 15, 20, 30, 37, 46]).

Using an allograft has its benefits: smaller incisions, shorter operation time, no donor-site morbidity and the possibility of using larger bone blocks at the end of the graft [11, 26, 32, 36, 51]. However, it also has its disadvantages: greater chance of infection, higher costs, higher chance of re-rupture and a mismatch of the length of the graft in particular when using a patellar tendon. In contrast, the disadvantages of using an autograft are: pain and muscle force deficits at the harvest side [23, 40, 50].

Despite functional improvements after an ACLR [42], which may be influenced by graft choice, one year after ACLR one-third of the patients do not manage to return to their preinjured level of sports and only 44% of the patients return to competitive sports after one year [2]. Moreover, Forbell et al. [18] found that only 22% of their patients still participated in sports after 3 years which may partly be due to ACL problems. Instability due to an increase in ATT may be an explanation for the low return to sports rate. Some patients may be able to compensate for the results of the injury using muscle activation patterns or efficient kinematics whereas others are not able to do this.

Fig. 3 MRI of a reconstructed ACL. The black bundle in the middle of the knee is the ACL bone-patellar-tendon-bone graft.

Control of anterior tibia translation

One possible explanation of the fact that some patients manage to return to sports (copers) whereas some patients do not manage to return to sports (non-copers) may be that copers are able to develop more effective strategies to compensate for the increased dynamic ATT (ATTd), (i.e. by using a specific muscle activation pattern) whereas non-copers rely more on the movement limiting force produced by the ACL.

This suggestion is supported by the finding of Kvist et al. [13] that there is no correlation between passive ATT (ATTp) and ATTd, which may suggest that during the dynamic situation, in contrast to ATTp, ATTd is controlled by other factors than the movement limiting force produced by the ACL (i.e. muscle activation patterns or the anatomy of the knee). It is shown that hamstring activity reduces in vivo ATTp and ATTd in computer simulations [4, 27, 43, 44]. It is also shown that non-copers have different dynamic muscle activation patterns compared to copers during one leg stance on a stabilization platform [9] and during a hop test [16]. We suggest that copers use different activation than non-copers, which may result in differences in kinematics and ATTd. More knowledge on how knee ATTd is controlled in healthy people and in patients after an ACL reconstruction may help to identify patients who are copers and non-copers before return to sports. It is expected that copers may have a solution to limit knee ATTd that non-copers do not have but may be able to learn.

Aims and outline of this thesis

The main aim of this thesis is to uncover possible strategies to control ATTd use by subjects after an ACLR.

Secondary Objective(s):

- To investigate whether graft choice influences the return to sports rate and level after an ACLR revision;
- To review the factors that determine ATTp in healthy patients, ACL injured patients, and patients with an ACL reconstruction;
- To investigate whether and how ATTd is limited by muscle activation patterns in healthy knees;
- To investigate whether and how ATTd is limited by muscle activation patterns and/or kinematics after ACLR;
- To investigate whether copers control their ATTd differently than non-copers do;
- To investigate whether patients with a steeper tibia plateau angle show larger ATTd.

Methodological objective:

- To analyse the sensitivity of the optical motion capture method to determine ATTd.

It is hypothesized that copers can limit their ATTd after an ACLR by developing effective muscle activation patterns, in agreement with their anatomy, whereas non-copers cannot compensate for the change in stability of the knee due to the injury and reconstruction.

The aim of the first study, of which the results are reported in **Chapter 2**, was to determine whether there are differences in functional results (i.e. return to sports rate and level) after revision (i.e. second) ACLR using an allograft patellar tendon or an autograft patellar tendon. The harvest of an autograft patellar tendon may result in a smaller knee extensor moment during jump tasks and isokinetic testing [40], and therefore a decrease in quadriceps-hamstrings ratio, which may influence the functional results after ACLR. When the quadriceps-hamstrings torque ratio becomes lower, the tibia is pulled posteriorly which reduces strain on the ACL. We used the results of this study to determine the inclusion criteria of Chapters 3 to 7.

The aim of the second study, of which the results are reported in **Chapter 3**, was to review what is known from the literature about ATTp in ACL-injured, ACLR, and healthy knees in order to find possible factors which could influence ATTp. The aim of the third study, of which the results are reported in **Chapter 4**, was to analyse the sensitivity of the SCoRE and SARA methods for determination of the rotational axes, one in the tibia and one in the femur, during tibiofemoral movements. The centers of the rotational axes can be used to calculate the tibia translation relative to the femur and with that ATTd. ATTp tests are commonly used to diagnose an ACL-injury and to select patients for ACLR [49]. However, ATTp may be misleading in terms of functional outcomes. For example, Kvist et al. [13] found that there is no correlation between ATTp and ATTd and suggests that this is due to the type of activity, the slope of the tibia plateau, or muscle activation patterns. In line with this suggestion, it is reported that ACL-injured patients with muscle strength asymmetry of the hamstrings or quadriceps showed altered knee mechanics in the sagittal plane [1, 38]. Patients after ACLR may compensate for the injury by changes in muscle activation patterns or kinematics. For example, ATTd may be limited in patients coping with the injury by using effective muscle activation patterns, whereas patients not coping with the injury may fail to compensate successfully for the limiting results of the injury. In order to be able to measure the ATTd, the SCoRE and SARA methods can be used. Using the results of this sensitivity analysis of Chapter 4 we measured and interpreted the ATTd, kinematics, kinetics and muscle activation patterns in subject with an intact native ACL (Chapter 5) and patients after an ACLR (Chapter 6). The aims of these studies, reported in Chapters, 5 and 6, were to investigate whether ATT can be limited by muscle activation patterns during a single leg hop for distance in healthy people (**Chapter 5**) and after ACLR (**Chapter 6**). In **Chapter 6** we also reported results between copers and non-copers. Our hypothesis was that ATTd may be different compared to ATTp due to muscle activation patterns, kinematics and/or kinetics and that the control of ATTd differs between copers and non-copers after an ACLR. The aim of **Chapter 7** was to determine whether the angle of the tibia plateau influences the ATTd during a single leg hop for distance after ACLR, as it is suggested that a difference in ATTd is partly explained by the slope of the tibia [43].

References

[1] Abourezk MN, Ithurburn MP, McNally MP (2017) Hamstring Strength Asymmetry at 3 Years after Anterior Cruciate Ligament Reconstruction Alters Knee Mechanics during Gait and Jogging. Am J Sports Med 45(1):97-105

[2] Ardern, CL, Webster, KE, Taylor, NF, Feller, JA (2011) Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and metaanalysis of the state of play. Br J Sports Med 45(7):596-606

[3] Balsly CR, Cotter AT, Williams LA, Gaskins BD, Moore MA, Wolfinbarger L Jr (2008) Effect of low dose and moderate dose gamma irradiation on the mechanical properties of bone and soft tissue allografts. Cell Tissue Bank 9(4):289–298

[4] Barcellona MG, Morrissey MC, Milligan P, Amis AA (2014) The effect of thigh muscle activity on anterior knee laxity in the uninjured and anterior cruciate ligament-injured knee. Knee Surg Sports Traumatol Arthrosc 22(11):2821–2829

[6] Blackburn, TA, Craig, E (1980) Knee anatomy: a brief review. Physical therapy 60(12):1556-1560

[7] Butler DL, Noyes FR, Grood ES (1980) Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg Am 62(2):259- 70.

[8] Cengiz, O, Demir, N, Dırvar, F (2019) Effects of graft selection in arthroscopic anterior cruciate ligament reconstruction: midterm functional results. Sisli Etfal Hastan Tip Bul 53(4):419- 425

[9] Chmielewski TL, Hurd WJ, Snyder-Mackler L (2005) Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. J Electromyogr Kinesiol 15(1):83-92.

[10] Choi, WR, Yang, JH, Jeong, SY, Lee, JK (2019) MRI comparison of injury mechanism and anatomical factors between sexes in non-contact anterior cruciate ligament injuries. PLoS one 14(8):e0219586

[11] Creighton RA, Bach BR Jr (2005) Revision anterior cruciate ligament reconstruction with patellar tendon allograft: surgical technique. Sports Med Arthrosc Rev 13(1):38–45

[12] Dai B, Garrett WE, Gross MT, Padua DA, Queen RM, Yu B. (2019) The effect of performance demands on lower extremity biomechanics during landing and cutting tasks. J Sport Health Sci 8(3):228-234

[13] Dejour D, Vanconcelos W, Bonin N, Saggin PRF (2013) Comparative study between mono-bundle bone-patellar tendon-bone, double-bundle hamstring and monobundle bone-patellar tendon-bone combined with a modified lemaire extra-articular procedure in anterior cruciate ligament reconstruction. Int Orthop 37(2):193–199

[14] Domnick C, Raschke MJ, Herbort M (2016) Biomechanics of the anterior cruciate ligament: physiology, rupture and reconstruction techniques. World J Orthop 7(2):82

[15] Edgar CM, Zimmer S, Kakar S, Jones H, Schepsis AA (2008) Prospective comparison of auto and allograft hamstring tendon constructs for ACL reconstruction. Clin Orthop Relat Res 466(9):2238–2246

[16] Eitzen I, Eitzen TJ, Holm I, Snyder-Mackler L, Risberg MA (2010) Anterior Cruciate Ligament-Deficient Potential Copers and Noncopers Reveal Different Isokinetic Quadriceps Strength Profiles in the Early Stage after Injury. Am J Sports Med 38(3):586-593

[17] Flandry, F., & Hommel, G. (2011). Normal anatomy and biomechanics of the knee. Sports Med Arthrosc Rev 19(2):82-92

[18] Frobell, RB, Roos, EM, Roos, HP, Ranstam, J, Lohmander, LS (2010) A randomized trial of treatment for acute anterior cruciate ligament tears. N Engl J Med 363(4):331-342

[19] Friden T, Erlandsson T, Zatterstrom R, Lindstrand A, Moritz U. (1995) Compression or distraction of the anterior cruciate injured knee. Variations in injury pattern in contact sports and downhill skiing. Knee Surg Sports Traumatol Arthrosc 3(3):144-7

[20] Ghodadra NS, Mall NA, Grumet R, Sherman SL, Kirk S, Provencher MT, Bach BR (2012) Interval arthrometric comparison of anterior cruciate ligament reconstruction using bone–patellar tendon–bone autograft versus allograft do grafts attenuate within the first year postoperatively? Am J Sports Med 40(6):1347–1354

[21] Girgis FG, Marshall JL, Monajem A (1975) The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res (106):216-31

[22] Halonen K, Mononen M, Toyras J, Kroger H, Joukainen A, Korhonen R (2016) Optimal graft stiffness and pre-strain restore normal joint motion and cartilage responses in ACL reconstructed knee. J Biomech 49(13):2566–2576

[23] Hart JM, Turman KA, Diduch DR, Hart JA, Miller MD (2011) Quadriceps muscle activation and radiographic osteoarthritis following ACL revision. Knee Surg Sports Traumatol Arthrosc 19(4):634–640

[24] Haughom, B, Schairer, W, Souza, RB, Carpenter, D, Ma, CB, Li, X (2012) Abnormal tibiofemoral kinematics following ACL reconstruction are associated with early cartilage matrix degeneration measured by MRI T1rho. The Knee 19(4):482-487

[25] Jarvinen, M, Natri, A, Laurila, S, Kannus, P (1994) Mechanisms of anterior cruciate ligament ruptures in skiing. Knee Surgery, Sports Traumatology, Arthroscopy 2(4):224-228.

[26] Kainer MA, Linden JV, Whaley DN, Holmes HT, Jarvis WR, Jernigan DB, Archibald LK (2004) Clostridium infections associated with musculoskeletal-tissue allografts. N Engl J Med 350(25):2564–2571

[27] Klyne DM, Keays SL, Bullock-Saxton JE, Newcombe PA (2012) The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: a study of alterations in emg measures and their relationship to knee joint stability. J Electromyogr Kinesiol 22(3):446–455

[28] Kvist J (2005) Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sports 15(3):148–158

[29] Lanier, AS, Knarr, BA, Stergiou, N, Snyder-Mackler, L, Buchanan, TS (2020) Acl Injury and Reconstruction Affect Control of Ground Reaction Forces Produced During a Novel Task That Simulates Cutting Movements. Journal of Orthopaedic Research 38(8):1746-1752

[30] Laoruengthana A, Pattayakorn S, Chotanaputhi T, Kosiyatrakul A (2009) Clinical comparison between six-strand hamstring tendon and patellar tendon autograft in arthroscopic anterior cruciate ligament reconstruction: a prospective, randomized clinical trial. J Med Assoc Thail 92(4):491

[31] Markatos, K, Kaseta, MK, Lallos, SN, Korres, DS, Efstathopoulos, N (2013) The anatomy of the ACL and its importance in ACL reconstruction. Eur J Orthop Surg Traumatol 23(7):747-52

[32] McGuire DA, Hendricks SD (2009) Allograft tissue in ACL reconstruction. Sports Med Arthrosc 17(4):224–233

[33] Moore, KL, Dalley, AF, Agur, AM (2013). Clinically oriented anatomy. Lippincott Williams & Wilkins

[34] Moses B, Orchard J, Orchard J (2012) Systematic Review: Annual Incidence of ACL Injury and Surgery in Various Populations. Res Sports Med 20(3-4):157-79

[35] Nederlandse Orthopaedische Vereniging (2011) Richtlijn Voorste kruisbandletsel. 's-hertogenbosch

[36] Nemzek JA, Arnoczky SP, Swenson CL (1994) Retroviral transmission by the transplantation of connective-tissue allografts. An experimental study. J Bone Joint Surg Am 76(7):1036–1041

[37] de Padua VBC, Maldonado H, Vilela JCR, Provenza AR, Monteiro C, de Oliveira Neto HC (2012) Comparative study of ACL reconstruction with anatomical positioning of the tunnels using the patellar tendon versus hamstring tendon. Rev Bras Ortop 47(1):50–56

[38] Palmieri-Smith RM, Lepley LK (2015) Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med 43(7):1662-1669

[39] Ren, S, Yu, Y, Shi, H, Miao, X, Jiang, Y, Liang, Z, Ao, Y (2018) Three dimen- sional knee kinematics and kinetics in ACL-deficient patients with and without medial meniscus posterior horn tear during level walking. Gait posture 66:26-31

[40] Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA (1992) Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. Am J Sports Med 20(5):519–526

[41] Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA (1992) Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. Am J Sports Med 20(5):519–526

[42] Shabani, B, Bytyqi, D, Lustig, S, Cheze, L, Bytyqi, C, Neyret, P (2015) Gait changes of the ACL-deficient knee 3D kinematic assessment. Knee Surgery, Sports Traumatology, Arthroscopy, 23(11):3259-3265.

[43] Shao Q, MacLeod TD, Manal K, Buchanan TS (2011) Estimation of ligament loading and anterior tibial translation in healthy and ACL-deficient knees during gait and the influence of increasing tibial slope using EMG-driven approach. Ann Biomed Eng 39(1):110–21

[44] Shelburne KB, Torry MR, Pandy MG (2005) Effect of muscle compensation on knee instability during ACL-deficient gait. Med Sci Sports Exerc 37(4):642–8

[45] Snook, GA (1983) A short history of the anterior cruciate ligament and the treatment of tears. Clin Orthop Relat Res (172):11-13

[46] Svensson M, Sernert N, Ejerhed L, Karlsson J, Kartus JT (2006) A prospective comparison of bone–patellar tendon–bone and hamstring grafts for anterior cruciate ligament reconstruction in female patients. Knee Surg Sports Traumatol Arthrosc 14(3):278–286

[47] Ueno, R, Navacchia, A, Bates, NA, Schilaty, ND, Krych, AJ, Hewett, TE (2020) Analysis of Internal Knee Forces Allows for the Prediction of Rupture Events in a Clinically Relevant Model of Anterior Cruciate Ligament Injuries. Orthop J Sports Med 8(1):2325967119893758.

[48] Vacek PM, Slauterbeck JR, Tourville TW, Sturnick DR, Holterman LA, Smith HC, Shultz SJ, Johnson RJ, Tourville KJ, Beynnon BD (2016) Multivariate Analysis of the Risk Factors for First-Time Noncontact ACL Injury in High School and College Athletes:

A Prospective Cohort Study With a Nested, Matched Case-Control Analysis. Am J Sports Med 44(6):1492-501.

[49] Vergis A, Hindriks M, Gillquist J (1997) Sagittal plane translations of the knee in anterior cruciate deficient subjects and controls. Med Sci Sports Exerc 29(12):1561–1566

[50] Victor J, Bellemans J, Witvrouw E, Govaers K, Fabry G (1997) Graft selection in anterior cruciate ligament reconstruction-prospective analysis of patellar tendon autografts compared with allografts. Int Orthop 21(2):93–97

[51] West RV, Harner CD (2005) Graft selection in anterior cruciate ligament reconstruction. J Am Acad Orthop Surg 13(3):197–207

Chapter 2

Superior Return to Sports Rate after Patellar Tendon Autograft over Patellar Tendon Allograft in Revision Anterior Cruciate Ligament Reconstruction

Michèle N.J. Keizer · Roy A.G. Hoogeslag · Jos J.A.M. van Raay · Egbert Otten · Reinoud W. Brouwer

Knee Surgery, Sports Traumatology, Arthroscopy 2018;26(2):574-581
http://dx.doi.org/10.1007/s00167-017-4612-9

Highlights

- After a minimum of 1 year after ACLR, no significant differences were found between grafts
- After a minimum of 2 years after ACLR, rate of RTS type is in favour of using an ipsilateral patellar tendon autograft compared to using a patellar tendon allograft
- RTS type rate after a minimum of 2 years after ACLR: 43.3% allograft & 75% allograft
- When the use of an allograft or autograft in revision ACLR is considered, choosing an autograft should be in favour

M.N.J. Keizer, R.A.G. Hoogeslag, J.J.A.M. van Raay, E. Otten, R.W. Brouwer

Abstract

Purpose: After revision anterior cruciate ligament reconstruction (ACLR), the rate of return to the pre-injury type of sport (RTS type) is low and graft choice might be an important factor. The aim of this study was to determine whether there is a difference in outcome after revision ACLR using a patellar tendon allograft compared to an ipsilateral patellar tendon autograft. It was hypothesized that the rate of RTS type using an ipsilateral patellar tendon autograft will be superior to using patellar tendon allograft.
Methods: The design is a retrospective cohort study. Inclusion criteria were patients who underwent revision ACLR with a minimum follow-up of 1 year after revision using a patellar allograft or ipsilateral autograft. Primary study parameter was rate of RTS type. Secondary study parameters were RTS level, subscores of the KOOS, the $\mathrm{IKDC}_{\mathrm{subjective}}$, the Tegner score and reasons for no RTS.
Results: Eighty-two patients participated in this study (36 allografts and 46 autografts). In patients with a minimum follow-up of 1 year, rate of RTS type was 51.4% for the patellar tendon allograft and 62.8% for the patellar tendon autograft group (n.s.). In patients with a minimum followup rate of 2 years, rate of RTS type was 43.3 versus 75.0%, respectively ($p = 0.027$). No differences in secondary study parameters were found. In patients with a minimum follow-up of 1 year, rate of RTS type was significantly higher ($p = 0.025$) for patients without anxiety compared to patients who were anxious to perform certain movements.
Conclusion: After a minimum follow-up of 2 years, rate of RTS type is in favour of using an ipsilateral patellar tendon autograft when compared to using a patellar tendon allograft in patients undergoing revision ACLR; after a minimum follow-up of 1 year, no significant difference was found. In revision ACLR, the results of this study might influence graft choice in favour of autologous graft when the use of an allograft or autograft patellar tendon is considered.

Level of evidence III.

Keywords ACL, Revision, Autograft, Allograft, Sports resumption, Anxiety

Introduction

In primary anterior cruciate ligament reconstruction (ACLR), graft choice might be of influence in rate of return to pre-injury type (RTS type) and level (RTS level) of sport, subjective outcome and residual laxity [8, 20, 23]. After revision ACLR, rate of RTS type and RTS level is slightly In primary anterior cruciate ligament reconstruction (ACLR), graft choice might be of influence in rate of return to pre-injury type (RTS type) and level (RTS level) of sport, subjective outcome and residual laxity [8, 20, 23]. After revision ACLR, rate of RTS type and RTS level is slightly lower than after primary ACLR [1, 16]. Options in graft choice for revision ACLR may include ipsilateral or contralateral hamstring, patellar or quadriceps autograft tendon, depending on the graft used for primary ACLR. For allograft use, more options are available. However, for revision ACLR, optimal graft choice is still controversial [9, 12]. Wright et al. [24] reported that of 12,000 patients in their cohort, graft choice for revision ACLR was 49% allograft, 48% autograft and 3% combined allograft and autograft. Patellar tendon - either allograft or autograft - was used most often.

The use of a patellar allograft tendon might have advantages over a patellar autograft tendon, such as smaller incision, shorter operating time, less postoperative pain [3, 14] and the possibility of using larger bone blocks at the end of the graft. Disadvantages of using a patellar allograft tendon include a small chance of bacterial infectious disease or virus transmission [2, 7, 15], higher costs, increased failure rates in more active individuals due to graft weakening from sterilization processes [22], age of the graft as donor grafts are frequently from older donors, a mismatch between size of the donor graft and patient's knee and availability [14]. By contrast, disadvantages of using a patellar autograft tendon might include anterior knee pain [21], donor site morbidity, quadriceps weakness [5, 21] and therefore a lower knee extensor moment [17].

The present study adds to the current literature the analysis of differences in rate of RTS type and RTS level between a patellar allograft tendon and a patellar autograft tendon in revision ACLR. We hypothesized that rate of RTS type and RTS level after revision ACLR using an ipsilateral patellar tendon autograft are superior to revision ACLR using patellar allograft tendon.

Materials and methods

A retrospective cohort study was conducted at the Orthopaedic Department of Martini Hospital in Groningen and Centre for Orthopaedic Surgery OCON in Hengelo, the Netherlands.

In the period between 2005 and 2015, 115 patients who underwent revision ACLR with a patellar tendon allograft or ipsilateral patellar tendon autograft with a minimum follow-up of 1 year after revision ACLR were eligible for this study (mean 44.7 months; minimum 12, maximum 108.9). Four surgeons performed the ACLRs. Exclusion criteria were patients with a history of second revision ACLR, contralateral ACLR and revision ACLR with a graft other than a patellar tendon allograft or ipsilateral autograft. Seventy-eight patients (67.8%) were included for analyses on rate of RTS type and RTS level. Eighty-two patients (71.3%) were included for analyses on functional results (KOOS, $IKDC_{subjective}$, Tegner scores). A subgroup analysis was conducted in patients with a minimum follow-up of 2 years. Fifty-five patients (47.8%) were eligible for this analysis. A flowchart of inclusion is presented in Fig. 1. Baseline characteristics at the time of revision ACLR are presented in Tables 1 and 2.

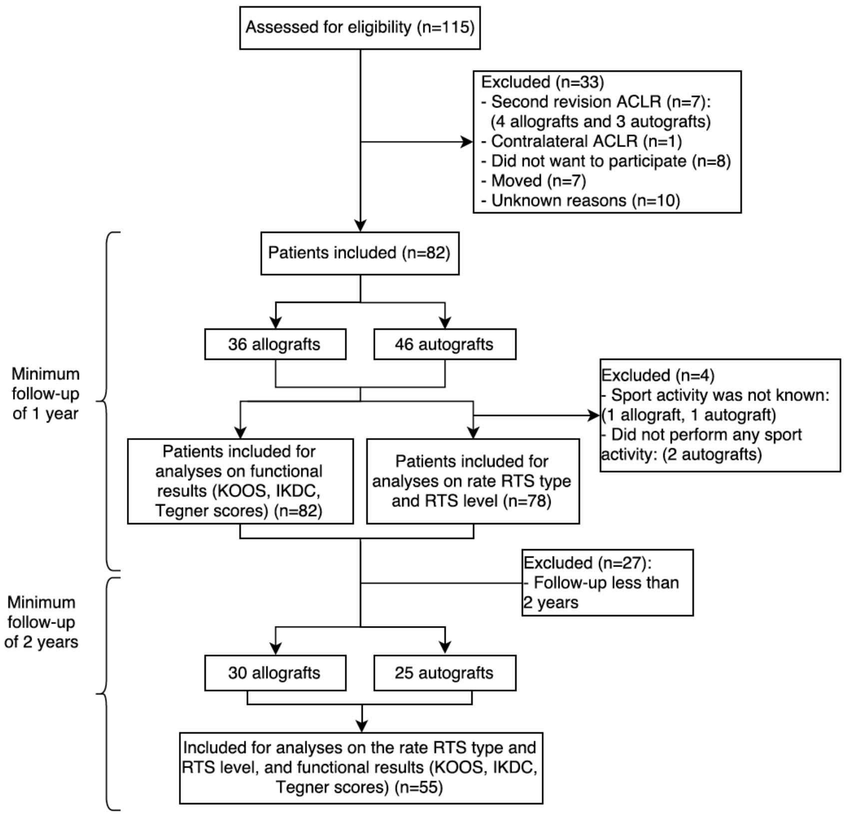


Fig. 1 Flow chart of the included patients.

Table 1 Baseline characteristics of the participants: allograft versus autograft.

	Allograft	Autograft	p value (allograft vs. autograft)	Lost to follow-up	p value (included vs. lost)
Number of patients	36	46		33	
Women/men	14/22	16/30	n.s.	11/22	n.s.
Age at revision ACLR [mean (SD)]	26.7 (10.3)	25.9 (6.6)	n.s.	25.9 (8.4)	n.s.
Left/right	15/21	18/28	n.s.	13/20	n.s.
Months between primary ACLR and revision ACLR [mean (SD)]	45.3 (53.5)	32.3 (26.4)	n.s.	40.8 (34.7)	n.s.
Primary graft used					
Hamstring autograft	25	43		28	
Hamstring allograft	1	1		0	
Hamstring contralateral	1	0		0	
Patellar autograft	8	0		2	
Patellar allograft	0	0		2	
Tuberositas tibialis graft	0	1		0	
Leeds-Keilo implant	1	0		0	
Not known	0	0		1	
Level of sport before primary injury			n.s.		
Did not do sports	1	1		-	
Recreational	3	7		-	
Competition regional	24	27		-	
Competition national	5	9		-	
Competition international	3	0		-	
Not known	0	2		-	

n.s. not significant

Table 2 Baseline characteristics for accompanying meniscal and/or cartilage injury at the moment of revision: allograft versus autograft.

	Allograft	Autograft	Lost to follow-up
Cartilage injury			
Medial	18	22	16
Lateral	9	15	9
Patellar	11	13	4
Meniscal injury medial			
No	14	25	13
Yes	5	7	3
Yes, subtotal meniscectomy	2	1	1
Yes, partial meniscectomy	15	11	13
Yes, meniscal repair	0	2	3
Meniscal injury lateral			
No	24	33	19
Yes	5	5	2
Yes, subtotal meniscectomy	0	0	1
Yes, meniscal repair	0	2	2

The primary outcome measure was rate of RTS type. Secondary outcome measures were rate of RTS level, the Dutch version of the Knee injury and Osteoarthritis Outcome Score (KOOS) [4], the International Knee Documentation Committee subjective form (IKDCsubjectve) [6], the Tegner score [19] and the reasons for not returning to sport. Rate of RTS level was divided into three categories based on the open questions; 1: patients who returned to sports on a lower than pre-injury level; 2: patients who returned to sport on their pre-injury level; 3: patients who returned to sport on a higher than their pre-injury level.

The Medical Ethical Committee of Martini Hospital approved the study design, procedures and protocol (METC number: 2014-87). All patients were informed about the study procedure and interest by letter or by e-mail.

Procedure

All patients included in the study were asked to fill in a questionnaire. This questionnaire was sent together with an accompanying letter explaining the interest and purpose of this study by mail or by e-mail using an online questionnaire. The questionnaire contained the Dutch version of the KOOS [4], the $\text{IKDC}_{\text{subjective}}$ [6], the Tegner score [19] and homemade open questions as presented in Table 3.

Table 3 Open questions included in the questionnaire (in Dutch).

What kind of sport(s) did you perform before your knee injury?
At what level did you perform these sport(s)?
Did you perform the same sport(s) again after your first ACLR?
If so, at what level did you perform your sport(s)?
Did you perform the same sport(s) again after revision ACLR?
If so, at which level did you perform your sport(s)?
If you did not return to the same sport(s), what was the reason?
Does your knee injury affect you in such a way that you are anxious to perform certain actions?
What kind of work or study did you do before you injured your ACL?
Did you change your work or study because of your knee injury?

Statistical analysis

The data were processed using SPSS Version 20 (IBM SPSS Statistics for Mac. Armonk, NY: IBM Corp.). A Chisquare test was used to compare the distribution of rate of RTS type between patients with a minimum follow-up of 1 and 2 years who underwent revision ACLR using a patellar tendon allograft or ipsilateral patellar tendon autograft. Fischer's exact test was used to compare rate of RTS level in patients with a minimum follow-up of 1 and 2 years who underwent revision ACLR using a patellar tendon allograft or ipsilateral patellar tendon autograft, as the criteria were not met for a Chi-square test.

The independent sample t test was used to compare the subscores $\text{KOOS}_{\text{sport}}$, $\text{KOOS}_{\text{symptoms}}$, KOOS_{qol} of the KOOS and $\text{IKDC}_{\text{subjective}}$ score between those patients with a minimum follow-up of 1 and 2 years who underwent revision ACLR using a patellar tendon allograft or ipsilateral patellar tendon autograft. As the score of the KOOS_{ADL} (kurtosis = 4.3) and the KOOSpain (kurtosis = 2.0) were not normally distributed and the Tegner score is an ordinal level, the Mann–Whitney U test was used to compare these scores among patients who underwent revision ACLR using a patellar tendon allograft or ipsilateral patellar tendon autograft.

In addition, a Chi-square analysis was used to compare rate of RTS type and anxiety to perform certain movements between patients with a minimum follow-up of 1 and 2 years.

An alpha level of $p < 0.05$ was considered to be significant. No sample size calculation was performed before conducting the study, as all patients who met the inclusion criteria were included in this study. A post hoc power calculation revealed a power of 84.1% for analysis regarding RTS type of patients at least 2 years postoperative and a power of 17.7% for analysis regarding RTS type of patients at least 1 year postoperative.

Results

Baseline characteristics

No significant differences were found in demographic characteristics (Table 1) or in meniscal and cartilage injury (Table 2). No significant differences were found for these parameters between patients who did not fill in the questionnaire and the patients who did fill in the questionnaire (Tables 2, 3).

Before primary ACL injury ten patients performed their sport at recreational level, 51 patients at regional competition level, 14 at national competition level and three patients performed sport their sport at international competition level. No significant differences were found between the groups for rate of RTS type and RTS level after primary ACL injury.

Rate of RTS type after revision ACLR

In patients with a minimum follow-up of 1 year, no significant difference was found between the groups (mean 56.0%, allograft 51.4%, autograft 62.8%; Table 4). However, in patients with a minimum follow-up of 2 years, rate of RTS type did reach a significant difference (p = 0.031) in favour of the patellar tendon autograft group (mean 57.4%, allograft 43.3%, autograft 75%; Table 5).

Table 4 Return to pre-injury type of sport (RTS type) rate, return to pre-injury level of sports (RTS level) rate, KOOS, Tegner and $IKDC_{subjective}$ score: Allograft versus Autograft in patients with a minimum follow-up of 1 year after surgery.

	Allograft	Autograft	*p* value (2-tailed)
RTS type rate (percentage)	51.4	62.8	n.s.
RTS level rate (percentage lower/same/higher)	41.2/52.9/5.9	63/37/0	n.s.
$KOOS_{symptoms}$ [mean (SD)]	55.5 (12.5)	59.2 (10.5)	n.s.
$KOOS_{pain}$ [mean (SD)]	76.5 (22.8)	83.4 (15.5)	n.s.
$KOOS_{ADL}$ [mean (SD)]	85.1 (20.1)	90.1 (13.5)	n.s.
$KOOS_{sport}$ [mean (SD)]	51.3 (29.8)	56.7 (28.6)	n.s.
$KOOS_{qol}$ [mean (SD)]	43.4 (15.2)	46.3 (13.2)	n.s.
Tegner score [median (range)]	4 (10)	4.5 (8)	n.s.
$IKDC_{subjective}$ [mean (SD)]	62.0 (10.2)	64.5 (9.8)	n.s.

n.s. not significant

Table 5 Return to pre-injury type of sport (RTS type) rate, return to pre-injury level of sport (RTS level) rate, KOOS, Tegner, and $IKDC_{subjective}$ score: Allograft versus Autograft in patients with a minimum follow-up of 2 years after surgery.

	Allograft	Autograft	*p* value (2-tailed)
RTS type rate (percentage yes/no) or	43.3	75	0.027*
RTS level (percentage lower/same/higher)	46.2/46.2/7.7	66.7/33.3/0	n.s.
$KOOS_{symptoms}$ [mean (SD)]	55.2 (12.8)	57.6 (10.1)	n.s.
$KOOS_{pain}$ [mean (SD)]	76.8 (21.0)	83.8 (16.0)	n.s.
$KOOS_{ADL}$ [mean (SD)]	86.6 (15.9)	90.5 (12.6)	n.s.
$KOOS_{sport}$ [mean (SD)]	49.2 (25.9)	58.2 (27.3)	n.s.
$KOOS_{qol}$ [mean (SD)]	43.3 (14.8)	44.8 (14.4)	n.s.
Tegner score [median (range)]	4 (8)	4 (10)	n.s.
$IKDC_{subjective}$ [mean (SD)]	61.6 (8.9)	64.3 (10.0)	n.s.

n.s. not significant; * significant

Rate of RTS level after revision ACLR

In those patients who did return to their pre-injury type of sports, no significant difference was found in rate of RTS level after revision ACLR using a patellar tendon allograft or patellar tendon autograft with a minimum follow-up of 1 year (Table 4) or 2 years (Table 5).

$IKDC_{subjective}$, KOOS and Tegner scores

No significant differences were found in $KOOS_{symptoms}$, $KOOS_{pain}$, $KOOS_{ADL}$, $KOOS_{sport}$, $KOOS_{qol}$, $IKDC_{subjective}$ or Tegner scores with a minimum follow-up of 1 year (Table 4) or 2 years (Table 5).

Reasons for not returning to pre-injury type of sports

For reasons for no RTS and anxiety about performing certain movements, see Table 6. A significant difference ($p = 0.025$) was found after a minimum follow-up of 1 year in rate of RTS type between patients who were anxious (rate RTS type: 49%) and patients who were not anxious about performing certain movements (rate RTS type: 82%). No significant difference in rate of RTS type between patients who were anxious and patients who were not anxious about performing certain movements was found after a minimum follow-up of 2 years.

Table 6 Reasons for no RTS and anxiety.

Reasons for not RTS	Number of participants	Anxiety about performing certain movements (69.6%)	Number of participants
Risk of re-injury	29	Tossing and turning	23
Knee pain	22	Kicking a ball	5
Knee swelling	3	Running	11
Knee instability	21	Jumping	22
Discouraged by physiotherapist or orthopaedic surgeon	6	Stair-climbing	1
		Squatting	3
		Sudden movements	7
		Kneeling	5
		Unstable movements	2
		New activities	1
		Sport-related activities	20

Discussion

The most important finding of the present study was that, in patients undergoing revision ACLR, after a minimum follow-up of 2 years there was a significant difference in rate of RTS type in favour of using an ipsilateral patellar tendon autograft over a patellar tendon allograft, even though after a minimum follow-up of 1 year no difference was found.

Ardern et al. [1] reported that two-thirds of patients after a primary ACLR have not returned to sport 1 year after surgery. This might explain the difference between rate of RTS type after a minimum follow-up of 1 versus 2 years, the shorter follow-up period may be too short and a follow-up of 2 years is more representative for this outcome measure. In contrast to the present study, Legnani et al. [10] reported that patients reconstructed with a contralateral autograft tendon returned to sport more quickly after revision ACLR than patients reconstructed with an allograft patellar or Achilles tendon. However, the autograft was harvested from the contralateral knee and in the allograft group patellar as well as Achilles tendon, grafts were used.

Furthermore, Reinhardt et al. [16] reported a higher rate of RTS level (52%) for patients with a minimum follow-up of 2 years when compared to the present study (24%). This difference might be explained by the older age of the studied population (the present study: 16–57; Reinhardt et al.: >18 years).

Few previous studies have compared use of an allograft and autograft for revision ACLR (see Table 7). Most outcome measures ($\mathrm{IKDC}_{\mathrm{subjective}}$ [22, 23], KOOS [23], re-rupture rate [11, 18, 23], incidence of lateral compartment knee osteoarthritis [13], femoral tunnel widening [13] and pain during walking downhill [13]) favoured using an autograft tendon. Some outcome measures (anterior translation [13], manual examination for stability [13], $\text{IKDC}_{\text{subjective}}$ [13], Lysholm score [18], Tegner activity scale [18] and patient satisfaction with outcome [18]) were similar in their use of an autograft and allograft tendon. Mayr et al. [13] reported greater extension deficits in patients who underwent revision ACLR with an autograft compared to a patellar tendon allograft. No significant differences in patient reported outcome measures were found in the present study.

Table 7 Studies comparing the use of an allograft and autograft tendon for revision ACLR.

Study	Graft type	Outcome scores: graft favoured
Wright et al. [23]	Not reported	$\text{IKDC}_{\text{subjective}}$ and KOOS: autograft Marx scale: combined allograft and autograft Re-rupture rate: autograft
Lind et al. [11]	Either hamstring or patellar tendon autograft or allograft	Re-rupture: autograft
Mayr et al. [13]	Patellar tendon	Anterior tibia translation, manual examination for stability, $\text{IKDC}_{\text{subjective}}$: autograft = allograft Extension deficits: allograft Lateral gonarthritis and femoral tunnel widening and pain during walking downhill: autograft
Steadman et al. [18]	Patellar tendon	Lysholm score, Tegner activity scale, and patient satisfaction with outcome: allograft = autograft Re-rupture rate: autograft
Legnani et al. [10]	Patellar or Achilles tendon	Quicker RTS time: autograft $\text{IKDC}_{\text{subjective}}$, KOOS: allograft = autograft RTS level: allograft = autograft Anterior tibia translation: allograft = autograft

A significant difference was found in rate of RTS type between patients who reported that they were anxious to perform certain movements and those that were not. A future study could investigate whether psychological treatment to reduce the anxiety may improve rate of RTS type.

Besides the retrospective nature of the present study, some other limitations need to be addressed. One such limitation is that no objective instrumented assessment was used to measure knee function. A future study could determine whether there is a difference in clinical instrumented tests between using a patellar tendon allograft or a patellar tendon autograft for revision ACLR. In addition, patients who declined to fill in the questionnaire (n = 8) or did not fill in the questionnaire for unknown reasons (n = 10) might have introduced a non-response bias. However, no significant differences were found in age at revision ACLR, sex, months between primary ACLR and revision ACLR, cartilage damage, or meniscal damage between responders and non-responders. Moreover, in the present study, patients participated at different levels of sports (recreational, regional, national or international) before their ACL injury. A lower pre-injury level might be easier to return to than a higher pre-injury level. As most patients in the present study participated in their pre-injured sports on a regional level, no analyses were conducted to determine this difference in rate of RTS. Future studies could identify if this. Preferably, a RCT is needed to confirm the results of the present study.

The clinical relevance of the present study is that, in revision ACLR, the results might influence the choice in favour of autologous graft when the use of an allograft or autograft patellar tendon is considered.

Conclusion

The results have shown that after a minimum follow-up of 2 years, rate of RTS type can be seen in favour of using an ipsilateral patellar tendon autograft over a patellar tendon allograft in patients undergoing revision ACLR; after a minimum follow-up of 1 year, no significant difference was found.

References

[1] Ardern CL, Webster KE, Taylor NF, Feller JA (2011) Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery two-thirds of patients have not returned by 12 months after surgery. Am J Sports Med 39(3):538–543

[2] Balsly CR, Cotter AT, Williams LA, Gaskins BD, Moore MA, Wolfinbarger L Jr (2008) Effect of low dose and moderate dose gamma irradiation on the mechanical properties of bone and soft tissue allografts. Cell Tissue Bank 9(4):289–298

[3] Creighton RA, Bach BR Jr (2005) Revision anterior cruciate ligament reconstruction with patellar tendon allograft: surgical technique. Sports Med Arthrosc Rev 13(1):38–45

[4] De Groot IB, Favejee MM, Reijman M, Verhaar JAN, Terwee CB (2008) The Dutch version of the Knee Injury and Osteoarthritis Outcome Score: a validation study. Health Qual Life Outcomes 6(1):1

[5] Hart JM, Turman KA, Diduch DR, Hart JA, Miller MD (2011) Quadriceps muscle activation and radiographic osteoarthritis following ACL revision. Knee Surg Sports Traumatol Arthrosc 19(4):634–640

[6] Haverkamp D, Sierevelt IN, Breugem SJM, Lohuis K, Blankevoort L, van Dijk CN (2006) Translation and validation of the Dutch version of the international knee documentation committee subjective knee form. Am J Sports Med 34(10):1680–1684

[7] Kainer MA, Linden JV, Whaley DN, Holmes HT, Jarvis WR, Jernigan DB, Archibald LK (2004) Clostridium infections associated with musculoskeletal-tissue allografts. N Engl J Med 350(25):2564–2571

[8] Kane PW, Wascher J, Dodson CC, Hammoud S, Cohen SB, Ciccotti MG (2016) Anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft versus allograft in skeletally mature patients aged 25 years or younger. Knee Surg Sports Traumatol Arthrosc 24(11):3627–3633

[9] Kim HS, Seon JK, Jo AR (2013) Current trends in anterior cruciate ligament reconstruction. Knee Surg Relat Res 25(4):165–173

[10] Legnani C, Zini S, Borgo E, Ventura A (2016) Can graft choice affect return to sport following revision anterior cruciate ligament reconstruction surgery? Arch Orthop Trauma Surg 136(4):527–531

[11] Lind M, Menhert F, Pedersen AB (2012) Incidence and outcome after revision anterior cruciate ligament reconstruction results from the Danish registry for knee ligament reconstructions. Am J Sports Med 40(7):1551–1557

[12] Magnussen RA, Trojani C, Granan LP, Neyret P, Colombet P, Engebretsen L, MARS Group (2015) Patient demographics and surgical characteristics in ACL revision: a comparison of French, Norwegian, and North American cohorts. Knee Surg Sports Traumatol Arthrosc 23(8):2339–2348

[13] Mayr HO, Willkomm D, Stoehr A, Schettle M, Suedkamp NP, Bernstein A, Hube R (2012) Revision of anterior cruciate ligament reconstruction with patellar tendon allograft and autograft: 2-and 5-year results. Arch Orthop Trauma Surg 132(6):867–874

[14] McGuire DA, Hendricks SD (2009) Allograft tissue in ACL reconstruction. Sports Med Arthrosc 17(4):224–233

[15] Nemzek JA, Arnoczky SP, Swenson CL (1994) Retroviral transmission by the transplantation of connective-tissue allografts. An experimental study. J Bone Joint Surg Am 76(7):1036–1041

[16] Reinhardt KR, Hammoud S, Bowers AL, Umunna B, Cordasco FA (2012) Revision ACL reconstruction in skeletally mature athletes younger than 18 years. Clin Orthop Relat Res 470(3):835–842

[17] Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA (1992) Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. Am J Sports Med 20(5):519–526

[18] Steadman JR, Matheny LM, Hurst JM, Briggs KK (2015) Patient-centered outcomes and revision rate in patients undergoing ACL reconstruction using bone-patellar tendon-bone autograft compared with bone-patellar tendon-bone allograft: a matched case-control study. Arthroscopy 31(12):2320–2326

[19] Tegner Y, Lysholm J (1985) Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 198:42–49

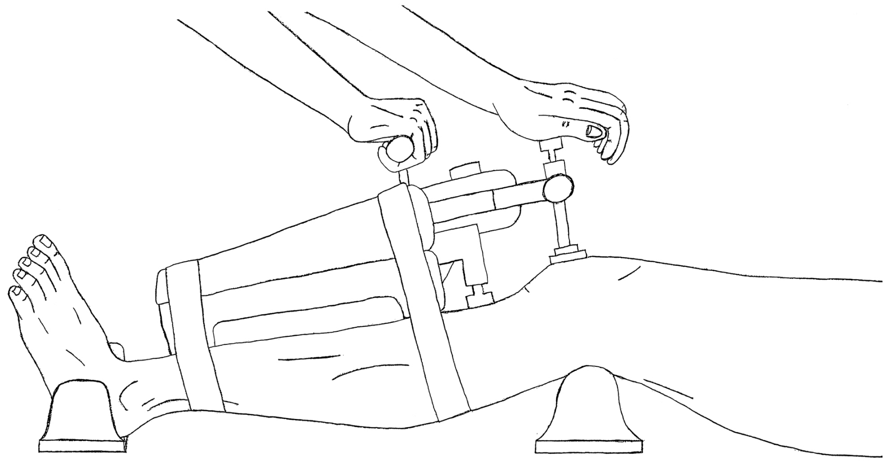
[20] Tibor LM, Long JL, Schilling PL, Lilly RJ, Carpenter JE, Miller BS (2010) Clinical outcomes after anterior cruciate ligament reconstruction: a meta-analysis of autograft versus allograft tissue. Sports Health 2(1):56–72

[21] Victor J, Bellemans J, Witvrouw E, Govaers K, Fabry G (1997) Graft selection in anterior cruciate ligament reconstruction-prospective analysis of patellar tendon autografts compared with allografts. Int Orthop 21(2):93–97

[22] West RV, Harner CD (2005) Graft selection in anterior cruciate ligament reconstruction. J Am Acad Orthop Surg 13(3):197–207

[23] Wright RW, MARS Group (2014) Effect of graft choice on the outcome of revision anterior cruciate ligament reconstruction in the Multicenter ACL Revision Study (MARS) Cohort. Am J Sports Med 42(10):2301–2310

[24] Wright RW, MARS Group (2016) Factors influencing graft choice in revision anterior cruciate ligament reconstruction in the MARS group. J Knee Surg 29(6):458–463



Chapter 3

Passive Anterior Tibia Translation in Anterior Cruciate Ligament-Injured, Anterior Cruciate Ligament-Reconstructed and Healthy Knees: a Systematic Review

Michèle N.J. Keizer · Egbert Otten

Musculoskelet Surgery 2019;103(2):121-130
http://dx.doi.org/10.1007/s12306-018-0572-6

Highlights

- Graft choice, ACL injury or reconstruction, intra-articular injuries and whether the injury is chronic or acute affect the passive ATT
- Autograft ACLR may give better results than an allograft ACLR as knee laxity is greater when using an allograft tendon
- Comparison of passive ATT between different measurement methods should be taken with caution
- More consistency in measuring devices used should be introduced

Abstract

Purpose: Anterior tibia translation (ATT) is mainly prevented by the anterior cruciate ligament. Passive ATT tests are commonly used to diagnose an anterior cruciate ligament (ACL) injury, to select patients for an ACL reconstruction (ACLR), and as an outcome measure after an ACLR. The aim of this review was to present an overview of possible factors determining ATT. A second purpose was to give a summary of the ATT measured in the literature in healthy, ACL-injured and ACLR knees and a comparison between those groups.

Methods: A literature search was conducted with PubMed. Inclusion criteria were full-text primary studies published in English between January 2006 and October 2016. Studies included reported ATT in explicit data in healthy as well as ACL-injured or ACLR knees or in ACL-injured as well as ACLR knees.

Results: Sixty-one articles met inclusion criteria. Two articles measured the ATT in healthy as well as ACL-injured knees, 51 in ACL-injured as well as in ACLR knees, three in ACLR as well as in healthy knees and three in healthy, ACL-injured and ACLR knees. A difference in ATT is found between healthy, contralateral, ACLR and ACL-injured knees and between chronic and acute ACL injury. Graft choices and intra-articular injuries are factors which could affect the ATT. The mean ATT was lowest to highest in ACLR knees using a bone–patella tendon–bone autograft, ACLR knees using a hamstring autograft, contralateral healthy knees, healthy knees, ACLR knees with an allograft and ACL-injured knees. Factors which could affect the ATT are graft choice, ACL injury or reconstruction, intra-articular injuries and whether an ACL injury is chronic or acute.

Conclusion: Comparison of ATT between studies should be taken with caution as a high number of different measurement methods are used. To be able to compare studies, more consistency in measuring devices used should be introduced to measuring ATT. The clinical relevance is that an autograft ACLR might give better results than an allograft ACLR as knee laxity is greater when using an allograft tendon.

Level of evidence III.

Keywords Knee laxity, Influences, ACL, Allograft, Autograft

Introduction

Anterior tibia translation (ATT) is mainly prevented by the anterior cruciate ligament (ACL) [1]. An ACL injury results in higher ATT with respect to the femur. To reduce the increased ATT after an ACL injury, an ACL reconstruction (ACLR) is warranted [2]. Passive ATT tests are commonly used to diagnose an ACL injury and to select patients for an ACLR [3]. Moreover, passive ATT tests are commonly used as an outcome measure after an ACLR, for example, to compare knee laxity after an ACLR using different types of grafts (i.e. [4, 5]).

Several methods can be used to assess the ATT. These tests could either be clinical tests, i.e. the Lachman test, or instrumental measuring methods (i.e. [6, 7]). The most frequently used instrumental measuring method is the KT-1000 arthrometer (KT-1000) (Medmetric Corp., San Diego, CA, USA) developed by Dale Daniel in 1983 [8]. Using the KT-1000 and its successors, the KT-2000 [9] and the ComputKT, an examiner applies forces to the tibia using a handle on top of the device. The anterior–posterior displacement is determined by the distance or relative motion between two sensing paddles: one on the patella and one on the tibial tubercle. The device is calibrated by the determination of the zero point which is done by performing several anterior and posterior translations of the tibia. Visual–manual records are displayed, and audible tones are reached at 15 N, 20 N, 30 N, 67 N, 89 N, 133 N, 134 N, maximal manual (Mm) or maximal personal (Mp) forces. The KT-2000 and the ComputKT have improved data visualisation.

Other methods to assess the ATT are the Kneelax (MR Systems, Haarlem, the Netherlands [10]), the Rolimeter (Aircast, Vista, CA, USA [11]), the Telos Stress Device (H.Tulaszew- ski, 6302 LICH-Ober-Blessingen, West Germany [12]), the electromagnetic measurement system (EMC) (FASTRAK, Polhemus, VT, USA [13]), the radiostereometric analysis (RSA [12]), fluoroscopic measurements (FM) (BV-29; Philips, Best, the Netherlands) and (computerassisted) navigation systems. The Kneelax is similar to the KT-1000, but the updated recording process allows digital recording of ATT at the same forces as the KT-1000. The Rolimeter can measure the ATT during the Lachman, anterior drawer and 'step-off' tests and is easy in use and cheap. The ends of the device are placed on the mid-patella and tibia, and ATT is measured using a calibrated stylus with 2-mm markers. The Telos Stress Device in combination with a radiostereometric analysis is expensive and results in radiation exposure. When mechanically a force of 150 N, 250 N or maximal manual (Mm) is applied, a stress radiograph is made. Recently, the Telos Stress Device is updated allowing to determine the ATT with a linear optical encoder and without radiographs.

The electromagnetic measurement system (EMS) is an in vivo noninvasive system using an electromagnetic sensor during the pivot-shift test. It monitors instantaneous 3D position and calculates the 3D acceleration of the motion. The radiostereometric analysis (RSA), developed by Selvik et al., has a high accuracy of 0.1-mm displacement. It is an invasive method relying on the implantation of tantalum beads. During a fluoroscopic measurement (FM), the device is placed on the medial side of the knee, and X-ray fluoroscopy captures the knee motion during a Lachman test. A (computer-assisted) navigation system can be used during surgery to measure three-dimensional knee kinematics when applying a specific amount of force on the tibia.

A variety of factors could determine the ATT. It is necessary to identify possible factors which could determine the ATT as knee laxity is shown to be associated with osteoarthritis [14, 15] and an increased chance of knee injuries [16], in particular an ACL injury [17, 18]. Besides, it is not clearly reported what the range of ATT is in healthy, ACL-injured and ACLR knees.

The main purpose of the current systematic review was to give an overview of possible factors determining the ATT. A second purpose was to present a summary of the ATT measured in the available literature in healthy, ACL-injured and ACLR knees and a comparison between those groups.

Methods

Inclusion criteria

In order to identify articles for inclusion, a systematic literature search was conducted with the PubMed electronic database on the 6 October 2016. The search terminology was based on the query "(Knee OR ACL) AND (Laxity OR Anterior Translation) NOT (cadaveric OR Shoulder OR Ankle OR PCL OR TKA OR TKR)".

Titles, abstracts and full texts were analysed by the first author (M.N.J.K). Articles were included if they were: (1) full-text primary studies; (2) published in the English language; (3) published between the 1 January 2006 and 1 October 2016, to reduce the high number of papers and as the measurement methods are improved; (4) studies that reported possible factors determining the ATT; (5) studies that reported ATT in either ACL-injured as well as in ACLR knees; in ACL-injured as well as in healthy knees; or in ACLR as well as in healthy knees; (6) studies that displayed the ATT in explicit data. Review articles were excluded. Articles were excluded when they only measured ATT in ACL-injured, ACLR or healthy participants, did not display ATT in explicit data, measured ATT in participants with additional (knee) injuries, measured tibia position instead of ATT or measured ATT in an active situation.

After identification of the articles, the Newcastle–Ottawa Scale was used by the first author (M.N.J.K.) to appraise the studies that were identified for inclusion in this review [19]. All included studies were found to have an average to good study quality with a score of 6 to 9 out of 9. No reasons were found to assume biases in the data.

Study characteristics

Articles which met inclusion criteria were analysed for patient demographics, measuring methods to access ATT, the ATT, factors determining the ATT, and, for articles with ACLR participants, type of graft used.

Fifty-eight articles reported factors which may determine the ATT. Two articles were identified reporting ATT in ACL-injured as well as healthy or contralateral healthy knees, 51 articles were identified reporting ATT in ACL injured as well as ACLR knees, and 3 articles were identified reporting ATT in ACLR as well as in healthy knees. Three articles were included in all three groups as they reported ATT in healthy, ACL-injured and ACLR knees. For analyses, sixty-one articles were included (Fig. 1).

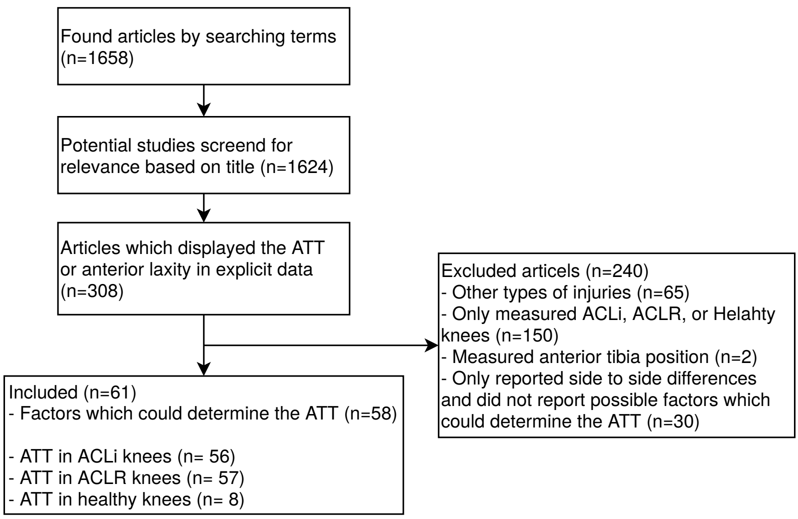


Fig. 1 Flow chart of the literature search.

The number of included participants per study ranged from 11 to 375. The average age of the participants included per study ranged from 13.9 to 54.4 year. Four studies did not include information on gender. In total, 2.583 of the patients were male, and 1651 were female. Forty-four of the studies used hamstring autografts for ACLR, 15 of the studies used bone–patellar tendon autografts for ACLR, and six of the studies used allograft for ACLR.

Synthesis of results

The mean ATT was measured for all measurement methods as well as for ACL-injured, ACL-reconstructed (split by type of graft) and (contralateral) healthy knees. These data were compared between groups.

Statistical analysis

In this review, the results of articles with a significant difference of $p < 0.05$ were declared as significant results.

An independent two-way factorial analysis of variance with interaction was conducted to find the effect of the type of devices and the groups (healthy, contralateral healthy, ACL-injured, ACLR with hamstring autograft tendon, ACLR with bone–patella tendon–bone autograft tendon and ACLR with allograft tendon knees) on the ATT, to find whether there is an interaction between groups and type of devices and to evaluate the coefficients of the groups and devices.

Results

Possible factors which could determine the ATT

Chen et al. [20] found that patients which had an acute ACL-injured ($n = 27$) had significantly lower ATT in comparison with patients who had chronic ACL-injured ($n = 28$). Christino et al. [6] found that ATT in patients without intra-articular injuries ($n = 19$) was significantly lower than in patients with intra-articular injuries ($n = 11$).

Of sixteen studies only two articles found significant differences in ATT between using a single-bundle and a double-bundle autograft tendon for ACLR in favour of a double-bundle autograft [4, 21]. Three of the six articles which compared allograft use and autograft use found a significant difference in favour of an autograft tendon [22–24]. Only one out of five studies which compared BPTB autograft and hamstring autograft use reported a significant difference in favour of hamstring autografts [23]. A significantly higher ATT was found in patients who underwent ACLR using a 4-strand compared to an 8-strand hamstring autograft [24], in patients who underwent ACLR using a Leeds-Keio ligament compared to using a BPTB autograft at 2 years after reconstruction [25] and in patients who underwent ACLR using a calcium phosphate-hybridised BPTB autograft in comparison with the conventional method [26].

Two studies reported significant differences between graft fixation methods [27, 28]. However, others did not report any differences in graft fixation methods [21, 29–34]. For all comparisons see Table 1.

Table 1 Factors which might determine the anterior tibia translation.

Study	Compared	Conclusion
20	Acute versus chronic ACL-injured knees	Chronic > acute*
6	Before ACLR in patients with versus without intra-articular injuries	With > without*
35	Males versus females	Females> males
36	Males versus females	Females >males
37	Males versus females	Females > males
4	SB versus DB hamstring aut	SB > DB*
38	SB versus DB hamstring aut	DB> SB
39	SB versus DB hamstring aut	SB > DB
40	SB versus DB hamstring aut	SB > DB
41	SB versus DB hamstring aut	SB > DB
42	SB versus DB hamstring aut	DB > SB
43	SB versus DB hamstring aut	SB > DB
44	SB versus DB hamstring aut	DB > SB
45	SB versus DB hamstring aut	0°, 30°, and 90°: SB > DB 60°: DB > SB
46	SB versus DB hamstring aut	SB> DB
47	SB versus DB hamstring aut	DB > SB
48	SB versus DB hamstring aut	SB > DB
49	SB versus DB hamstring aut	DB > SB
50	SB versus DB hamstring aut	SB > DB
51	SB versus DB BPTB all	SB > DB
52	TB versus SB hamstring aut	KT-1000: TB > SB Telos: SB > TB
19	Anatomic versus nonanatomic DB hamstring	SB > anatomic* Nonanatomic >anatomic
53	All versus hamstring aut	All > aut
28	All versus BPTB aut	All >aut
54	All versus hamstring aut	All > aut*
55	Hamstring aut versus irradiated all	All > aut*
22	BPTB aut versus fresh-frozen all (all1) or y-irradiated all (all2)	All2* > all1 > aut
56	All free tendon Achilles versus hamstring aut	All > aut
23	BPTB versus hamstring aut	BPTB > hamstring*
57	BPTB versus hamstring aut	Hamstring >BPTB
58	BPTB versus hamstring aut	Hamstring >BPTB
59	BPTB versus hamstring aut	Hamstring > BPTB

60	DB hamstring (1) versus BPTB (2) versus BPTB_L (3)	Medial: 3 > 2 > 1 Lateral: 2 > 3 > 1 BPTB_L reduced most*
61	DB hamstring aut versus aug	KT-1000: DB >aug Telos: aug > DB
62	4-Strand versus 8-strand hamstring aut	4-strand > 8-strand
63	Hamstring versus quadriceps aut	Quadriceps > hamstring
25	BPTB versus LK 2 y after	ACLR: LK > BPTB* 5 y after ACLR: BPTB > LK
64	Qf versus BPTB	BPTB > Qf
65	Cas versus non-Cas surgery	Non-Cas > Cas
66	High versus low tension BPTB or hamstring aut	High > low
26	CaP versus CM BPTB	CM > CaP*
67	A20 versus P20 versus A20P0 versus A20P20 versus A20P45 bundle fixation	P20 > A20* A20 > A20P0* P20 > A20 > A20P20* P20 > A20 > A20P45*
68	With versus without navigation system	With > without
21	TT versus AM SB hamstring aut	TT > AM
69	Metal versus PLLA screw	Metal = PLLA
70	BioCryl versus RigidFix fixation	BioCryl > RigidFix
27	Cortical with versus without aperture fixation	Without > with*
29	TransFix versus Endobutton fixation	Endobutton > TransFix
31	TransFix versus bioscrew fixation	Bioscrew > TransFix
71	Bioabsorbable versus metal screw fixation	Metal > bioabsorbable
72	Metal versus PLLA screw hamstring aut	PLLA > metal
73	RigidFix and intrafix (1) versus RigidFix and bioscrew (2) versus bioscrew and intrafix (3) versus bioscrew and bioscrew fixation (4)	3 > 2 > 4 > 1
74	Femoral knot/press fit (1) versus femoral interference screw fixation (2)	2 > 1
75	Early extension versus late extension during rehabilitation	Late > early
76	Greater than 20% versus lower than 20% strength deficit	Greater > lower
77	Three-day versus 2-week immobilisation	3 Days > 2 weeks
78	Brace versus nonbrace after ACLR	Nonbrace > brace
34	Left-handed versus right-handed physiotherapists using the KT-1000	LH > RH*

ACL anterior cruciate ligament, *ACLR* anterior cruciate ligament reconstruction *SB* single bundle, *DB* double bundle, *all* allograft, *aut* autograft, *BPTB* bone-patellar tendon-bone, *TB* triple bundle, *BPTB-L* mono-bundle BPTB combined with extra-articular reconstruction, *aug* remnantpreserving augmentation, *LK* Leeds-Keio ligament, *y* years, *Qf* quadruple flexor, *Cas* computer-assisted surgery, *A20* anteromedial bundle fixation only at 20° of flexion, *P20* posterolateral bundle fixation only at 20° of flexion, *A20P0* anteromedial bundle fixation at 20° and posterolateral bundle fixation at 0° of flexion, *A20P20* anteromedial bundle fixation at 20° and posterolateral bundle fixation at 20°

of flexion, *A20P45* anteromedial bundle fixation at 20° and posterolateral bundle fixation at 45° of flexion, *TT* transtibial femoral tunnel preparation, *AM* anteromedial femoral tunnel preparation, *CaP* hybridising calcium phosphate, *CM* conventional method, *PLLA* biodegradable interference screw, *LH* lefthanded, *RH* right-handed *n.s.* not significant

Factor analysis of groups and devices on ATT

Two devices (FM and EMS) showed much higher ATT than the other devices, and therefore, these two devices were excluded for calculation of mean ATT per group. A nonsignificant interaction between groups and devices was seen ($p = 0.73$). No p values could be calculated for the groups and devices separately, as the number of observations of some groups and some devices was too low. The coefficients of all groups ranged from -1.75 to 2.89 with a mean of 0.00. The coefficients of all devices ranged from -3.30 to 4.07 with a mean of 0.21. In Table 2 the coefficients of the groups, of devices which were lower than -1 and higher than 1, and of the interaction which were lower than -3 and higher than 3 are reported. For the ATT for each device per group see Fig. 2.

Table 2 Highest coefficients of an independent two-way factorial analysis of variance with interaction. Only coefficients for devices lower than -1 and higher than 1 are reported. Only interaction coefficients lower than -3 and higher than 3 are reported.

Group	Coef	Device	Coef	Device	Coef	Interaction	Coef
ACL-injured	2.89	ComputKT (134 N)	4.07	KT-1000 (133 N)	-1.26	Telos * healthy	4.51
Contra-lateral	0.85	Navigation	3.59	Kneelax (98 N)	-1.45	Telos (150 N) * ACL-injured	4.17
Allograft	-0.18	Navigation (MF)	2.64	KT-1000 (15 N)	-1.84	Rolimeter (Mm) * contralateral	3.82
Healthy	-0.24	KT-1000 (Mm)	1.84	Telos (150 N)	-2.56	KT-1000 (89 N) * hamstring	3.58
BPTB	-1.53	KT-1000 (300 N)	1.68	Kneelax (132 N)	-2.79	Navigation (100 N) * ACL-injured	3.24
Hamstring	-1.75	Rolimeter	1.66	Rolimeter (Mm)	-3.30	RSA * BPTB	3.02
		KT-1000 (134 N)	1.02			ComputKT (134 N) * ACL-injured	-3.16
		KT-2000 (Mm)	1.01			KT-1000 (Mp) * ACL-injured	-3.38

Coef: coefficient

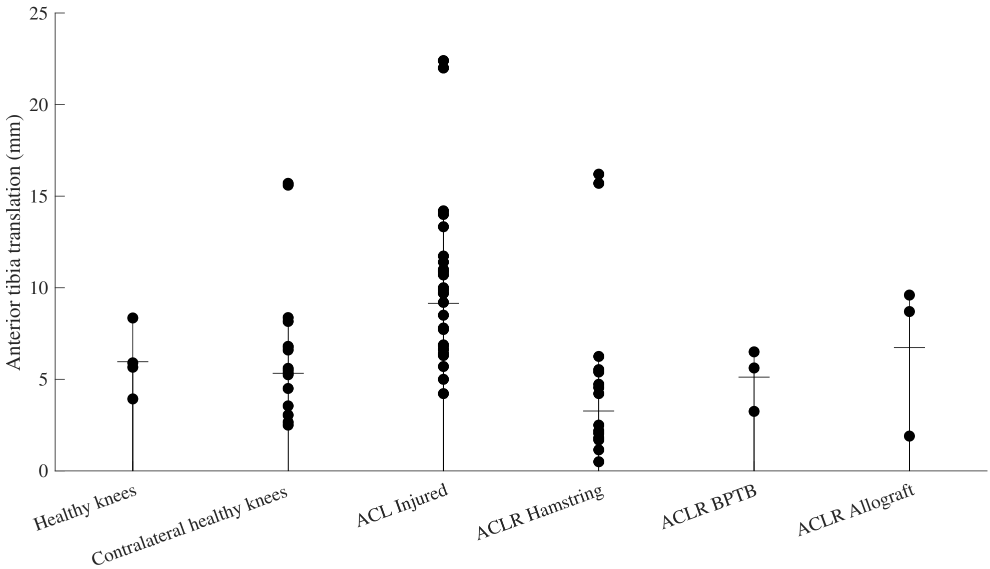


Fig. 2 Absolute anterior tibia translation per group (healthy, contralateral healthy, ACL injured, ACL reconstructed with hamstring autograft tendon, ACL reconstructed with bone–patella tendon–bone autograft tendon and ACL reconstructed with allograft tendon knees) of each device (black dots). The black horizontal lines indicate the mean ATT of the groups. The six separate dots indicate the devices excluded from analysis.

Discussion

The mean finding of this review was that graft choice, ACL injury or reconstruction, intra-articular injuries and whether an ACL injury is chronic or acute are factors which could determine the ATT. Other possible factors, such as fixation techniques, were inconclusive. The mean absolute ATT is, respectively, lowest to highest in ACLR knees with a BPTB autograft (3.25 mm), ACLR knees with a hamstring autograft (3.27 mm), contralateral healthy knees (5.33 mm), healthy knees (5.96 mm), ACLR knees with an allograft tendon (6.73 mm) and ACL-injured knees (9.15 mm).

The mean ATT measured in ACLR knees with an allograft was twice as high as the ATT measured in ACLR knees with an BPTB autograft. This finding is consistent with the finding of Tian et al. [55], however, in contrast with the finding of Ghodadra et al. [28] who did not report a significant difference between BPTB autograft and allograft use. In addition, Laoruengthana et al. [23] reported that ATT is significantly higher in ACLR knees with BPTB autograft compared to ACLR knees with hamstring autograft. This is in contrast with the data presented in this review. The mean ATT in knees with a BPTB autograft was only 0.02 mm lower than in ACLR knees with a hamstring autograft.

The methods used to assess ATT might have introduced a systematic measurement error. In healthy knees, ATT ranged from 3.93 mm (KT-1000 89N) to 8.35 mm (ComputKT) and in contralateral healthy knees from 2.5 mm (KT-1000 67N) to 15.7 mm (EMS). In addition, the range of coefficients measured using an independent two-way factorial analysis of variance with interaction was greater in range for the devices (range: -3.30 to 4.07) in comparison with the groups (range: -1.75 to 2.89). Therefore, comparison of ATT between devices should be taken with caution as the choice of measuring device might be paramount. However, some interactions between devices and groups were strong (Table 2), for example: the coefficient of the interaction between the ComputKT and BPTB group was -3.16. Therefore, the difference in ATT between devices might also have been caused by differences in characteristic of subjects measured in the studies in which those devices were used. More consistency in measuring device used to assess ATT should be introduced. Pugh et al. [30] in their review suggest that the KT-1000 and the Rolimeter provide better results than the Telos Stress Radiography and some other devices not covered in this review. Fortunately, the KT-1000 arthrometer is the most frequently used.

For almost all devices a variety of forces can be used to measure the ATT. The relation between forces and ATT is reported by Lin et al. [33] for healthy knees and ACL-injured knees. They reported a significantly larger displacement and a significantly larger stiffness of the injured knee compared to healthy knees. In line with these results the mean ATT of the studies in this review was smaller in healthy and contralateral knees in comparison with ACL-injured knees. However, the relationship between force and ATT is not seen in the data of the current review. This might be due to differences between studies in, i.e. subject characteristics and other factors which could also have determined the ATT. For example, a significant difference in ATT measured using a KT-1000 between right-handed physiotherapists and lefthanded physiotherapists was reported by Sernert et al. [34]. A between-studies comparison of ATT should be taken with caution, especially when different measurement methods or forces are used.

Muscle activity might also have determined the ATT. Klyne et al. [79] found in patients with an ACL injury a relation between ATT in a passive situation and prolonged muscle activity of the medial gastrocnemius during a jump test. Barcellona et al. [80] found that hamstrings activity reduces anterior knee laxity in a passive situation in ACLinjured patients. This indicates that patients with an ACL injury might compensate for knee laxity by increasing the duration of muscle activity. However, Goradia et al. [76] did not find a difference in ATT between patients with strength deficit and patients without strength deficit. Kvist [81] found that there is no correlation between ATT in a passive situation and ATT in an active situation, which might indicate that muscle activity does play a role in the control of ATT during activity. Future studies could investigate the effect of muscle activity on ATT and could investigate ATT in an active situation, i.e. by using the method to assess ATT of Boeth et al. [82].

Some limitations of this review should be addressed. Systematic reviews are limited by the weaknesses of each study. This might include a small number of participants, a shortterm follow-up time and a high variability of participants. However, no reasons were found to assume biases in the data. One article which was determined to have a poor quality was excluded from further analysis. In addition, a limitation of this review was the large variety of measurement devices used to assess the ATT, which made a comparison between studies difficult. However, this also makes clear that more consistency should be introduced in measuring method for ATT.

Conclusion

Surprisingly reported ATT, in comparison with healthy knees, is higher after an ACLR using an allograft tendon and lower in knees using a bone–patella tendon–bone autograft. In addition, ATT was significantly higher in chronic than in acute ACL injuries and in knees with intra-articular injuries compared to knees without intra-articular injuries. Inconclusive results were found for other factors such as fixation techniques. When excluding two devices which measured much higher ATT than the other devices, mean ATT was lowest to highest in ACLR knees using a bone–patella tendon–bone (BPTB) autograft, ACLR knees using a hamstring autograft, contralateral healthy knees, healthy knees, ACLR knees with an allograft and ACL-injured knees. Between-studies comparison of the ATT should be taken with caution as lots of different measurement methods with different forces were used to measure the ATT. To make the compatibility of studies more reliable, more consistency in measuring methods to assess ATT should be introduced. The clinical relevance of this study is that even though the ATT was smaller after an ACLR in comparison with ACL-injured knees, using an allograft tendon, the ATT was greater than healthy knees, whereas by using an autograft tendon the ATT was smaller than in healthy knees. An increase in ATT is found to be a risk factor for osteoarthritis and a chance of knee injuries; therefore, an autograft ACLR might give better results in comparison with an allograft ACLR.

References

[1] Domnick C, Raschke MJ, Herbort M (2016) Biomechanics of the anterior cruciate ligament: physiology, rupture and reconstruction techniques. World J Orthop 7(2):82

[2] Halonen K, Mononen M, Toÿräs J, Kröger H, Joukainen A, Korhonen R (2016) Optimal graft stiffness and pre-strain restore normal joint motion and cartilage responses in ACL reconstructed knee. J Biomech 49(13):2566–2576

[3] Vergis A, Hindriks M, Gillquist J (1997) Sagittal plane translations of the knee in anterior cruciate deficient subjects and controls. Med Sci Sports Exerc 29(12):1561–1566

[4] Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N (2010) Comparison between single-and double-bundle anterior cruciate ligament reconstruction a prospective, randomized, single-blinded clinical trial. Am J Sports Med 38(1):25–34

[5] Arbes S, Resinger C, Vécsei V, Nau T (2007) The functional outcome of total tears of the anterior cruciate ligament (ACL) in the skeletally immature patient. Int Orthop 31(4):471–475

[6] Christino MA, Vopat BG, Waryasz GR, Mayer A, Reinert SE, Shalvoy RM (2014) Adolescent differences in knee stability following computer-assisted anterior cruciate ligament reconstruction. Orthop Rev (Pavia) 6(4):5653

[7] Isberg J, Faxèn E, Brandsson S, Eriksson BI, Kärrholm J, Karlsson J (2006) KT-1000 records smaller side-to-side differences than radiostereometric analysis before and after an ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 14(6):529–535

[8] Sernert N, Kartus J, Kohler K, Ejerhed L, Karlsson J (2001) Evaluation of the reproducibility of the KT-1000 arthrometer. Scand J Med Sci Sport 11(2):120–125

[9] Myrer JW, Schulthies SS, Fellingham GW (1996) Relative and absolute reliability of the KT-2000 arthrometer for uninjured knees. Am J Sports Med 24(1):104–108

[10] Paine R, Lowe W (2012) Comparison of Kneelax and KT-1000 knee ligament arthrometers. J Knee Surg 25(2):151–154

[11] Balasch H, Schiller M, Friebel H, Hoffmann F (1999) Evaluation of anterior knee joint instability with the Rolimeter. Knee Surg Sports Traumatol Arthrosc 7(4):204–208

[12] Sørensen OG, Larsen K, Jakobsen BW, Kold S, Hansen TB, Lind M, Søballe K (2011) The combination of radiostereometric analysis and the Telos stress device results in poor precision for knee laxity measurements after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19(3):355–362

[13] Araki D, Kuroda R, Kubo S, Nagamune K, Hoshino Y, Nishimoto K, Takayama K, Matsushita T, Tei K, Yamaguchi M, Kurosaka M (2011) The use of an electromagnetic measurement system for anterior tibial displacement during the Lachman test. Arthroscopy 27(6):792–802

[14] Knoop J, Dekker J, Klein JP, Van Der Leeden M, Van Der Esch M, Reiding D, Voorneman RE, Gerritsen M, Roorda LD, Steultjens MP, Lems WF (2012) Biomechanical factors and physical examination findings in osteoarthritis of the knee: associations with tissue abnormalities assessed by conventional radiography and high-resolution 3.0 tesla magnetic resonance imaging. Arthritis Res Ther 14(5):1

[15] Miyazaki T, Uchida K, Wada M, Sato M, Sugita D, Shimada S, Baba H (2012) Anteroposterior and varus–valgus laxity of the knee increase after stair climbing in patients with mild osteoarthritis. Rheumatol Int 32(9):2823–2828

[16] Vauhnik R, Morrissey MC, Rutherford OM, Turk Z, Pilih IA, Pohar M (2008) Knee anterior laxity: a risk factor for traumatic knee injury among sports women? Knee Surg Sports Traumatol Arthrosc 16(9):823–833

[17] Myer GD, Ford KR, Paterno MV, Nick TG, Hewett TE (2008) The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. Am J Sports Med 36(6):1073–1080

[18] Ramesh R, Von Arx O, Azzopardi T, Schranz P (2005) The risk of anterior cruciate ligament rupture with generalised joint laxity. J Bone Joint Surg Br 87(6):800–803

[19] Wells GA, Shea B, O'Connell D et al (2004) The Newcastle- Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in metaanalyses. http://www.ohri.ca/programs/clinical_epidemiology/oxford.htm. Accessed 6 Oct 2016

[20] Chen J, Gu A, Jiang H, Zhang W, Yu X (2015) A comparison of acute and chronic anterior cruciate ligament reconstruction using lars artificial ligaments: a randomized prospective study with a 5-year follow-up. Arch Orthop Trauma Surg 135(1):95–102

[21] Zaffagnini S, Grassi A, Muccioli GM, Tsapralis K, Ricci M, Bragonzoni L, Della Villa S, Marcacci M (2014) Return to sport after anterior cruciate ligament reconstruction in professional soccer players. Knee 21(3):731–735

[22] Guo L, Yang L, Duan XJ, He R, Chen GX, Wang FY, Zhang Y (2012) Anterior cruciate ligament reconstruction with bone- patellar tendon-bone graft: comparison of autograft, fresh-frozen allograft, and γ-irradiated allograft. Arthroscopy 28(2):211–217

[23] Laoruengthana A, Pattayakorn S, Chotanaputhi T, Kosiyatrakul A (2009) Clinical comparison between six-strand hamstring tendon and patellar tendon autograft in arthroscopic anterior cruciate ligament reconstruction: a prospective, randomized clinical trial. J Med Assoc Thail 92(4):491

[24] Zhao J, He Y, Wang J (2007) Double-bundle anterior cruciate ligament reconstruction: four versus eight strands of hamstring tendon graft. Arthroscopy 23(7):766–770

[25] Ghalayini S, Helm A, Bonshahi A, Lavender A, Johnson D, Smith R (2010) Arthroscopic anterior cruciate ligament surgery: results of autogenous patellar tendon graft versus the

Leeds-Keio synthetic graft: five year follow-up of a prospective randomised controlled trial. Knee 17(5):334–339

[26] Mutsuzaki H, Kanamori A, Ikeda K, Hioki S, Kinugasa T, Sakane M (2012) Effect of calcium phosphate–hybridized tendon graft in anterior cruciate ligament reconstruction a randomized controlled trial. Am J Sports Med 40(8):1772–1780

[27] Porter MD, Shadbolt B (2016) Femoral aperture fixation improves anterior cruciate ligament graft function when added to cortical suspensory fixation an in vivo computer navigation study. Orthop J Sports Med 4(9):2325967116665795

[28] Ghodadra NS, Mall NA, Grumet R, Sherman SL, Kirk S, Provencher MT, Bach BR (2012) Interval arthrometric comparison of anterior cruciate ligament reconstruction using bone–patellar tendon–bone autograft versus allograft do grafts attenuate within the first year postoperatively? Am J Sports Med 40(6):1347–1354

[29] Price R, Stoney J, Brown G (2010) Prospective randomized comparison of endobutton versus cross-pin femoral fixation in hamstring anterior cruciate ligament reconstruction with 2-year follow-up. ANZ J Surg 80(3):162–165

[30] Pugh L, Mascarenhas R, Arneja S, Chin PY, Leith JM (2009) Current concepts in instrumented knee-laxity testing. Am J Sports Med 37(1):199–210

[31] Rose T, Hepp P, Venus J, Stockmar C, Josten C, Lill H (2006) Prospective randomized clinical comparison of femoral transfixation versus bioscrew fixation in hamstring tendon ACL reconstruction: a preliminary report. Knee Surg Sports Traumatol Arthrosc 14(8):730–738

[32] Sandon A, Werner S, Forssblad M (2015) Factors associated with returning to football after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(9):2514–2521

[33] Lin H, Hsu H, Chang C, Lai W (2009) Analyzing anterior knee laxity with an arthrometer for assisting diagnosis of anterior cruciate ligament rupture. In: IEEE 35th annual northeast bioengineering conference. IEEE, pp 1–2

[34] Sernert N, Helmers J, Kartus C, Ejerhed L, Kartus J (2007) Kneelaxity measurements examined by a left-hand-and a right-handdominant physiotherapist, in patients with anterior cruciate ligament injuries and healthy controls. Knee Surg Sports Traumatol Arthrosc 15(10):1181–1186

[35] Ahldén M, Sernert N, Karlsson J, Kartus J (2012) Outcome of anterior cruciate ligament reconstruction with emphasis on sexrelated differences. Scand J Med Sci Sports 22(5):618–626

[36] Lindström M, Strandberg S, Wredmark T, Felländer-Tsai L, Henriksson M (2013) Functional and muscle morphometric effects of ACL reconstruction: A prospective CT study with 1 year followup. Scand J Med Sci Sports 23(4):431–442

[37] Teitsma XM, van der Hoeven H, Tamminga R, de Bie RA (2014) Impact of patient sex on clinical outcomes data from an anterior cruciate ligament reconstruction registry, 2008–2013. Orthop J Sports Med 2(9):2325967114550638

[38] Ahldén M, Sernert N, Karlsson J, Kartus J (2013) A prospective randomized study comparing double-and single-bundle techniques for anterior cruciate ligament reconstruction. Am J Sports Med 41(11):2484-91

[39] Gobbi A, Mahajan V, Karnatzikos G, Nakamura N (2012) Singleversus double-bundle ACL reconstruction: is there any difference in stability and function at 3-year followup? Clin Orthop Relat Res 470(3):824–834

[40] Gong X, Jiang D, Wang YJ, Wang J, Ao YF, Yu JK (2013) Second- look arthroscopic evaluation of chondral lesions after isolated anterior cruciate ligament reconstruction single-versus doublebundle reconstruction. Am J Sports Med 41(10):2362–2367

[41] Hofbauer M, Valentin P, Kdolsky R, Ostermann R, Graf A, Figl M, Aldrian S (2010) Rotational and translational laxity after computer-navigated single-and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18(9):1201–1207

[42] Järvelä T, Moisala AS, Paakkala T, Paakkala A (2008) Tunnel enlargement after double-bundle anterior cruciate ligament reconstruction: a prospective, randomized study. Arthroscopy 24(12):1349–1357

[43] Kanaya A, Ochi M, Deie M, Adachi N, Nishimori M, Nakamae A (2009) Intraoperative evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament reconstruction: lower femoral tunnel placed single-bundle versus double-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 17(8):907–913

[44] Lao ML, Chen JH, Wang CJ, Siu KK (2013) Functional outcomes of y-graft double-bundle and single-bundle anterior cruciate ligament reconstruction of the knee. Arthroscopy 29(9):1525–1532

[45] Lee S, Kim H, Jang J, Seong SC, Lee MC (2012) Comparison of anterior and rotatory laxity using navigation between single-and double-bundle ACL reconstruction: prospective randomized trial. Knee Surg Sports Traumatol Arthrosc 20(4):752–761

[46] Monaco E, Labianca L, Conteduca F, De Carli A, Ferretti A (2007) Double bundle or single bundle plus extraarticular tenodesis in ACL reconstruction? a CAOS study. Knee Surg Sports Traumatol Arthrosc 15(10):1168–1174

[47] Ohkawa S, Adachi N, Deie M, Nakamae A, Nakasa T, Ochi M (2012) The relationship of anterior and rotatory laxity between surgical navigation and clinical outcome after ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 20(4):778–784

[48] Park SJ, Jung YB, Jung HJ, Jung HJ, Shin HK, Kim E, Song KS, Kim GS, Cheon HY, Kim S (2010) Outcome of arthroscopic single-bundle versus double-bundle reconstruction

of the anterior cruciate ligament: a preliminary 2-year prospective study. Arthroscopy 26(5):630–636

[49] Streich NA, Friedrich K, Gotterbarm T, Schmitt H (2008) Reconstruction of the ACL with a semitendinosus tendon graft: a prospective randomized single blinded comparison of double-bundle versus single-bundle technique in male athletes. Knee Surg Sports Traumatol Arthrosc 16(3):232–238

[50] Ventura A, Legnani C, Terzaghi C, Borgo E (2012) Singleand double-bundle anterior cruciate ligament reconstruction in patients aged over 50 years. Arthroscopy 28(11):1702–1709

[51] Jiang D, Ao YF, Gong X, Wang YJ, Luo H, Chen LX, Wang HJ, Xie X, Zhang JY, Yu JK (2012) Double-bundle anterior cruciate ligament reconstruction using bone–patellar tendon–bone allograft technique and 2- to 5-year follow-up. Am J Sports Med 40(5):1084–1092

[52] Zhang Q, Zhang S, Li R, Liu Y, Cao X (2007) Comparison of two methods of femoral tunnel preparation in single-bundle anterior cruciate ligament reconstruction: a prospective randomized study. Acta Cir Bras 27(8):572–576

[53] Edgar CM, Zimmer S, Kakar S, Jones H, Schepsis AA (2008) Prospective comparison of auto and allograft hamstring tendon constructs for ACL reconstruction. Clin Orthop Relat Res 466(9):2238–2246

[54] Sun K, Zhang J, Wang Y, Xia C, Zhang C, Yu T, Tian S (2011) Arthroscopic anterior cruciate ligament reconstruction with at least 2.5 years' follow-up comparing hamstring tendon autograft and irradiated allograft. Arthroscopy 27(9):1195–1202

[55] Tian S, Wang B, Liu L, Wang Y, Ha C, Li Q, Yang X, Sun K (2016) Irradiated hamstring tendon allograft versus autograft for anatomic double-bundle anterior cruciate ligament reconstruction midterm clinical outcomes. Am J Sports Med 44(10):2579–2588

[56] Noh JH, Yi SR, Song SJ, Kim SW, Kim W (2011) Comparison between hamstring autograft and free tendon achilles allograft: minimum 2-year follow-up after anterior cruciate ligament reconstruction using endobutton and intrafix. Knee Surg Sports Traumatol Arthrosc 19(5):816–822

[57] Laxdal G, Sernert N, Ejerhed L, Karlsson J, Kartus JT (2007) A prospective comparison of bone–patellar tendon–bone and hamstring tendon grafts for anterior cruciate ligament reconstruction in male patients. Knee Surg Sports Traumatol Arthrosc 15(2):115–125

[58] Zouita Ben Moussa A, Zouita S, Dziri C, Ben Salah FZ (2009) Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. Ann Phys Rehabil Med 52(6):475–484

[59] Svensson M, Sernert N, Ejerhed L, Karlsson J, Kartus JT (2006) A prospective comparison of bone–patellar tendon–bone and hamstring grafts for anterior cruciate ligament reconstruction in female patients. Knee Surg Sports Traumatol Arthrosc 14(3):278–286

[60] Dejour D, Vanconcelos W, Bonin N, Saggin PRF (2013) Comparative study between mono-bundle bone-patellar tendon-bone, double-bundle hamstring and mono-bundle bone-patellar tendon-bone combined with a modified lemaire extra-articular procedure in anterior cruciate ligament reconstruction. Int Orthop 37(2):193–199

[61] Park SY, Oh H, Park SW, Lee JH, Lee SH, Yoon KH (2012) Clinical outcomes of remnant-preserving augmentation versus doublebundle reconstruction in the anterior cruciate ligament reconstruction. Arthroscopy 28(12):1833–1841

[62] Zhang Z, Gu B, Zhu W, Zhu L, Li Q, Du Y (2013) Arthroscopic single-bundle versus triple-bundle anterior cruciate ligament reconstruction. Acta Orthop Traumatol Turc 48(4):413–418

[63] Lee JK, Lee S, Lee MC (2016) Outcomes of anatomic anterior cruciate ligament reconstruction: bone-quadriceps tendon graft versus double-bundle hamstring tendon graft. Am J Sports Med 44(9):2323–2329

[64] de Pádua VBC, Maldonado H, Vilela JCR, Provenza AR, Monteiro C, de Oliveira Neto HC (2012) Comparative study of ACL reconstruction with anatomical positioning of the tunnels using the patellar tendon versus hamstring tendon. Rev Bras Ortop 47(1):50–56

[65] Chouteau J, Benareau I, Testa R, Fessy MH, Lerat JL, Moyen B (2008) Comparative study of knee anterior cruciate ligament reconstruction with or without fluoroscopic assistance: a prospective study of 73 cases. Arch Orthop Trauma Surg 128(9):945–950

[66] Fleming BC, Fadale PD, Hulstyn MJ, Shalvoy RM, Oksendahl HL, Badger GJ, Tung GA (2012) The effect of initial graft tension after anterior cruciate ligament reconstruction a randomized clinical trial with 36-month follow-up. Am J Sports Med 41(1):25–34

[67] Koga H, Muneta T, Yagishita K, Ju YJ, Sekiya I (2012) The effect of graft fixation angles on anteroposterior and rotational knee laxity in double-bundle anterior cruciate ligament reconstruction evaluation using computerized navigation. Am J Sports Med 40(3):615–623

[68] Plaweski S, Cazal J, Rosell P, Merloz P (2006) Anterior cruciate ligament reconstruction using navigation a comparative study on 60 patients. Am J Sports Med 34(4):542–552

[69] Stener S, Ejerhed L, Sernert N, Laxdal G, Rostgård-Christensen L, Kartus J (2010) A long-term, prospective, randomized study comparing biodegradable and metal interference screws in anterior cruciate ligament reconstruction surgery radiographic results and clinical outcome. Am J Sports Med 38(8):1598–1605

[70] Stengel D, Casper D, Bauwens K, Ekkernkamp A, Wich M (2009) Bioresorbable pins and interference screws for fixation of hamstring tendon grafts in anterior cruciate ligament reconstruction surgery a randomized controlled trial. Am J Sports Med 37(9):1692–1698

[71] Moisala AS, Järvelä T, Paakkala A, Paakkala T, Kannus P, Järvinen M (2008) Comparison of the bioabsorbable and metal screw fixation after ACL reconstruction with a

hamstring autograft in MRI and clinical outcome: a prospective randomized study. Knee Surg Sports Traumatol Arthrosc 16(12):1080–1086

[72] Laxdal G, Kartus J, Eriksson BI, Faxén E, Sernert N, Karlsson J (2006) Biodegradable and metallic interference screws in anterior cruciate ligament reconstruction surgery using hamstring tendon grafts prospective randomized study of radiographic results and clinical outcome. Am J Sports Med 34(10):1574–1580

[73] Harilainen A, Sandelin J (2009) A prospective comparison of 3 hamstring ACL fixation devices-rigidfix, bioscrew, and intrafixrandomized into 4 groups with 2 years of follow-up. Am J Sports Med 37(4):699–706

[74] Ho WP, Lee CH, Huang CH, Chen CH, Chuang TY (2014) Clinical results of hamstring autografts in anterior cruciate ligament reconstruction: a comparison of femoral knot/press-fit fixation and interference screw fixation. Arthroscopy 30(7):823–832

[75] Isberg J, Faxén E, Brandsson S, Eriksson BI, Kärrholm J, Karlsson J (2006) Early active extension after anterior cruciate ligament reconstruction does not result in increased laxity of the knee. Knee Surg Sports Traumatol Arthrosc 14(11):1108–1115

[76] Goradia VK, Grana WA, Pearson SE (2006) Factors associated with decreased muscle strength after anterior cruciate ligament reconstruction with hamstring tendon grafts. Arthroscopy 22(1):80-e1

[77] Ito Y, Deie M, Adachi N, Kobayashi K, Kanaya A, Miyamoto A, Nakasa T, Ochi M (2007) A prospective study of 3-day versus 2-week immobilization period after anterior cruciate ligament reconstruction. Knee 14(1):34–38

[78] Myer GD, Ford KR, Foss KDB, Rauh MJ, Paterno MV, Hewett TE (2014) A predictive model to estimate knee-abduction moment: implications for development of a clinically applicable patellofemoral pain screening tool in female athletes. J Athl Train 49(3):389–398

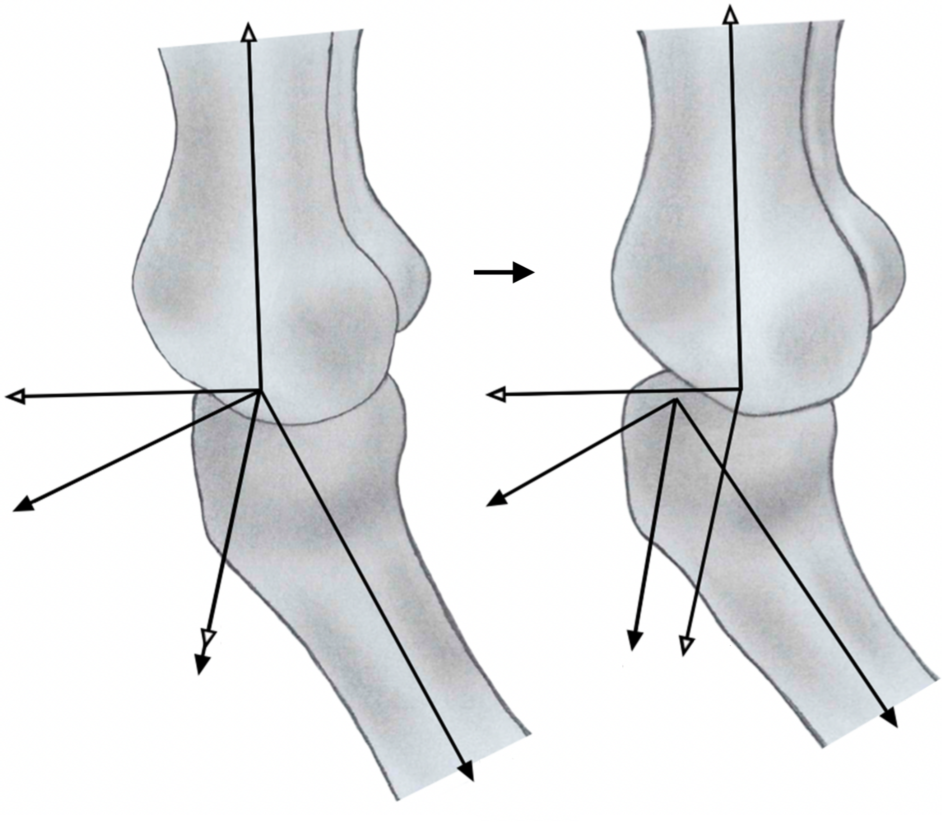
[79] Klyne DM, Keays SL, Bullock-Saxton JE, Newcombe PA (2012) The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: a study of alterations in emg measures and their relationship to knee joint stability. J Electromyogr Kinesiol 22(3):446–455

[80] Barcellona MG, Morrissey MC, Milligan P, Amis AA (2014) The effect of thigh muscle activity on anterior knee laxity in the uninjured and anterior cruciate ligament-injured knee. Knee Surg Sports Traumatol Arthrosc 22(11):2821–2829

[81] Kvist J (2005) Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sports 15(3):148–158

[82] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, Moewis P, Scheffler S, Taylor WR (2013) Anterior cruciate ligament-deficient patients with passive knee joint

laxity have a decreased range of anterior–posterior motion during active movements. Am J Sports Med 41(5):1051–1057



Chapter 4

Technical Note: Sensitivity Analysis of the SCoRE and SARA methods for Determining Rotational Axes during Tibiofemoral Movements using Optical Motion Capture

4

Michèle N.J. Keizer · Egbert Otten

Journal of Experimental Orthopaedics 2020;7(1):6
http://dx.doi.org/10.1186/s40634-020-0219-z

Highlights

- Transients in dynamic ATT less than 2.32 mm should be taken with caution
- Transients in dynamic ETR less than 1.70 degrees should be taken with caution
- The marker setup should be chosen carefully
- A marker setup with markers spread over the whole femur may give the best results

Abstract

Purpose: The first aim was to report the sensitivity of calculated tibiofemoral movements for the choice of placement of the set of femoral markers. The second aim was to report the influence of accuracy of the motion captured positions of the markers on the calculated tibiofemoral movements.
Methods: Tibiofemoral kinematics during single leg hops for distance were calculated. For the first aim, an experiment was conducted in which four different setups of the femoral markers were used to calculated tibiofemoral movements. For the second aim, an experiment was conducted in which all raw marker positions were mathematically moved independently with the known Vicon position error with a distance and in a random direction in each frame, repeated a hundred times. Each time, the tibiofemoral movements were calculated.
Results: The first experiment yields that the standard deviation of the calculated anterior tibia translation between marker setups was 0.88 mm and the standard deviation of the external tibia rotation between marker setups was 0.76 degrees. The second experiment yields that the standard deviation was 0.76 mm for anterior tibia translation and 0.38 degrees for external tibia rotation.
Conclusion: A combined standard deviation of both experiments revealed that transients in anterior tibia translation less than 2.32 mm and external tibia rotations less than 1.70 degrees should be taken with caution. These results are 19.42% of the range of the anterior tibia translation and 13.51% of the rotation range during the jump task. The marker setup should be chosen carefully.

Keywords Functional axis of rotation, knee laxity, tibia translation, tibia rotation

Introduction

Hip centers and knee rotation axes can be calculated using a three-dimensional motion capture system. There are various methods to estimate the joint center of rotation and axis of rotation (i.e. [7, 8, 12, 16]). In this technical note the symmetrical center of rotation estimation (SCoRE) [9] and the symmetrical axes of rotation approach (SARA) [10] which are implemented in the software of the motion capture system Vicon (VICON Motion Systems Ltd, Oxford, UK) are investigated. Since the combination of these two methods can be used to calculate tibiofemoral movements [5] and are now easily available it makes sense to test its accuracy, which has not be done before. Being able to calculate these movements in demanding in vivo tasks may be of high interest in anterior cruciate ligament injury and reconstruction research. Currently in ACL research passive tibiofemoral movements are highly investigated, for example to compare surgical technics [1, 3] or to compare the results of non-copers with copers [4, 24]. However, it is found in literature that there is no correlation between passive and active anterior tibia translation [13, 25]. To be able to evaluate the functional highly significant dynamic movement, such a method is very useful.

To calculate tibiofemoral movements, first the optimal common shape technique (OCST) should be performed [26]. Using the OCST, the markers on each segment are virtually replaced so that the markers of each segment act as a rigid body: the mutual distances between the markers do not chance over time. Based on the OCST markers, two coinciding points of rotation can be reconstructed in the knee using the SARA method. These points are estimated using dynamic calibration frames of a knee flexion-extension movement. One of these coinciding points is fixed in the rigid body of the tibia segment ($SARAtib$) and one in the rigid body of the femur segment ($SARAfem$) (Figure 1.A). In addition, based on the OCST markers, two centers of the knee (knee joint centers), one fixed in the rigid body of the tibia ($SCoREtib$) and one fixed in the rigid body of the femur ($SCoREtib$), can be calculated by the SCoRE method. Using these SARA and SCoRE data, two axes of rotation can be reconstructed in the knee, one in the tibia segment ($AXtib$) and one in the femur segment ($AXfem$). Moreover, based on the OCST markers, the point of rotation in the hip (hip joint center) can be calculated by the SCoRE method using dynamic calibration frames of a star-arc movement. For the mathematical model of these methods, see Ehrig et al. [9] and Ehrig et al. [10]. The dynamic translation and rotation of $AXtib$ relative to $AXfem$ estimate the tibiofemoral movements (Figure 1.B).

The reliability of the SCoRE and SARA methods including their application by Boeth et al. [5] have been studied several times [8, 18, 28, 27]. A high reliability (Intraclass correlation coefficient > 0.8) and no significant differences between five different observers who placed the marker set and between measure days was found in functional femur and tibia length (distances between the centers of the axis of rotation and the hip center or ankle center) calculated based on the SCoRE and SARA methods [27]. It was also reported that SARA showed a better inter-trial consistency of locations of the axis of rotation; however, worse consistency of the orientations of the axis of rotation compared to geometry-based axes while performing isokinetic knee flexion-extension [28]. Differences in ETR relative to the femur between using SARA and fluoroscopic (invasive) techniques were reported between 5.7 and 9.6 degrees [18]. A correction equation led to a sum of the root mean square error of between 0.6 and 0.8 degrees for the SARA method [18]. In addition, De Rosario et al. [8] presented a mathematical model of soft tissue artefacts propagation to the position and direction of variable and fixed axes as calculated by three methods. One of these methods was the SARA method. They reported that SARA, measured in one subject, showed an absolute difference in position error of the measured and estimated axes of rotation of 6.3 mm and no method was superior to another. However, their marker setup was atypical: markers were placed relatively close to the knee.

A few studies have been published using the SCoRE and/or SARA method for research [5, 12, 16, 19, 22]. In the these studies, systematic errors could have been introduced. No studies are published on the influences of markers placements and measuring errors of the motion capture system on calculated tibiofemoral movements. The aims of the experiments in this technical note were to:

1. determine the sensitivity of the calculated tibiofemoral movements for the choice of the placement of the set of femoral markers.

2. determine the sensitivity of the calculated tibiofemoral movements for the errors in the captured positions of the Vicon markers found in previous research.

Method

Data

Tibiofemoral kinematics during a single leg hop for distance of one healthy subject (woman, 23 years old) were calculated using the SCoRE and SARA methods implemented in Nexus 2 of a Vicon system (10-camera, VICON MX-F40; VICON Motion Systems Ltd, Oxford, UK) in a lab of 5 by 10 meter and 3 meter high. The single leg hop for distance is used as the impact on the knee is greater than in common motion analysis experiments (gait, stair-ascending) and consequentially the sudden transla-

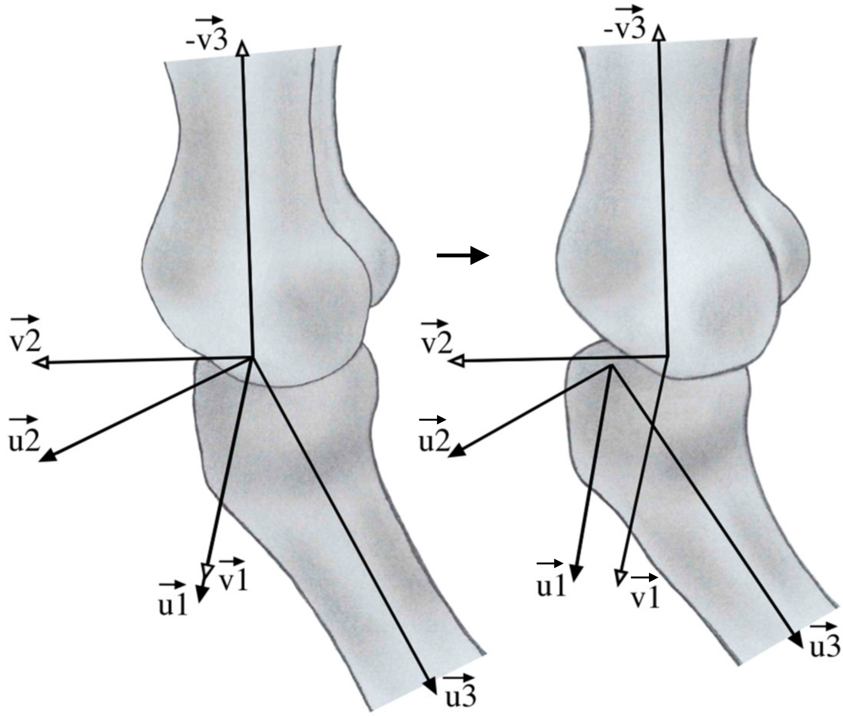


Fig. 1 Coordination systems in the femur and tibia. Both coordination systems of the tibia and femur based on the SCoRE and SARA data. u1: the axis of rotation fixed in the tibia system; v1: the axis of rotation fixed in the femur system; u2 and v2: the cross product of the first and third axes; v3: vector from the center of rotation of the femur to the center of rotation of the hip; u3: vector from the center of rotation of the tibia to the center of the ankle. A) Coinciding axis of rotation and therefore no anterior tibia translation. B) Anterior translation and external rotation of the tibia.

tions and rotations are believed to be greater. The sample frequency was 100Hz for each of the markers.

To be able to estimate the center of the hip, calibration frames of a star-arc movement of the tested leg were captured. To be able to estimate the coinciding rotation axes in the knee, calibration frames of an open kinetic flexion-extension movement with the tested leg raised from the ground was captured. Then, the subject performed six hops for distance with her preferred leg which was the left one. Markers were placed by the first author as shown in Figure 2, adapted from Boeth et al. [5]. The motion capture of the hops were subsequently used to calculate the tibiofemoral movements with the method described in the next section.

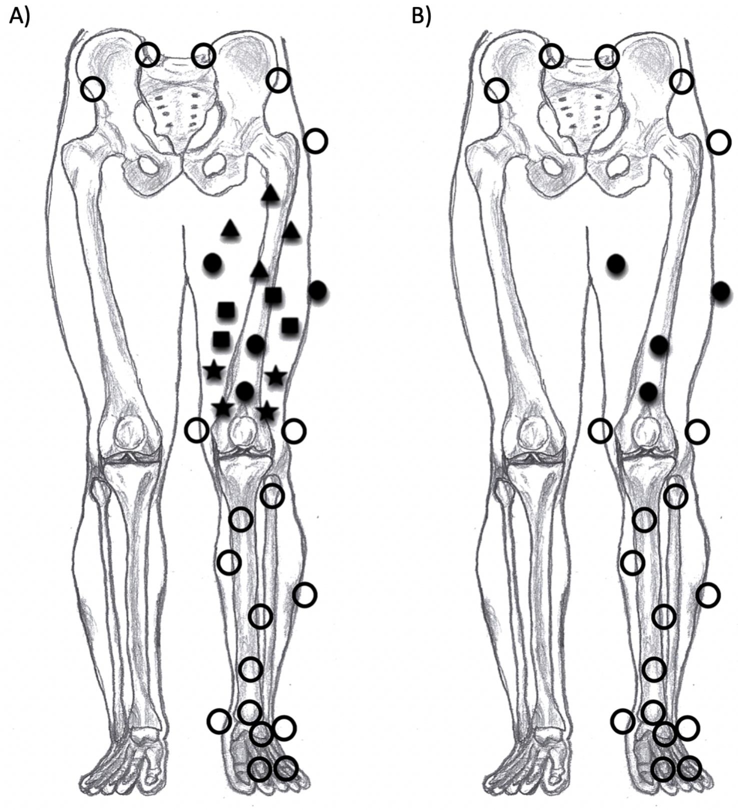


Fig. 2 Marker setup. Marker setup of experiment 1 and 2. For both experiments, markers were attached on the right and left anterior and posterior superior iliac spine, greater trochanter, medial and lateral epicondyle of the femur, medial and lateral malleoli of the ankle; the heel; anterior on the proximal foot; and the first and fifth metatarsophalangeal joints. In addition, six additional markers were attached to the tibia. A) For experiment 1, sixteen additional markers were attached to the femur (four groups of four additional markers; the black filled markers with different shapes). B) For experiment 2, four additional femur markers were attached (filled black markers)

Computations of tibiofemoral movements

In order to compute tibiofemoral movements, based on the method of Boeth et al. (2013), first OCST markers of all raw markers were calculated. Then, two coordinate systems were set up using a customized MATLAB (version 9.5, The MathWorks Inc., Natick, Massachusetts) script: one coordinate system in the femoral segment (parent system) and one in the tibia segment (child system). The first axes (u_1 and v_1) of both coordinate systems were calculated from the normalized axis of rotation of the corresponding segment calculated by the SCoRE and SARA methods (Figure 1). The centers of these axes (centers of rotation; u_{1c} and v_{1c}) were calculated by projecting the mean OCST corrected medial and lateral epicondyle markers on the rotation axes and were defined as the origin of the coordinate systems. The third axis of the tibia segment (u_3) was the normalised vector from the center of rotation of the tibia (u_{1c}) to the mean OCST corrected malleoli markers. The direction of this axis was changed to the opposite direction to make the system righthanded. The third axis of the femur segment (v_3) was the normalized vector from the center of rotation of the femur to the center of rotation of the hip. The second axis of both coordinate systems (u_2 and v_2) were reconstructed by taking the cross product of the first and third axes of the coordinate systems. Hereafter, the coordinate systems were made orthogonal by another cross product of the first and second axes. In this way the direction of the first axis remains unchanged.

The coordinate systems U and V were defined from the collection of unit vectors u_1, u_2, u_3 and v_1, v_2, v_3 in their columns. The transpose of V and U were the rotation matrices of tibia and femur system (see equations (4.1) and (4.2)). The rotation matrix from the tibia system to the femur system can be calculated from these two matrices (equation (4.3)). The femoral translation relative to the tibia is expressed in equation (4.4). The euler rotation angles are given in equations (4.5), (4.6) and (4.7) of the supplementary material, in which the indices represent the positions in the matrices (columns, rows). These euler angles are computed using the equations from Robertson [23]. The inverted femoral translation and the euler rotation angles relative to the tibia estimate the motion of the tibia relative to the femur.

$$M_{Tib} = U^T \tag{4.1}$$

$$M_{Fem} = V^T \tag{4.2}$$

$$M_{TibFem} = M_{Tib} * M_{Fem}^T \tag{4.3}$$

$$Tr = M_{Tib} * (u_{1c} - v_{1c}) \tag{4.4}$$

4

$$\alpha = \operatorname{arctan2}\left(-M_{TibFem(3,2)}, M_{TibFem(3,3)}\right) \tag{4.5}$$

$$\beta = \arctan\left(\frac{M_{TibFem(3,1)}}{\sqrt{{M_{TibFem(1,1)}}^2 + {M_{TibFem(2,1)}}^2}}\right) \tag{4.6}$$

$$\gamma = \arctan\left(\frac{-M_{TibFem(2,1)}}{M_{TibFem(1,1)}}\right) \tag{4.7}$$

Experiment 1: the sensitivity of the measured tibiofemoral movements depending on the placement of the set of markers

On top of three bony landmark markers on the femur, sixteen additional markers were physically attached to the upper leg. For each single leg hop for distance, calculations of tibiofemoral movements were performed four times using different groups of four additional femur markers on different heights of the femur: one group of proximal femur markers (the triangles in Figure 2.A), one group of markers in the middle of the femur (the squares in Figure 2.A), one group of distal femur markers (the stars in Figure 2.A), and one group of markers spread over the femur (the black filled circles in Figure 2.A). This to study the effect of soft tissue artefacts (wobbling masses) of the upper leg.

In addition, calculations were performed using all sixteen additional femur markers. The results of any set of four femur markers were compared to the results where all markers were used, as it is believed on the basis from observing soft tissue motion in high speed video footage that using more markers will average out more soft tissue artefacts. Moreover, there is no golden standard.

Experiment 2: the sensitivity of the measured tibiofemoral movements depending on Vicon's marker position errors

For this experiment the additional group of markers spread over the femur (shown in Figure 2.B) was used. A standard deviation of the position error of Vicon of 1.84 mm based on the error reported by Merriaux et al (2017) [17] with correction for our camera distance was used. The following two steps were performed 100 times for the same single leg hop:

1. All markers (raw data) were mathematically moved. For this, in each frame all markers were randomly displaced in a random direction. A normal distribution with a standard deviation of 1.84 mm was used as the amount of displacement and direction for each marker.

2. Each time, after displacement of the markers tibiofemoral movements were calculated.

This procedure was repeated for each 6 single leg hops for distance.

Data analysis

For both experiments, the standard deviation of anterior tibia translation and external tibia rotation for each frame between the 4 marker setups or the 100 trails were the markers were moved was calculated. Then, the mean of this standard deviation over time and over the 6 single leg hops for distance was calculated.

Also, the maximal, minimal and range of anterior tibia translation and external tibia rotation was calculated for each frame. Then, the mean, maximal and minimal values of the range were calculated.

To determine the effect of both the Vicon's position errors and marker setup combined on the tibiofemoral movements, a combined standard deviation was calculated. For this only one single leg hop was used. The standard deviations of both experiments were squared and added together. Then, the square root of this value was calculated, which accounts for a combination of two standard deviations which have an independent origin.

Results and discussion

Experiment 1: the sensitivity of the measured tibiofemoral movements depending on the placement of the set of markers

The tibiofemoral movements resulting from the different marker groups have been depicted in Figure 3. For the range of the ATT and ETR between results obtained with the different marker sets see Table 1. The standard deviation of the calculated ATT, when using different marker setups, is 0.88 mm and for ETR 0.76 degrees. To compare this result with the measurements: for the condition where all markers were used, the range of the ATT over the whole hop was 11.97 mm and of the ETR 12.58 degrees. When different marker setups are used, calculated differences during transients in ATT of less than twice the standard deviation (1.76 mm) and ETR (1.52 degrees) should be taken with caution.

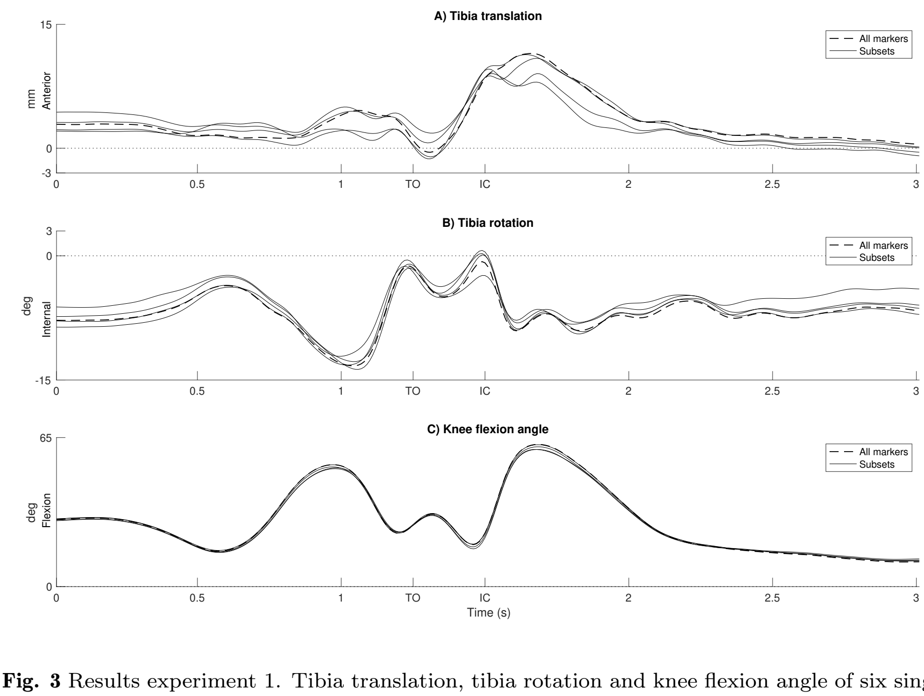


Fig. 3 Results experiment 1. Tibia translation, tibia rotation and knee flexion angle of six single leg hops for distance over time with the different lines being computations with four different groups of femoral markers. The black dotted line is the situation where all sixteen femur markers where used. TO: too off; IC: initial contact.

Table 1 The mean, maximal and minimal range in anterior tibia translation (ATT) and external tibia rotation (ETR) between the different conditions and the mean standard deviation over time. Experiment 1: the sensitivity for the marker placement. Experiment 2: the sensitivity for Vicon's position errors.

	Experiment 1		Experiment 2	
	ATT (mm)	ETR (deg)	ATT (mm)	ETR (deg)
Mean StD over time	0.88	0.76	0.76	0.38
Mean of the range	1.91	1.72	3.82	1.93
Max of the range	4.46	3.08	3.93	2.03
Min of the range	0.85	0.46	3.79	1.87

See Table 2 for the mean, maximal and minimal difference between the results of the different marker setups compared with the results of the marker setup where all markers where used. The tibiofemoral movements computed with the marker setup where the markers were spread over the femur (the black filled circles in Figure 2.A) is most similar to the situation where all markers where used. This may be due to the cancelation of movements of soft tissue relative to the bone when applying markers over the whole femur, while as when using markers for example only proximal and medial on the femur, soft tissue artefacts may result in greater errors because these markers tend to move more as one group.

Table 2 Mean, minimal and maximal absolute differences between the results of the different marker setups compared with the results of the marker setup where all markers where used. S1: proximal femur markers; S2: markers in the middle of the femur; S3: distal femur markers; S4: group of markers spread over the femur.

	S1		S2		S3		S4	
	ATT	ETR	ATT	ETR	ATT	ETR	ATT	ETR
Mean difference	1.09	1.38	1.31	0.34	0.9	0.43	0.35	0.71
Min difference	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.13
Max difference	4.17	2.63	3.66	1.08	2.35	1.43	1.45	1.52

These results imply that the marker setup should be chosen with care. We advise using a marker setup with markers spread over the femur (black filled circles in Figure 2.A) as in that case soft tissue artefacts may partly be canceled out.

Experiment 2: the sensitivity of the measured tibiofemoral movements depending on Vicon's marker position errors

The mean and standard deviation of the tibiofemoral movements and the knee flexion angle resulting from all 100 trials where markers were moved have been depicted in Figure 4. For the range of the tibiofemoral movements between the different trials see Table1. The standard deviation between trials of the computed ATT and ETR was 0.76 mm and 0.38 degrees respectively.

These results imply that the position error of Vicon results in an error of ATT of 1.5 mm and ETR of 0.76 degrees (twice the standard deviation).

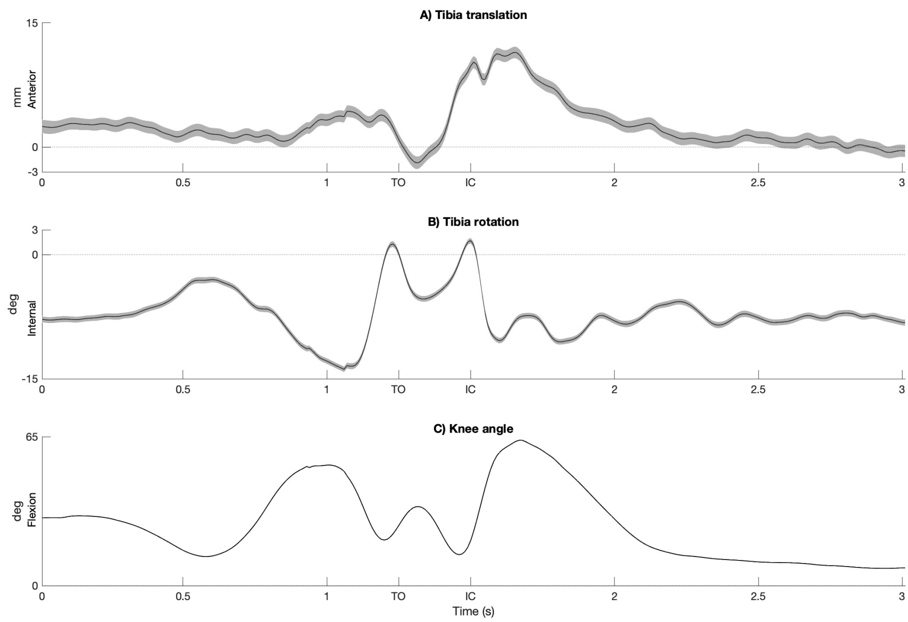


Fig. 4 Results experiment 2. Tibia translation, tibia rotation and knee flexion of one single leg hop for distance over time. The black line is the mean of all trails. The grey area is the standard deviations in tibia translation and rotation of the 100 trials when all marker, per trail, were moved in a random direction. TO: too off; IC: initial contact.

The sensitivity of the measured tibiofemoral movements depending on both the Vicon's marker position errors and the placement of the set of markers

To determine the combined effect of both the Vicon's position error and marker setup on the tibiofemoral movements, a combined standard deviation was calculated for one single leg hop for distance. For ATT this standard deviation was 1.16 mm and for ETR 0.85 degrees. The combination of the effect of the marker setup (wobbling masses) and Vicon's position error may result in an error in tibiofemoral movements of twice the standard deviation; which is for ATT 2.32 mm and for ETR 1.70 degrees. These results are 19.42% of the range of the anterior tibia translation and 13.51% of the rotation range.

Strong points and limitations

This is the first study which addresses the effects of the marker placement and Vicon's position error on the ATT and ETR in a high demanding dynamic situation. The effects of marker placements and Vicon's position error have been investigated [20, 21, 29]; however, as far as known to the authors no studies are published investigating those effects on tibiofemoral movements. A number of publications using the SCoRE and/or SARA method are relevant in light of such an investigation. The methods in the present sensitivity analysis and the ability to measure the ATT and ETR using such methods may be of high intrest in anterior cruciate ligament injury and reconstruction research, especially since the SCoRE and SARA methods are easily available.

Some possible limitations of this study need to be addressed. One possible limitation is that only one subject has been studied. The aim of this study was to observe the sensitivity of using different marker setups and the effect of Vicon's position errors on the outcome measures of interest. For this, only one subject could be used on which the necessary parameters could be varied. We have chosen a subject who is active in recreational sport activities with a BMI of 22.7. This choice was made since the subject is representative of the population in which an ACL injury occurs frequently [11]. An addition to this study may have been to study subjects with very low and very high BMI in terms of wobbling masses. A future study could investigate this.

A second limitation may be the relative low frequency of 100Hz in which the marker positions were captured. This may have introduced loss of interesting data. However, 100Hz is ample to capture the frequency content of human movements, even during collisions such as with the ground.

Another possible limitation is that no data of a golden standard to measure the ATT and ETR is available, like bi-planar fluoroscopy data. Previous studies found an absolute range of ATT using bi-planar fluoroscopy model-based data during running of +/- 10 mm [2] and +/- 25 mm [14]. The results of Anderst et al. [2] are comparable to our results (12 mm). However, bi-planar fluoroscopy itself has its limitations [14]. A lack of a golden standard makes it impossible to verify the outcomes of the methods developed by Boeth et al. [5]. However, given the method, the present study seeks to find the effects of marker placement and measurement errors on the produced outcome measures. The results of the current study gives interesting information on determining ATT and ETR using the VICON motion capture system in dynamic situations. Being able to measure the ATT and ETR in high demanding tasks is of high interest in knee ligament research, for example to compare results after two different types of anterior cruciate ligament reconstruction or the results after different rehabilitation programs.

Conclusion

Especially when different sets of markers are used, calculated differences in anterior tibia translation, i.e. between subjects, and transients of anterior tibia translations of less than 2.32 mm and of external tibia rotations of less than 1.70 degrees should be taken with caution. These results are 19.42% of the range of the anterior tibia translation and 13.51% of the rotation range. When using the SCoRE and SARA methods, the marker setup should be chosen carefully. We advise a marker setup with markers spread over the whole femur.

References

[1] Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N (2010) Comparison between single-and double-bundle anterior cruciate ligament reconstruction a prospective, randomized, single-blinded clinical trial. Am J Sports Med 38(1):25–34

[2] Anderst W, Zauel R, Bishop J, Demps E, Tashman S (2009) Validation of three-dimensional model-based tibio-femoral tracking during running. Med Eng Phys 31(1):10-16

[3] Arbes S, Resinger C, Vécsei V, Nau T (2007) The functional outcome of total tears of the anterior cruciate ligament (ACL) in the skeletally immature patient. Int Orthop 31(4):471–475

[4] Barrance PJ, Williams GN, Snyder-Mackler L, Buchanan TS (2007) Do ACL-injured copers exhibit differences in knee kinematics?: An MRI study. Clinical Orthopaedics and Related Research 454:74-80

[5] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, et al. (2013) Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. Am J Sports Med 41(5):1051-7

[6] Lin CC, Li JD, Lu TW, Kuo MY, Kuo CC, Hsu HC (2018) A model-based tracking method for measuring 3D dynamic joint motion using an alternating biplane x-ray imaging system. Medical physics, 45(8):3637-3649

[7] Colle F, Lopomo N, Visani A, Zaffagnini S, Marcacci M (2016) Comparison of three formal methods used to estimate the functional axis of rotation: an extensive in-vivo analysis performed on the knee joint. Comput Methods Biomech Biomed Engin 19(5):484-92

[8] De Rosario H, Page A, Besa A (2017) Analytical study of the effects of soft tissue artefacts on functional techniques to define axes of rotation. J Biomech 62:60-67

[9] Ehrig RM, Taylor WR, Duda GN, Heller MO (2006) A survey of formal methods for determining the centre of rotation of ball joints. J Biomech 39(15):2798-809

[10] Ehrig RM, Taylor WR, Duda GN, Heller MO (2007) A survey of formal methods for determining functional joint axes. J Biomech 40(10):2150-7

[11] Gianotti SM, Marshall SW, Hume PA, Bunt L (2009) Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. J Sci Med Sport 12(6):622-627

[12] Kratzenstein S, Kornaropoulos EI, Ehrig RM, Heller MO, Pöpplau BM, Taylor WR (2012) Effective marker placement for functional identification of the centre of rotation at the hip. Gait Posture 36(3):482-6

[13] Kvist J (2005) Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sports 15(3):148–58

[14] Lin CC. Li JD. Lu TW. Kuo MY. Kuo CC. Hsu HC (2018) A model-based tracking method for measuring 3D dynamic joint motion using an alternating biplane x-ray imaging system. Med phy 45(8):3637-3649

[15] Lopomo N, Sun L, Zaffagnini S, Giordano G, Safran MR (2010) Evaluation of formal methods in hip joint center assessment: an in vitro analysis. Clin Biomech (Bristol, Avon) 25(3):206-12

[16] Meireles S, De Groote F, Van Rossom S, Verschueren S, Jonkers I (2017) Differences in knee adduction moment between healthy subjects and patients with osteoarthritis depend on the knee axis definition. Gait Posture 53:104-109. Clin Biomech (Bristol, Avon) 25(3):206-12

[17] Merriaux P, Dupuis Y, Boutteau R, Vasseur P, Savatier X (2017) A study of vicon system positioning performance. Sensors (Switzerland) 53:104-109

[18] Moewis P, Boeth H, Heller MO, Yntema C, Jung T, Doyscher R, et al. (2014) Towards understanding knee joint laxity: Errors in non-invasive assessment of joint rotation can be corrected. Med Eng Phys 36(7):889-95

[19] Moewis P, Duda GN, Jung T, Heller MO, Boeth H, Kaptein B, et al. (2016) The restoration of passive rotational tibio-femoral laxity after anterior cruciate ligament reconstruction. PLoS One 11(7):e0159600

[20] Mok KM, Kristianslund EK, Krosshaug T (2015) The effect of thigh marker placement on knee valgus angles in vertical drop jumps and sidestep cutting. J Appl Biomech 31(4):269-274

[21] Osis ST, Hettinga BA, Macdonald S, Ferber R (2016) Effects of simulated marker placement deviations on running kinematics and evaluation of a morphometric-based placement feedback method. PloS one 11(1):e0147111

[22] Pfitzner T, Moewis P, Stein P, Boeth H, Trepczynski A, von Roth P, et al. (2018) Modifications of femoral component design in multi-radius total knee arthroplasty lead to higher lateral posterior femoro-tibial translation. Knee Surgery, Sport Traumatol Arthrosc 26(6):1645-1655

[23] Robertson G, Caldwell G, Hamill J, Kamen G, Whittlesy S (2013) Research methods in biomechanics, 2E. Hum. Kinet

[24] Snyder-Mackler L, Fitzgerald GK, Bartolozzi III, AR, Ciccotti MG (1997) The relationship between passive joint laxity and functional outcome after anterior cruciate ligament injury. The American Journal of Sports Medicine 25(2):191-195

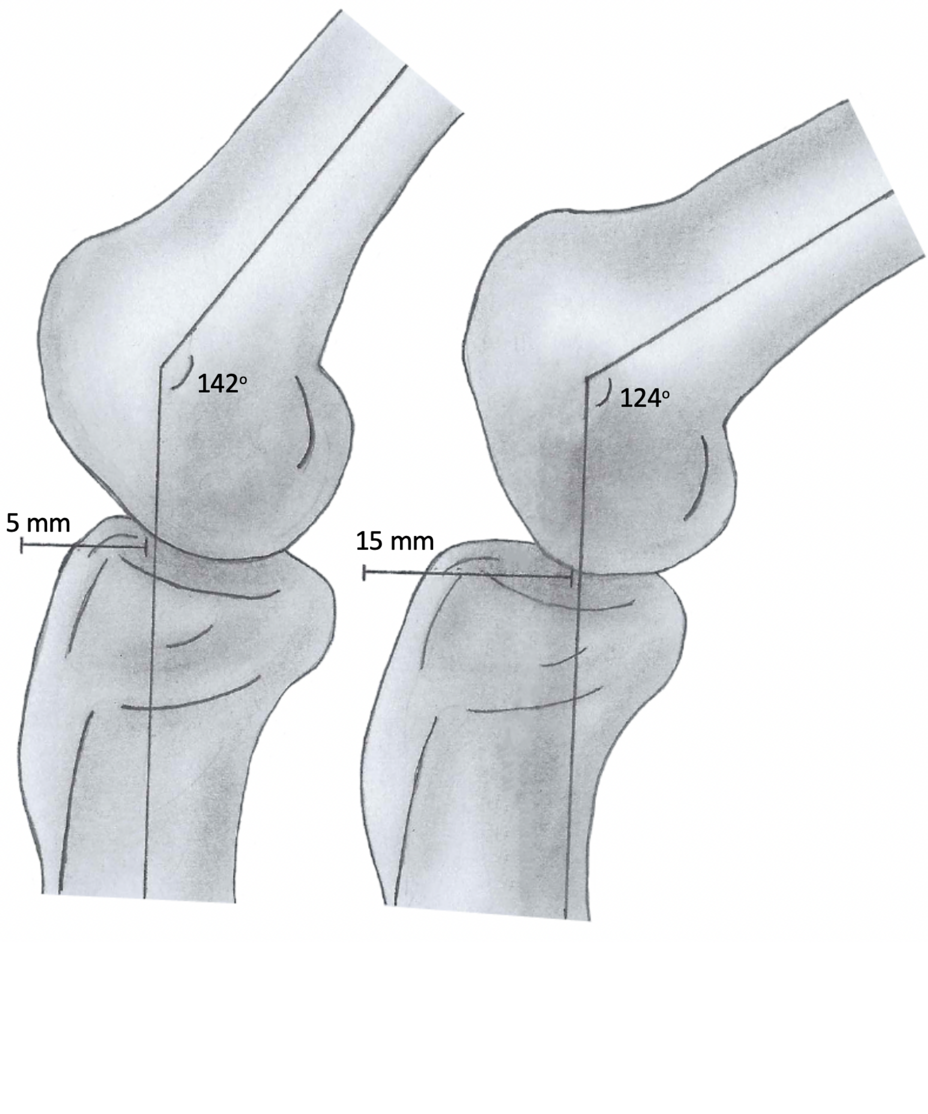
[25] Tagesson S, Öberg B, Kvist J (2015) Static and dynamic tibial translation before, 5 weeks after, and 5 years after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(12):3691–7

[26] Taylor WR, Ehrig RM, Duda GN, Schell H, Seebeck P, Heller MO (2005) On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res 23(4):726-34

[27] Taylor WR, Kornaropoulos EI, Duda GN, Kratzenstein S, Ehrig RM, Arampatzis A, et al. (2010) Repeatability and reproducibility of OSSCA, a functional approach for assessing the kinematics of the lower limb. Gait Posture 32(2):231-6

[28] Van Campen A, De Groote F, Bosmans L, Scheys L, Jonkers I, De Schutter J (2011) Functional knee axis based on isokinetic dynamometry data: Comparison of two methods, MRI validation, and effect on knee joint kinematics. J Biomech 13;44(15):2595-600

[29] Wen Y, Huang H, Yu Y, Zhang S, Yang J, Ao Y, Xia S (2018) Effect of tibia marker placement on knee joint kinematic analysis. Gait Posture 60:99-103


142°
5 mm
124°
15 mm

Chapter 5

Healthy Subjects with Lax Knees use Less Knee Flexion Rather than Muscle Control to Limit Anterior Tibia Translation during Landing

Michèle N.J. Keizer · Juha M. Hijmans · Alli Gokeler · Anne Benjaminse · Egbert Otten

5

Journal of Experimental Orthopaedics 2020;7(1):32
http://dx.doi.org/10.1186/s40634-020-00246-6

Highlights

- Participants with more passive knee laxity (ATTp) showed smaller dynamic laxity (ATTd)
- Muscle activation did not contribute in such a way that ATTd was limited at the observed knee angles
- Less knee flexion angle at impact is associated with larger ATTd

Abstract

Purpose: It has been reported that there is no correlation between anterior tibia translation (ATT) in passive and dynamic situations. Passive ATT (ATTp) may be different to dynamic ATT (ATTd) due to muscle activation patterns. This study aimed to investigate whether muscle activation during jumping can control ATT in healthy participants.
Methods: ATTp of twenty-one healthy participants was measured using a KT-1000 arthrometer. All participants performed single leg hops for distance during which ATTd, knee flexion angles and knee flexion moments were measured using a 3D motion capture system. During both tests, sEMG signals were recorded.
Results: A negative correlation was found between ATTp and the maximal ATTd ($r=-0.47$, $p=0.028$). An N-Way ANOVA showed that larger semitendinosus activity was seen when ATTd was larger, while less biceps femoris activity and rectus femoris activity were seen. Moreover, larger knee extension moment, knee flexion angle and ground reaction force in the anterior-posterior direction were seen when ATTd was larger.
Conclusion: Participants with more ATTp showed smaller ATTd during jump landing. Muscle activation did not contribute to reduce ATTd during impact of a jump-landing at the observed knee angles. However, subjects with large ATTp landed with less knee flexion and consequently showed less ATTd. The results of this study give information on how healthy people control knee laxity during jump-landing.

Level of Evidence: III

Keywords knee, knee laxity, muscle activity, motor control

Introduction

Passive anterior tibia translation (ATTp) is often studied in literature, for example in people with hypermobility [33], anterior cruciate ligament (ACL) injured patients [15], or after a total knee arthroplasty [14]. ATTp, however, only gives information about knee laxity in situations where muscle activation and extern forces are absent or minimal. People with large ATTp may compensate for knee laxity by using effective muscle activation patterns in dynamic tasks or by amending their kinematics and kinetics in such a way that anterior tibia translation is limited. Therefore, anterior tibia translation in dynamic situations (ATTd) may give new information additional to ATTp. This can also be suggested by the absence of correlation between ATTp and ATTd found during normal gait, active extension, heel raises, cycling, one-legged squat and chair squat [21, 34]. This absence of correlation may be due to the contribution of muscle activation patterns and external forces in a dynamic situation. Previous studies found a relation between ATTp and pre-activation of the muscles [20, 31, 32], and ATTp and hamstrings activity [3]. Computer models showed that simulated hamstrings activity reduces the ATTd [29], and also showed that muscle activation patterns influence ATTd.

To the best of our knowledge, in literature no information is available on whether there is an in vivo correlation between ATTd and muscle activation patterns and between ATTd and knee kinetics in healthy people. Such information will enlarge the knowledge about how healthy people control knee laxity and may give us valuable information for people with hypermobility, with knee injuries or for ACL injury prevention programs. Those people, especially when large ATTp is observed, may be able to learn effective muscle activation patterns and landing strategies to limit ATTd. The present study will add to the current literature insight into the control of ATTd by muscle recruitment, kinematics and kinetics during a jumping task in healthy people. The aims of this study were to investigate:

1. Whether there is a correlation between ATTd and ATTp. To verify whether the absence of correlation between ATTd and ATTp found in literature holds during jump landing.

2. Whether quadriceps, hamstrings, and gastrocnemius activity are correlated with ATTd.

3. Whether the knee flexion angle and knee flexion moment are correlated with ATTd.

We hypothesized that quadriceps activity will increase ATTd, and hamstrings and gastrocnemius activity will decrease ATTd due to their anatomical insertions and lever arms. Moreover, we hypothesized that landing with more flexed knees and larger knee flexion moment will increase ATTd

Methods

A study was conducted at the motion lab of the Department of Rehabilitation Medicine of the UMCG. The study design, procedure, and protocol are approved by the local Ethics Committee (ECB number: 2016.12.06.2 R2). All participants were informed about the procedures and the aim of the study by e-mail and signed an informed consent form.

Participants

Twenty-one healthy participants (13 women and 8 men) who participated in recreational team sports (see Table 1) at least twice a week, and in addition played a match at least once a week, were included in the study. Moreover, the participants had to be between 18 and 45 years of age. Participants with any history of knee trauma, previous lower limb surgery, or self-reported disorders of the leg were excluded (Table 2).

Table 1 Sports of the participants.

Sports	n
Football	10
Volleyball	3
Korfball	2
Hockey	5
Handball	1
Total	21

Table 2 Baseline characteristics

	Mean	Standard deviation	Range
Age (years)	21	2.48	18-26
Mass (kg)	71.7	8.32	60.7-91.3
Height (mm)	178.3	2.37	165-197.5
BMI (kg/m^2)	23.7	2.94	19.1-32.8
Hours of sport (a week)	5.9	2.37	3 – 13
Tested leg (right/left)	20/1		

Evaluation protocol

Each participant was measured in a single session. The passive test (condition 1) and the SLHD task (condition 2) were performed in a random order. The same researcher performed all procedures for every participant: electrode placements, marker placements and measurements.

First, sEMG-electrodes surface electromyographic (sEMG; Cometa Wave Plus Wireless sEMG system, Cisliano Milano, Italy) were attached according to SENIAM guidelines [26]. The skin was prepared by being shaved and cleaned with alcohol. All EMG-electrode pairs were placed along the length of the muscle fibers on the bulk of the muscles to reduce cross-talking [26]. For condition 1, the patterns of muscle activation were determined using the electrical signals of the medial hamstring (MH), lateral hamstring (LH), rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) using sEMG. The patterns of muscle activation of the gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) were not measured in condition 1 because of interference of the attachment of the KT-1000. For condition 2, the patterns of muscle activation were determined using the electrical signals of the MH, LH, RF, VM, VL, GM and GL. The sEMG signals were recorded at a sampling frequency of 1000Hz.

During condition 1 (passive), ATTp was measured using a KT-1000 arthrometer (MEDmetric Corp, San Diego, California, USA) at a force of 133N with the knee supported at approximately 30 degrees of flexion. The participants were laying supine and were instructed to relax their leg which the examiner verified by observing the sEMG recordings. This test was repeated three times and the average was taken.

For condition 2 (dynamic), retroreflective markers were attached to the tested leg, the dominant leg of the participant (the leg that the participant prefers to use when kicking a ball [25]). Markers were attached as shown in Figure 1 (adapted from Boeth et al. [6]). The 3D marker positions were measured with an 8-camera three-

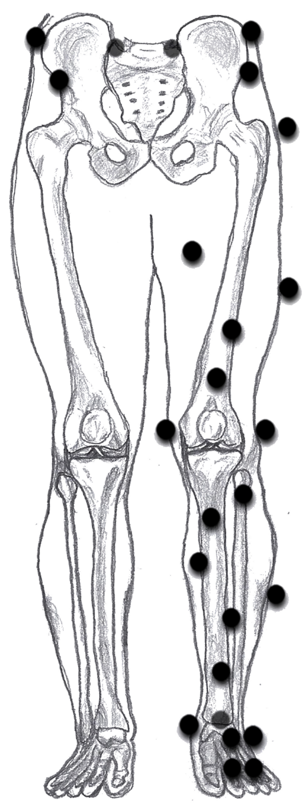


Fig. 1 Marker placement. Markers were attached on the right and left anterior and posterior superior iliac spine, the right and left iliac crest, the greater trochanter, the medial and lateral epicondyles of the knee, the medial and lateral malleoli of the ankle, the heel, anterior of the talus bone and the first and fifth metatarsophalangeal joints. Besides, two additional markers were attached to the pelvis, two to the thigh, and six additional markers were attached to the shank (adapted from Boeth et al. (2013) [6]).

dimensional motion capture system (VICON MX3+; VICON Motion Systems Ltd, Oxford, UK) at a frequency of 100Hz. After attaching markers, calibration frames of a flexion-extension movement and a star-arc movement, as prescribed by the manual of VICON, were performed to be able to identify the joint hip and knee centers and axes of rotation of the knee [8, 9]. Then, the participants performed SLHD wearing sports shoes and with their arms in free motion. First, three practice SLHD were performed. The participants started on their tested leg in a stationary posture and jumped as far as possible in a horizontal direction. The participants had to stand still on the same leg after landing for a minimum of three seconds. The distance of the furthest practice SLHD was used for the starting distance from the force plate. Next, ten successful SLHD were performed.

Data analysis

The data were processed using a customized MATLAB (version 9.4, The MathWorks Inc., Natick, Massachusetts) script. The 3D marker position data were filtered using a convolution filter with low pass frequency of 10Hz with zero lag, while gaps in the data of a maximum of 10 frames were filled with a quadratic spline interpolation. ATTd was determined based on a combination of the optimal common shape technique, symmetrical axis of rotation approach, and symmetrical center of rotation estimation combined [6]. For quantifications of ATTd and knee angles see Keizer and Otten [16]. It should be noted that results from this method should be taken with caution when transients are below 2.32 mm [16]. However, the intraclass correlation coefficient between observers who placed the markers is higher than 0.8 [36]. Knee flexion moment was calculated from the GRF vector and its lever arm to the center of the knee of the stance leg. ATTd, knee flexion angle, and knee flexion moment during each SLHD were determined for 1.5 seconds before the instant of first ground contact until 1.5 seconds after that instant. The time point of first ground contact was determined as the time where the vertical GRF on the force plate was at least five percent of the body weight.

Muscle activity around the instant of first ground contact, taking into account an electromechanical delay of 50 ms [4], was rectified and filtered using a fourth order low pass frequency Butterworth filter at 6 Hz with zero lag. Muscle activity was scaled to a percentage of the mean muscle activity during the SLHD for each participant to reduce the influence of body fat.

Statistical analysis

An a-priori power analysis based on the correlation between ATTp and ATTd of a healthy knees (contralateral knees of ACL injured patients; R2 = 0.34) [6], indicated that a total sample size of 18 participants would be required to achieve statistical significance at a 0.05 level with 80% power.

The data were analyzed using the Statistics Toolbox from MATLAB version 9.7 (The MathWorks Inc., Natick, Massachusetts). Pearson correlation analyses were performed between ATTp and maximal ATTd, and ATTp and range of ATTd.

In addition, an N-Way ANOVA was performed using a type II sum of squares and no interactions. For this analysis data from initial contact until 0.25 seconds after initial contact was used. The dependent variable was the ATTd and the independent variables were the activity of the independent muscles, the knee flexion angle, the knee extension moment and the ground reaction force rotated towards the tibia system in the medial-lateral and anterior-posterior direction. All variables were normalized to a scale of 0 to 1 by dividing their values by their maximal value during a session.

Correlations were considered to be significant with an alpha of < 0.05. If a correlation was significant, a correlation coefficient of 0.2-0.49, 0.5-0.79 and 0.8-1 were considered to represent a weak, a moderate and a strong association, respectively [13].

Results

Passive and dynamic ATT

The mean ATTp was 3.4 mm (range: 0.9-8.8 mm). During the passive test, no more muscle activity than noise was found in a flat background signal of the sEMG.

The ATTd for each participant is presented in Figure 2. A weak negative correlation was found between ATTp and maximal ATTd (r=-0.47, p=0.028; Figure 3A). No correlation was found between ATTp and the range of the anterior posterior tibia translation during jump landing (r=0.38, p=0.087; Figure 3B).

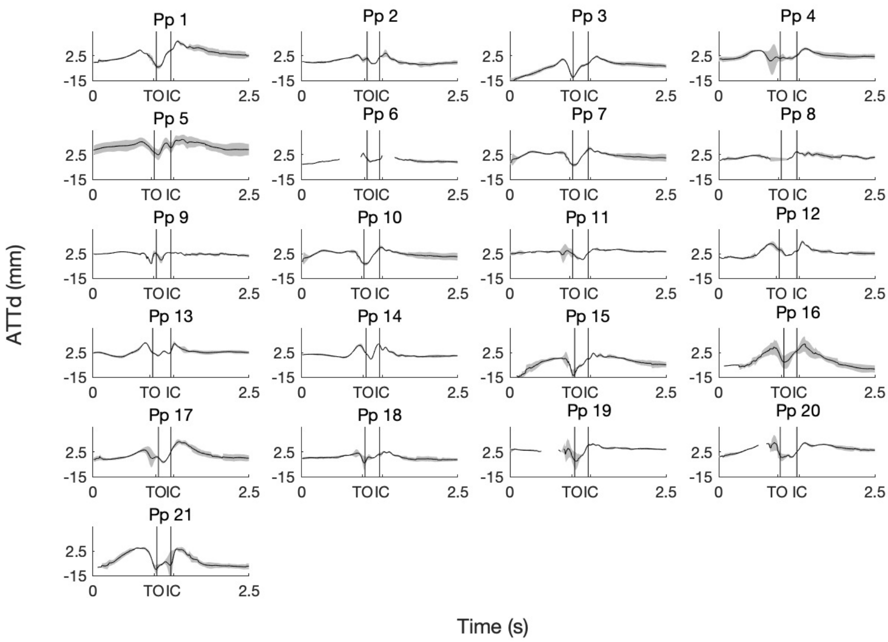


Fig. 2 Mean and standard deviations of the dynamic anterior tibia translation (ATTd) of ten trials of a single hop for distance of all participants (Pp). TO: toe-off; IC: initial ground contact.

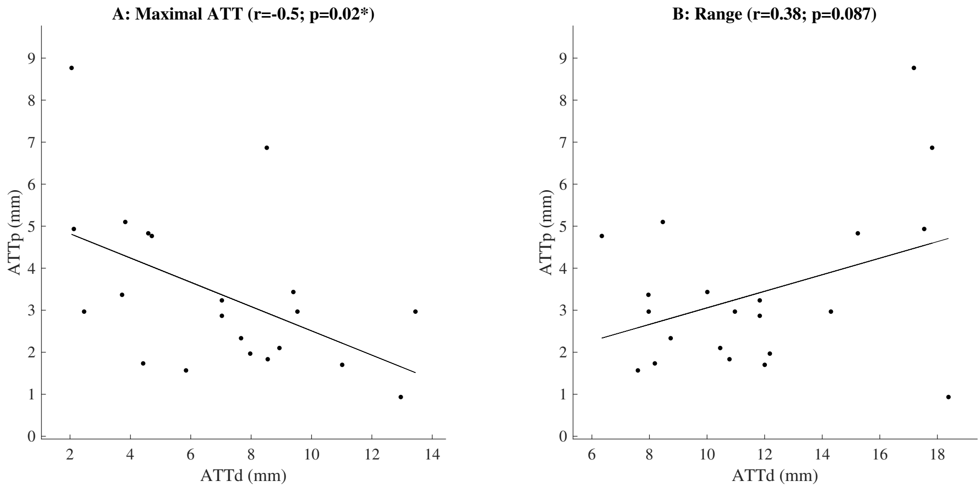


Fig. 3 Passive anterior tibia translation (ATTp; KT-1000 arthrometer) v.s. the maximal dynamic anterior tibia translation (ATTd) and the range of dynamic anterior posterior tibia translation during a single hop for distance; *: significant.

Control of ATT in a dynamic situation

In Table 3 the sum of squares, mean of squares, F-value, p-value and weight coefficients of the N-Way ANOVA are presented. The knee extension moment, knee flexion angle, GRFap, ST activity, BF activity and RF activity resulted in significant effects on ATTd.

Table 3 Sum of squares, degrees of freedom, mean squares, F-values, p-values and coefficient of the N-way ANOVA with the dependent variable being dynamic anterior tibia translation.

Variable	Sum of squares (type II)	d.f.	Mean squares	F	p-value	Weight coefficient
KM	49.3	1	49.26	5.36	0.0208*	3.9112
KA	796.3	1	796.344	86.69	< 0.000*	8.0731
GRFml	4.1	1	4.056	0.44	0.5065	0.0004
GRFap	158.7	1	158.699	17.28	<0.000*	5.8964
ST	241.5	1	241.537	26.3	<0.000*	5.8438
BF	36.6	1	36.636	3.99	0.0461*	-2.1236
GM	11.7	1	11.704	1.27	0.2593	1.3573
GL	5.7	1	5.657	0.62	0.4328	-1.6735
RF	83.7	1	83.734	9.12	0.0026*	-3.148
VM	6.8	1	6.796	0.71	0.3899	1.4945
VL	2.7	1	2.699	0.29	0.5879	-1.0857
Error	9507.1	1035	9.186			
Total	14429.5	1046				

*:significant; KM: knee extension moment; KA: knee flexion angle; GRFml: ground reaction force in the medial-lateral direction; GRFap: ground reaction force in the anterior-posterior direction; ST: semitendinosus; BF: biceps femoris; GM: gastrocnemius medialis; GL: gastrocnemius lateralis; RF: rectus femoris; VM: vastus medialis; VL: vastus lateralis.

Discussion

The most important findings of this study were:

1. A negative correlation between ATTp and maximal ATTd.
2. That larger ST activity was seen when ATTd was higher, while BF activity and RF activity were lower.
3. That higher knee extension moment, knee flexion angle and GRFap were seen when ATTd was higher.

ATT compared to literature

A review showed a range of ATTp of approximately 2.5-8.4 mm in healthy knees [17]. The present study found a range of 0.9-8.8 mm, which is comparable to the literature study. A lack of golden standard of ATTd measurement makes it difficult to verify the outcomes of the methods developed by Boeth et al. [6]. However, the ATTd found in our study is comparable with that of previous studies. In our study the mean range of ATTd was 11.5 mm (-4.7 to 6.8 mm). Previous studies found an absolute range of

ATTd using bi-planar fluoroscopy model based data during running of around 10 mm (8 to 18 mm) [1] and +/- 25 mm [23], and using the same methods as in the present study around 12 mm (-2 to 10 mm) [16]; all in healthy subjects.

Correlation between ATTd and ATTp

The present study revealed a significant negative correlation between ATTp and maximal ATTd. In contrast with these findings, Boeth et al. [6] did find a significant positive correlation between the ATTp measured also using the KT-1000 arthrometer and the range of the anterior posterior tibia translation during walking. This difference in results may be related to the task: jumping is more challenging in terms of net joint moments of force and anterior tibia shear force, which may allow less room for phasic co-activation of the muscles in a much shorter time window in which the joint load is growing. In addition, others did not find a correlation between ATTp and ATTd (during gait) measured using a CA-4000 electrogoniometer in ACL deficient knees [34]. This may be due to differences in measurement method, due to the task or due to the injury. During walking ATTd may not be maximal as the impact on the knee is small and a knee injury may result in an inhomogeneous group of participants.

The finding of the current study that people with high ATTp tent to show low ATTd suggest that passive ATT tests are not representative for ATTd, and that people with high ATTp may be able to control their knee laxity during jump landing, i.e. by using adequate muscle activation patterns or kinematics.

Active control of ATTd

Surprisingly, the effect of the knee flexion angle on the ATTd and the effect of extension moment on the ATTd were higher than the effect of muscle activation on ATTd. This result might imply that muscle activation patterns do not contribute to reduce ATTd in healthy people during a SLHD landing. This can also be seen in the sign of the predictive weight coefficient of the ST and RF activity with ATTd. ST activity has a positive predictive weight coefficient whereas RF activity has a negative predictive weight coefficient on ATTd, which is in line with the fact that the hamstrings are known to pull the tibia posteriorly relative to the femur and the quadriceps pull the tibia anteriorly [7, 12]. However, according to measurements of Kirkendall and Garrett [19] landing with low knee flexion does increase the knee extensor activity and landing with higher knee flexion does increase the hamstring activity. This is in line with our results. These results might mean that the pattern of muscle activity at the observed net knee moment is unable to limit the ATTd at that knee angle. Participants with a large ATTp use less knee flexion while landing and have less ATTd.

In literature it is shown that ACL strain increases when the knee is more extended (between 0 and 30 degrees) in cadaveric knees using a strain transducer on the anteromedial bundle of the ACL [2, 27] and in healthy knees using an MRI and fluoroscopy based model during jump landing [35]. Therefore, it is previously suggested that landing with a more flexed knee (so called soft landing) may protect the ACL since it is not strained [10, 11, 22]. In physiotherapy after an ACL injury and reconstruction as well as in ACL injury prevention, people are therefore instructed to land with more knee flexion to protect the ACL [5, 37]. The predictive weight coefficient between knee flexion angle and ATTd was positive. This might imply that there is more room for ATTd during jump landing when the knee is more flexed. When there is more room for ATTd the possible anterior tibia acceleration might be higher and therefore the sudden impact of the tibia on the ACL strain might be higher during uncontrolled movements. For example, in expert skiers it is shown that the ACL can be torn when the quadriceps contract in a short time period while the knee is in a high flexion which results in a high anterior tibia acceleration [24]. Note that this all depends on the inertial properties of the elements and their accelerations. Nevertheless, a numbers of studies suggest that most ACL injuries occur while the knee is near full extension or in hyperextension [18, 30].

Future research and limitations

Further research is necessary to corroborate or reject our findings that landing kinematics and kinetics are more important in the control of ATTd than muscle activation. Perhaps in people with larger knee laxity, a suitable landing strategy is already found autonomously. Also, future studies could investigate if patients after an ACL injury can compensate for the dynamic knee laxity using effective landing kinematics, kinetics and muscle activation patterns. Such studies can be designed to investigate if patients who can cope with the injury may compensate for the available passive knee laxity by using effective landing strategies and muscle activation patterns in a dynamic situation whereas patients who cannot cope with the injury might not be able to compensate for the results of the injury. Also, more research is needed on the contribution of limiting ATT by respectively strain in the ACL and muscle forces. This requires a good 3D model fed by material properties, geometrical data and experimental data in dynamical situations.

Other factors such as anatomical differences, i.e. the slope of the tibia plateau, might also be important for the observed ATTd. Shao et al. [28] reported by using a biomechanical computer model that ATT is influenced by the slope of the tibia plateau. Further research is necessary to investigate the influence of anatomical differences on the ATTd.

Some limitations of this study need to be addressed. There may be errors in the results of ATTd due to wobbling masses of the muscles in the upper and lower leg on which the optical markers were affixed, falsely represented as ATTd. However, a sensitivity analysis of the methods used in the present study revealed that only transients less than 2.32 mm should be taken with caution [16]. A second limitation is the method of normalization of muscle activity. We have chosen to normalize the muscle activity to the percentage of the mean muscle activity during the SLHD. This normalized muscle activity might be more comparable between participants than the absolute muscle activity since the influence of variables like conductance and body fat are canceled. We have chosen not to normalize to a maximal voluntary contraction task, as we found that some participants showed different isometric activation strategies than others in those tasks. A third limitation might be the sample size. Even though we met the number of participants calculated with a power calculation, the variety in the ATTd within the study group was high. This might explain the lack of correlations or when significant, only weak or moderate correlations.

Conclusion

The results of this study show that participants who have more knee laxity during the passive test have smaller ATTd during the SLHD. Subjects with a large ATTp land with less knee flexion and have less ATTd. Participants did not use muscle activation at impact in such a way that ATTd is reduced during a jump-landing task. The pattern of muscle activity at the observed knee moment is unable to limit the ATTd at that knee angle.

References

[1] Anderst W, Zauel R, Bishop J, Demps E, Tashman S (2009) Validation of Three-Dimensional Model-Based Tibio-Femoral Tracking During Running. Med Eng Phys 31(1):10-6

[2] Bakker R, Tomescu S, Brenneman E, Hangalur G, Laing A, Chandrashekar N (2016) Effect of sagittal plane mechanics on ACL strain during jump landing; Effect of sagittal plane mechanics on ACL strain during jump landing. J Orthop Res 34(9):1636–44

[3] Barcellona MG, Morrissey MC, Milligan P, Amis AA (2014) The effect of thigh muscle activity on anterior knee laxity in the uninjured and anterior cruciate ligament-injured knee. Knee Surg Sports Traumatol Arthrosc 22(11):2821–9

[4] Begovic H, Zhou G-Q, Li T, Wang Y, Zheng Y-P (2014) Detection of the electromechanical delay and its components during voluntary isometric contraction of the quadriceps femoris muscle. Front Physiol 5:494

[5] Benjaminse A, Gokeler A, Dowling AV, Faigenbaum A, Ford KR, Hewett TE, Onate JA, Otten B, Myer GD (2015) Optimization of the anterior cruciate ligament injury prevention paradigm: Novel feedback techniques to enhance motor learning and reduce injury risk. J Orthop Sports Phys Ther 45(3):170–182

[6] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, Moewis P, Scheffler S, Taylor WR (2013) Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. Am J Sports Med 41(5):1051–7

[7] Van Den Bogert AJ (2002) Comment on "quadriceps protects the anterior cruciate ligament." J Orthop Res 20(5):1133–4

[8] Ehrig RM, Taylor WR, Duda GN, Heller MO (2006) A survey of formal methods for determining the centre of rotation of ball joints. J Biomech 39(15):2798–809

[9] Ehrig RM, Taylor WR, Duda GN, Heller MO (2007) A survey of formal methods for determining functional joint axes. J Biomech 40(10):2150–7

[10] Escamilla RF, MacLeod TD, Wilk KE, Paulos L, Andrews JR (2012) Cruciate ligament loading during common knee rehabilitation exercises. Proc Inst Mech Eng H 226(9):670–80

[11] Gokeler A, Benjaminse A, Hewett TE, Paterno MV, Ford KR, Otten E, Myer GD (2013) Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: Implications for motor control and reduction of second injury risk. Sport Med 43(11):1065–74

[12] Imran A, O'Connor JJ (1998) Control of knee stability after ACL injury or repair: Interaction between hamstrings contraction and tibial translation. Clin Biomech 13(3):153-62

[13] Cohen J (1969) Statistical Power Analysis for the Behavioral Sciences. New York: Academic Press

[14] Jones CW, Jacobs H, Shumborski S, Talbot S, Redgment A, Brighton R, Walter WL (2020) Sagittal Stability and Implant Design Affect Patient Reported Outcomes After Total Knee Arthroplasty. J Arthroplasty 35(3):747–51

[15] Kaeding CC, Léger-St-Jean B, Magnussen RA (2017) Epidemiology and Diagnosis of Anterior Cruciate Ligament Injuries. Clin Sports Med 36(1):1–8

[16] Keizer MNJ, Otten E (2020) Technical note: sensitivity analysis of the SCoRE and SARA methods for determining rotational axes during tibiofemoral movements using optical motion capture. J Exp Orthop 7(1):6

[17] Keizer MNJ, Otten E (2019) Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review. Musculoskelet Surg 103(2):121-30

[18] Kim SY, Spritzer CE, Utturkar GM, Toth AP, Garrett WE, Defrate LE (2015) Knee Kinematics During Non-contact ACL Injury as Determined from Bone Bruise Location. Am J Sports Med 43(10):2515-21

[19] Kirkendall DT, Garrett WE jr (2000) The Anterior Cruciate Ligament Enigma. Injury mechanisms and prevention. Clin Orthop Relat Res (372):64–8

[20] Klyne DM, Keays SL, Bullock-Saxton JE, Newcombe PA (2012) The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: A study of alterations in EMG measures and their relationship to knee joint stability. J Electromyogr Kinesiol 22(3):446–55

[21] Kvist J (2005) Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sport 15:148–58

[22] Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'connor KM (2011) The effects of single-leg landing technique on ACL loading. J Biomech 44(10):1845–51

[23] Lin CC, Li JD, Lu TW, Kuo MY, Kuo CC, Hsu HC (2018) A model-based tracking method for measuring 3D dynamic joint motion using an alternating biplane x-ray imaging system. Med Phys 45(8):3637–49

[24] Mcconkey JP (1986) Anterior cruciate ligament rupture in skiing: A new mechanism of injury. Am J Sports Med 14(2):160–4

[25] van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH (2017) How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. PLoS One 12 (12):e0189876

[26] Project TS (2016) Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles. SENIAM guidelines.

[27] Renström P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 14(1):83-7

[28] Shao Q, MacLeod TD, Manal K, Buchanan TS (2011) Estimation of ligament loading and anterior tibial translation in healthy and ACL-deficient knees during gait and the influence of increasing tibial slope using EMG-driven approach. Ann Biomed Eng 39(1):110–21

[29] Shelburne KB, Torry MR, Pandy MG (2005) Effect of muscle compensation on knee instability during ACL-deficient gait. Med Sci Sports Exerc 37(4):642–8

[30] Shimokochi Y, Shultz SJ (2008) Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train 43(4):396-408

[31] Shultz SJ, Carcia CR, Perrin DH (2004) Knee joint laxity affects muscle activation patterns in the healthy knee. J Electromyogr Kinesiol 14(4):475–83

[32] Shultz SJ, Schmitz RJ, Nguyen AD, Levine BJ (2010) Joint laxity is related to lower extremity energetics during a drop jump landing. Med Sci Sports Exerc 42(4):771–80

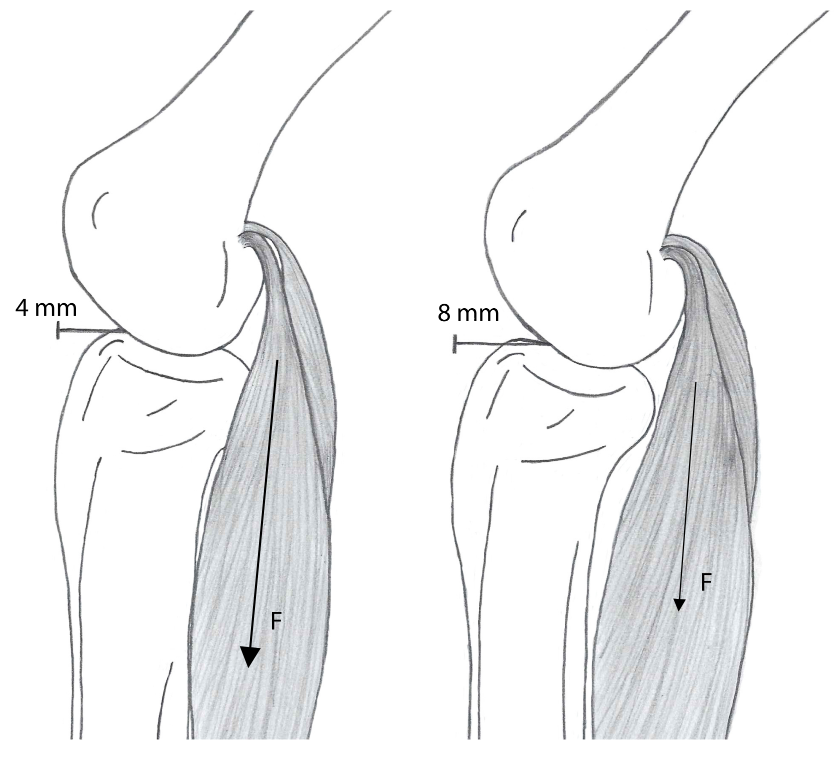
[33] Stettler M, Luder G, Schmid S, Mueller Mebes C, Stutz U, Ziswiler HR, Radlinger L (2018) Passive anterior tibial translation in women with and without joint hypermobility: an exploratory study. Int J Rheum Dis 21(10):1756–62

[34] Tagesson S, Öberg B, Kvist J (2015) Static and dynamic tibial translation before, 5 weeks after, and 5 years after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(12):3691–7

[35] Taylor KA, Terry ME, Utturkar GM, Spritzer CE, Queen RM, Irribarra LA, Garrett WE, DeFrate LE (2011) Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. J Biomech 44(3):365–71

[36] Taylor WR, Kornaropoulos EI, Duda GN, Kratzenstein S, Ehrig RM, Arampatzis A, Heller MO (2010) Repeatability and reproducibility of OSSCA, a functional approach for assessing the kinematics of the lower limb. Gait Posture 32(2):231–6

[37] Welling W, Benjaminse A, Gokeler A, Otten B (2017) Retention of movement technique: implications for primary prevention of ACL injuries. Int J Sport Phys Ther 12(6):908–20



4 mm
F
8 mm
F

Chapter 6

Copers and Non-copers use Different Landing Techniques to Limit Anterior Tibia Translation after an ACL Reconstruction

Michèle N.J. Keizer · Reinoud. W. Brouwer · Chantal M.I. Beijersbergen · Egbert Otten · Juha M. Hijmans

Orthopaedic Journal of Sports Medicine 2020. Accepted

Highlights

- There is a positive correlation between ATTp and ATTd in copers, however not in non-copers
- Copers and non-copers use different landing techniques
- Only the copers show a negative correlation between ATTd and gastrocnemius activity of their operated leg
- Non-copers show a positive correlation between ATTd and knee extension moment

Abstract

Background: One year after anterior cruciate ligament reconstruction (ACLR) two-thirds of the patients manage to return to sports (copers) whereas one-third of the patients do not manage to return to sports (non-copers). Passive ATT during clinical tests does not correlate with dynamic ATT (ATTd). Copers v.s. non-copers show different muscle activation patterns compared to copers and non-copers may not be able to control dynamic ATT as well as copers.

Study Design: Retrospective cohort study.

Hypothesis/Purpose: To investigate whether 1) there is a positive correlation between ATTp or general joint laxity and ATTd during jump landing; 2) ATTd is moderated by muscle activating patterns; 3) there is a difference in moderating ATTd between copers and non-copers. It is hypothesized that ACLR patients compensate for dynamic ATT by developing effective muscle strategies, that are more effective in copers compared to non-copers.

Method: Forty unilateral ACLR patients performed ten single leg hops for distance with both legs. Lower body kinematic and kinetic data were measured using a motion capture system and the ATTd was determined with an embedded method. Muscle activity was measured using EMG signals. Bilateral ATTp was measured using a KT-1000 arthrometer. In addition, the Beighton score was taken.

Results: There is no significant correlation between ATTp and ATTd in copers, however there is a positive correlation in non-copers in the operated knee. There is a positive correlation between the Beighton score and ATTp and between the Beighton score and ATTd in both copers and non-copers in the operated knee. Copers showed a negative correlation between ATTd and gastrocnemius activity of their operated leg. Non-copers showed a positive correlation between ATTd and knee flexion moment in the operated knee.

Conclusion: Copers vs. non-copers use different landing techniques. Copers use an increase of gastrocnemius activity to reduce ATTd whereas non-copers moderate ATTd by generating smaller knee flexion moment.

Clinical Relevance: ATT in ACLR patients is a risk factor for second ACL injury. This study shows that those who return to sport have sufficient plantarflexor activation to limit ATTd. Future studies should investigate whether focusing on plantarflexor during rehab will increase the number of return to sport after ACLR.

Keywords: knee, knee laxity, muscle activity, motor control

Introduction

An anterior cruciate ligament (ACL) injury results in greater knee laxity and alterations of muscle activation patterns [1, 4, 19]. An ACL reconstruction (ACLR) reduces knee laxity [24]. One year after an ACLR, however, 82% of the patients return to any sports while only 62% are able to return to their pre-injured level of sports and only 44% manage to return to competitive sports [5]. The discrepancy between return to any type of sports and return to pre-injured level of sports may be caused by learned muscle control or adjustments of kinematics. Some patients are not able to control dynamic knee laxity, i.e. anterior tibia translation (ATT), during landing after an ACLR whereas others are.

There is no association between ATT in a passive situation (ATTp), i.e. during a Lachman or KT-1000 arthrometer test, and ATT in a dynamic situation (ATTd) such as normal gait, active extension, heel raises, cycling, one-legged squat and chair squat for ACL deficient, ACLR, or healthy knees [28, 40]. One previous study even found that healthy participants with high ATTp showed low ATTd [23]. These findings suggest that next to the passive resisting force of the ACL and knee ligament properties other factors are involved for controlling ATTd, for example dynamic muscle activation patterns or landing kinematics and kinetics [23]. One possibility is that ACLR patients who manage to return to pre-injured type and level of sports (copers) are able to use muscle activation patterns that limit the strain of the ACL whereas ACLR patients who do not manage to return to pre-injured type of sports (non-copers) rely more on the resisting force from the ACL. In literature it is stated that non-copers have different dynamic muscle activation patterns compared to copers during one leg stance on a stabilization platform [12] and during a hop test [17]. Copers use different muscle activation patterns compared to non-copers and we hypothesize that this is because copers are able to control ATTd using muscle activation patterns whereas non-copers are not. In line with the suggestion that knee laxity can be mitigated by muscle activation patterns in a dynamic situation, it is reported that ACL injured patients with low muscle strength of the quadriceps or large inter-leg hamstrings muscle strength asymmetry show greater movement asymmetry in the sagittal plane [1, 31]. This may be due to an imbalance of the quadriceps to hamstring ratio, which may result in modified kinematics, kinetics and ATTd [2, 38]. Besides, it is found that residual muscle activity of the medial gastrocnemius and hamstrings modulates ATTp [7, 26] and computer models have shown that hamstring activity reduces ATTd during gait [37]. As far as known by the authors, no study has been conducted to study in vivo the relation between ATTd and muscle activation patterns. This may be of interest for patients after an ACLR since copers may have a solution to limit knee ATTd that non-copers do not have but may be able to learn. The aims of this study were therefore to investigate:

1. the relationships between both the ATTp and general joint laxity (Beighton score) with ATTd during jump landing in ACLR patients;
2. whether ATTd in ACLR patients can be moderated by muscle activation patterns during a single leg hop for distance after ACLR;
3. whether there is a difference in ATTd between copers and non-copers.

We hypothesize that copers compensate for knee laxity in dynamic situations by developing effective muscle activation strategies whereas non-copers are not able to actively moderate knee laxity.

Methods

Participants

The correlation between ATTd and ATTp was used for an a priori power analysis [13](R2 of 0.47). Based on an effect size of 0.69, statistical power set at $\alpha \leqslant 0.05$ and a power of 80% to detect statistically significant differences, 12 participants were needed. We included forty patients (15 women and 25 men; age: 18-45). Inclusion criteria were: patients 12 to 24 months post-ACLR and an ACLR performed using autograft hamstring tendons. Exclusion criteria were patients with cartilage pathology that needed concomitant surgical treatment, revision ACLR, osteotomies or contralateral ACL injury.

The ACLR for all patients was performed by using an ipsilateral gracilis and semitendinosus autograft and was fixed using an endobutton (Endobutton CL Ultra; Smith & Nephew) in the femoral socket and a plug and a PEEK interference screw (Biosure; Smith & Nephew) in the tibial tunnel.

The study was a collaboration between the Martini Hospital Groningen and the University Medical Center Groningen (UMCG). Patients were included and underwent surgery via the Martini Hospital Groningen and tests were performed at in the UMCG in the period from April 2018 - November 2019. The study design, procedure, and protocol are approved by the Medical Ethical Committee of the UMCG (METC number: 2017.658). All participants were informed about the proceedings and aims of the study by e-mail and they signed an informed consent form.

Study parameters

The primary outcome measures were ATTd during a single leg hop for distance (SLHD) [44], observed ATTp measured using a KT-1000 arthrometer (MEDmetric Corporation, San Diego, California, USA) and the patterns of muscle activation during both tests for both legs. The coefficient of variation of this procedure determining the ATTd across 16 healthy knees is 5.2% +/- 1.2% and excellent reproducibility was observed (ICC(3,1) = 0.92) [13]. Moreover, Keizer and Otten [25] showed that ATTd higher than 2.32 millimetre (mm) is reliable in terms of wobbling masses and the Vicon position error. Previous studies found an average error of the KT-1000 of 0.13 mm [27] and an interrater interclass correlation coefficient of 0.79 [12]. In addition, secondary study parameters during the jump test were the knee flexion angle, knee external flexion moment, and the vertical ground reaction force magnitude for both legs. The Beighton score (score from 0 to 9) [10], a scoring system for joint laxity and hypermobility, was also taken as secondary study parameter.

Procedure

Each participant was measured in a single session. First, participants completed a questionnaire about sports participation and fear and the Beighton score was taken. The questionnaire was used to divide copers (those who are able to return to pre-injured type of sports) versus non-copers (those who are not able to return to pre-injured type of sports) for the subsequent data analysis. A passive test (condition 1) and a dynamic test (condition 2) were performed. The order of the conditions was randomized to reduce the effect of fatigue on knee laxity [8].

Surface electromyographic (sEMG) electrodes (Cometa Wave Plus Wireless sEMG system, Cisliano Milano, Italy) were attached according to SENIAM guidelines [32]. For condition 2 (single leg jumps), we recorded the EMG signals of the medial hamstring (MH), lateral hamstring (LH), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL). For condition 1 (passive ATT test), the EMG signals were recorded of the MH, LH, RF, VM, VL. The gastrocnemius activity was not measured in condition 1 because the location of the EMG electrodes interfered with the attachment of the KT-1000 apparatus. The same researcher performed all electrode placements.

During condition 1 (passive test) ATTp was measured in millimetres with the knee at 30 degrees of flexion using a KT-1000 arthrometer (MEDmetric Corporation, San Diego, California, USA) [33] under a force of 67, 89 and 133 Newton. The participants were laying supine and were instructed to relax their leg which was verified by observing the sEMG recordings. This test was repeated three times for both legs.

During condition 2 (dynamic test) ten SLHD's were performed subsequently with both legs. During this test, ATTd, the muscle activation patterns, knee flexion angle, and external knee flexion moment were determined. 3D marker positions were measured using a 10-camera three-dimensional motion capture system (VICON VERO; VICON Motion Systems Ltd, Oxford, UK) at a frequency of 200 Hertz (Hz). Markers were attached as shown in Figure 1 (adapted from Boeth et al. [13]). Marker placements were performed by the same researcher for each participant. After attaching markers, calibration frames of a flexion-extension movement and a star-arc movement, as prescribed by the manual of VICON, were performed to be able to identify the hip and knee joint centers and axis of rotation of the knees [15, 16]. See Keizer and Otten 2020 [25] for the whole procedure. The participants performed three practice SLHD subsequently with both legs, starting with the uninjured leg. The participants started standing still on their tested leg and hopped forward as far as possible. Participants were instructed to stand still for at least three seconds after landing to assure a controlled landing. For each leg, the median of the distance of the three practice jumps was used for the starting distance from the middle of a 40x60 cm force platform (AMTI; Watertown, MA). Ten successful jumps were recorded with both legs. The starting leg was randomized.

Data analysis

Data were processed and analyzed using the Statistics Toolbox from MATLAB version 9.7 (The MathWorks Inc., Natick, Massachusetts). All kinematic and kinetic data and muscle activity during each jump were determined between 1 second (s) before and 1.5 s after initial contact (IC), defined as the moment where vertical ground reaction force was $> 5\%$ of the bodyweight. The zero-point of ATTd were calibrated using the frames captured during a flexion-extension task. Raw 3D marker position data were filtered using a low pass frequency convolution filter of 10Hz with zero lag. Gaps smaller than 20 frames were filled using quadratic spline interpolation with zero lag. Trials with larger gaps were excluded.

The knee flexion moment was calculated from the GRF vector and its lever arm to the center of the knee of the stance leg. For quantification of ATTd and knee angles two coordinate systems were reconstructed in the tested knee using a customized MATLAB script based on the method of Boeth et al. [13]. One system was reconstructed in the femoral segment (parent system) and one in the tibia segment (child system). See Keizer and Otten [25] for this procedure. The motion of each coordinate system is consistent with the movement of the respective segment. The ATTd was quantified in millimeters using the relative movement of the origin of the coordi-

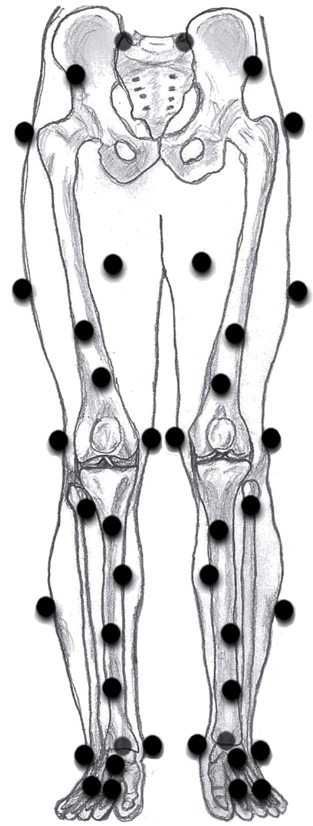


Fig. 1 Marker placement. Markers were attached on the right and left anterior and posterior superior iliac spine, the right and left iliac crest, the greater trochanter, the medial and lateral epicondyles of the femur, the medial and lateral malleoli of the ankle, the heel, anterior of the talus bone and the first and fifth metatarsophalangeal joints. Two additional markers were attached to the pelvis, two to the thigh, and six additional markers were attached to the shank [13].

nate system of the tibia relative to that of the femoral coordinate system. The knee flexion angles and the rotations between both coordinate systems, tibia and femur, were calculated. The rotations are obtained using scalar products as in the equations explained in Robertson et al. [35]

The sEMG signals were recorded at a sampling frequency of 1000 Hz. Muscle activity around the point of first ground contact, taking into account an electromechanical delay of 49.7 milliseconds (ms) [9], was rectified and filtered using a fourth-order low pass frequency Butterworth filter at 6 Hz with zero lag. To minimize the influence of body fat and skin conductivity we scaled the EMG signals to the mean muscle activity during 1s before IC until 1.5s after IC of the SLHD for each participant. Due to large variations in peak activation, especially of the semitendinosus muscle, during a maximal isometric contraction task, we did not scale to this muscle activity. Maximal isometric contraction tasks are notorious for this kind of large variations.

The mean of the kinematics data, kinetic data and muscle activation patterns of the 10 trails represented participant‘s movement pattern.

Statistical analysis

The subsequent statistical analysis were performed on the means of the 10 trails of each subject. A Pearson correlation was calculated between ATTp of the operated leg and the Beighton score and a statistical parametric mapping (SPM) regression analysis was performed to analyze the relation between ATTd of the operated leg over time and the Beighton score. Pearson correlations were calculated between maximal ATTd and ATTp for the operated as well as the contralateral leg, both for copers and non-copers separately.

To analyze the EMG signals over time we used SPM canonical correlation analysis (CCA) to find the significance between muscle activity and ATTd and between muscle activity and kinetics. SPM$\{x^2\}$ analyses were performed using the open-source spm1d code (v.M.0.1, www.spm1d.org) in MATLAB version 9.7. For this, data from initial contact until 0.5 seconds after initial contact was used. The dependent variable was ATTd and the independent variables were the activity of the independent muscles, knee flexion angle and external knee flexion moment over time. When the original SPM$\{x^2\}$ exceeded the calculated critical x^2-value (threshold) based on an α of $\leqslant$ 0.05, the null hypothesis was rejected, implying a correlation. When significant values were reached, a post-hoc regression analysis was performed for each independent muscle activity and kinetics variables as independent variables. This procedure was done for the whole group, for only the copers separately, and for the non-copers.

P-values were considered to be significant with an alpha of $\alpha \leqslant 0.05$. If a correlation was significant, a correlation coefficient of 0.2-0.49, 0.5-0.79 and 0.8-1 were considered to represent a weak, a moderate and a strong association, respectively [20].

Results

Baseline characteristics of the participants are displayed in Table 1. Figure 2 shows the means and standard deviations of the kinetic and kinematic data over the 10 trials of the operated leg divided in copers and non-copers, and Figure 3 shows similar data for the contralateral leg.

Table 1 Baseline Characteristics Copers v.s. Non-copers.

	Copers		Non-copers		T-test / Chi-square (p-value)
Number of patients (M/F)	17/9		8/6		0.6
	Mean	Range	Mean	Range	
Age	26.5	19-39	26.1	18-42	0.97
Length (cm)	181	161-198	181	163 - 196	0.81
Weight (kg)	79	61-112	76	52-107	0.66
Month post-surgery	16.5	12-24	17	12-24	0.82
Beighton score	2.2	0-7	1.9	0-6	0.75
ATTp reconstructed (mm)	5.2	1.1-9.5	4.6	1.7-8.5	0.69
ATTp contralateral (mm)	4.2	1.6-8.7	3.3	0.8-7.7	0.24
ATTd reconstructed (mm)	12.5	-0.1-22.3	11.1	1.5-19.4	0.51
ATTd contralateral (mm)	12.5	4.5-20.0	11.3	5.5-16.6	0.42
Anxious (Y/N)	9/17		10/4		0.03*

ATTp passive anterior tibia translation during the KT-1000 arthrometer under 133N; *ATTd* dynamic anterior tibia translation during a single leg jump landing; * = significant

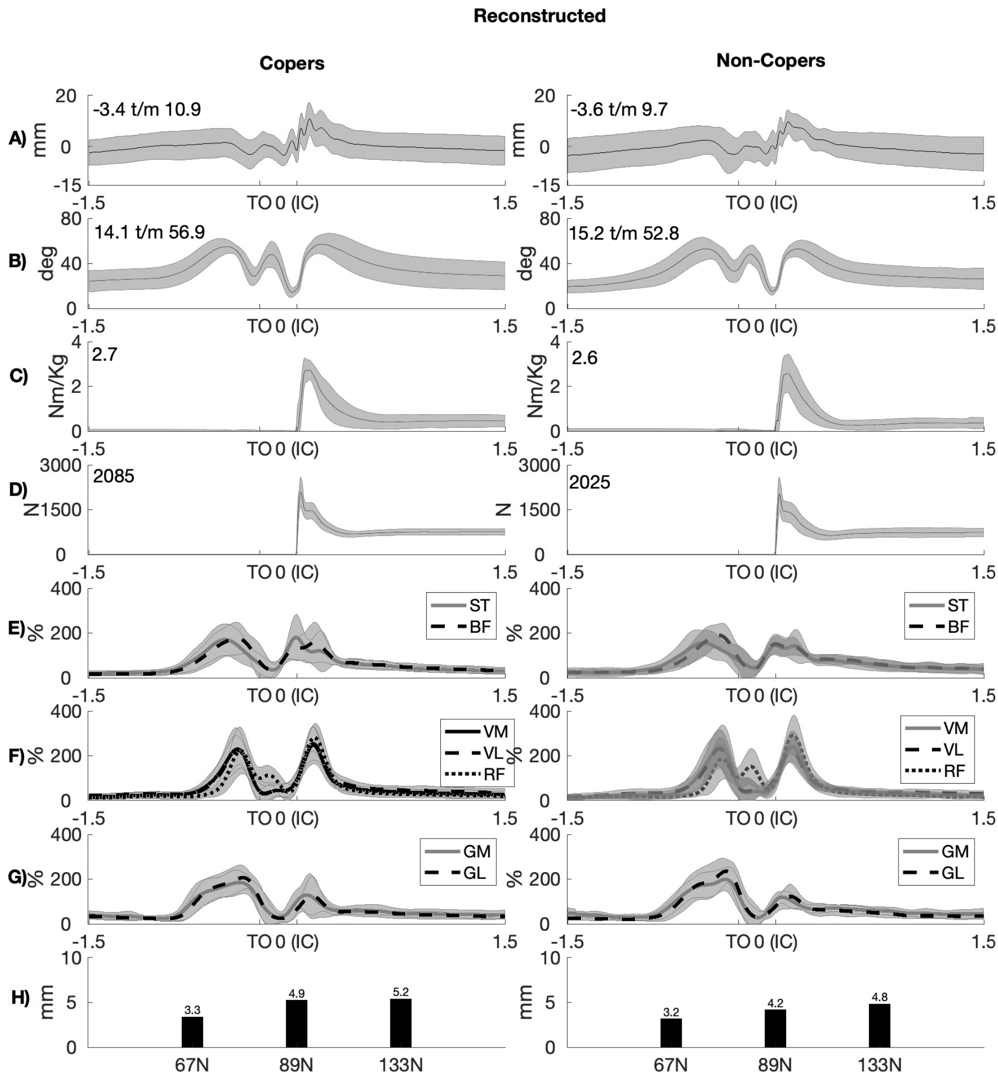


Fig. 2 The mean and standard deviation (gray area) of the A) ATTd, B) knee flexion angle, C) external knee flexion moment, D) vertical ground reaction force, E) mean of the medial and lateral hamstrings activity expressed as % of mean EMG, F) vastus medialis, vastus lateralis and rectus femoris activity expressed as % of mean EMG, G) gastrocnemius medialis and lateralis activity expressed as % of mean EMG, and H) passive ATT of the operated leg divided in copers and non-copers.

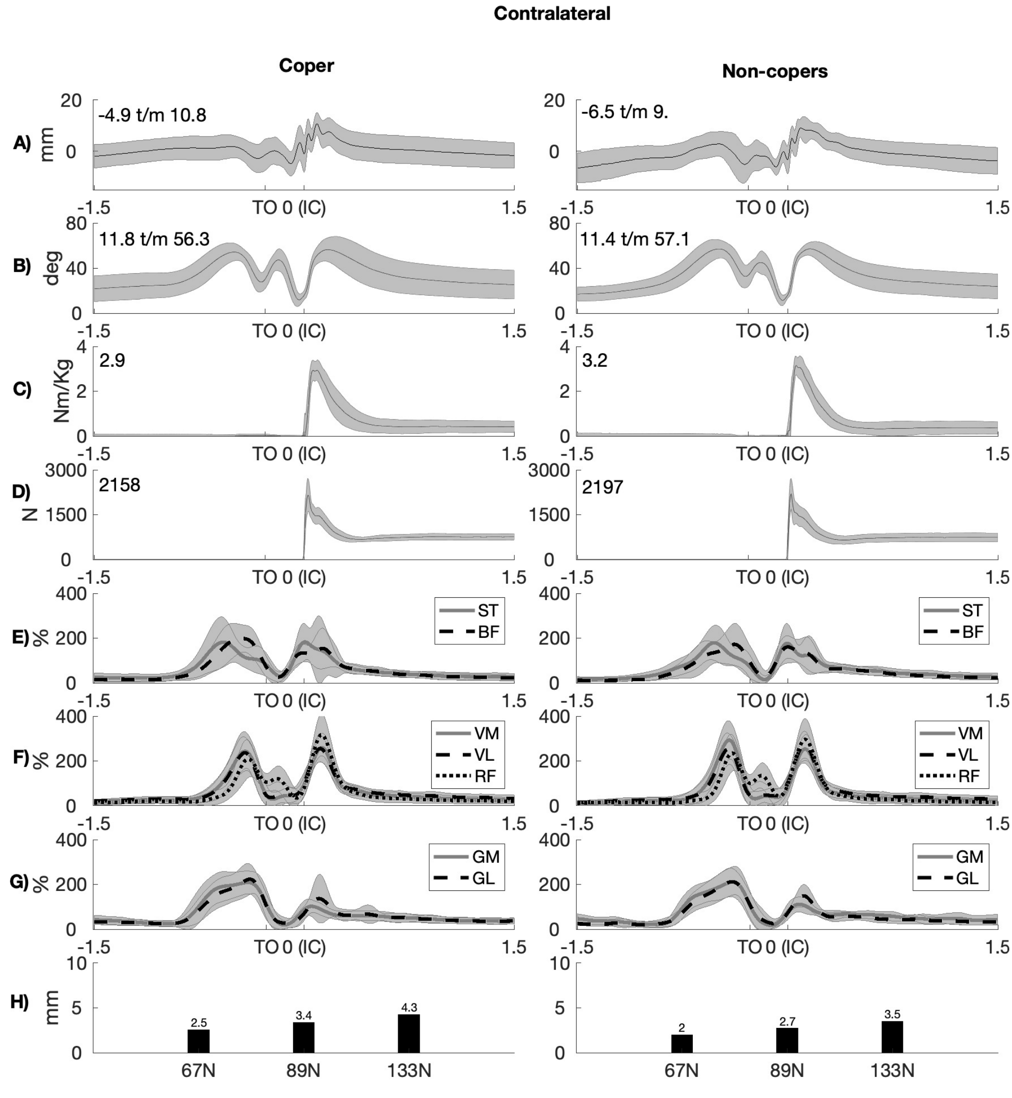


Fig. 3 The mean and standard deviation (gray area) of the A) ATTd, B) knee flexion angle, C) external knee flexion moment, D) vertical ground reaction force, E) mean of the medial and lateral hamstrings activity expressed as % of mean EMG, F) vastus medialis, vastus lateralis and rectus femoris activity expressed as % of mean EMG, G) gastrocnemius medialis and lateralis activity expressed as % of mean EMG, and H) passive ATT of the contralateral leg divided in copers and non-copers.

General joint laxity and ATT

There is a weak significant positive correlation between the Beighton score and ATTp of the operated leg (r=0.42, p=0.007). The SPM{t} regression analysis (Figure 4) shows a significant positive correlation between the Beighton score and ATTd of the operated leg between 0.19 s and 0.08 s before initial contact (IC) (p=0.003).

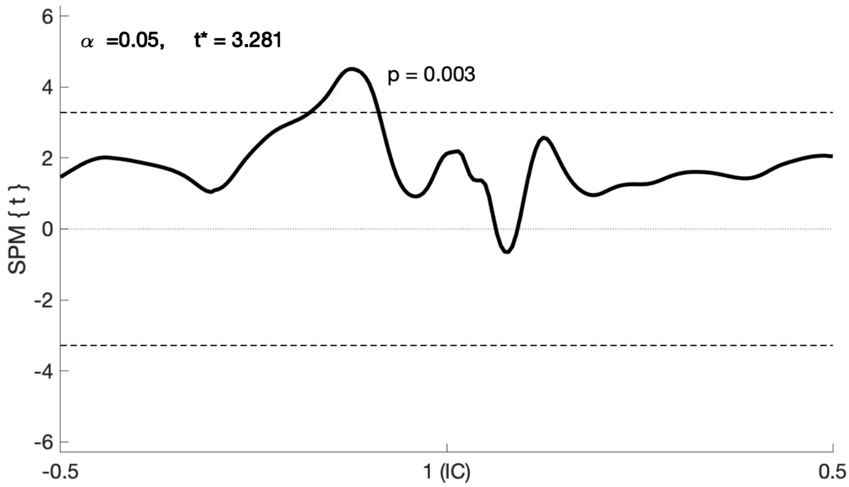


Fig. 4 SPM{t} regression analysis between the Beighton score and ATTd.

ATT of copers v.s. non-copers

There is no significant correlation between ATTp and maximal ATTd of the operated leg for copers (r=0.05, p=0.82) and there is a moderate significant positive correlation for non-copers (r=0.55, p=0.04). There are no statistically significant difference between ATTp and maximal ATTd for copers nor noncopers in the contralateral knee (r= 0.05, p=0.82 and r=0.38, p=0.18, respectively).

The correlation of ATTp between the operated leg and contralateral leg is moderate significant for both the copers and non-copers (copers: r=0.56, p=0.003; non-copers: r=0.68, p=0.008; see figure 5A). The correlation of ATTd between the operated leg and contralateral leg is significant but weak for the copers (r=0.39, p=0.047) and moderate significant for non-coper (r=0.76, p=0.002) (figure 5B).

Control of ATTd

For the whole group, the SPM{x^2} analyses of the operated leg shows a significant CCA between 2 ms and 3 ms after IC (p = 0.049) and between 11 ms and 17 ms after

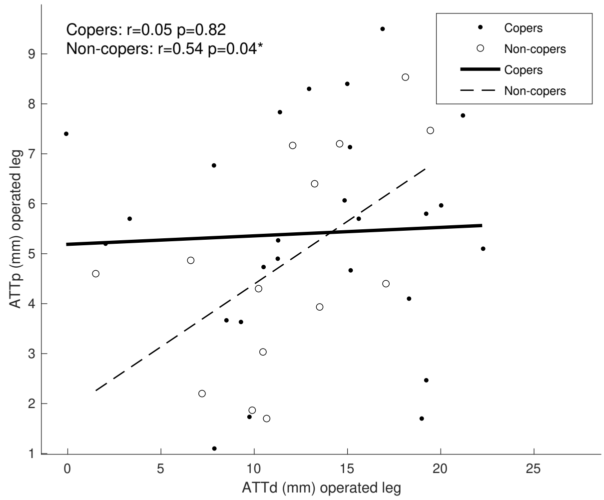


Fig. 5 Correlation between the passive anterior tibia translation (ATTp) and dynamic anterior tibia translation (ATTd) of the operated leg. * = significant

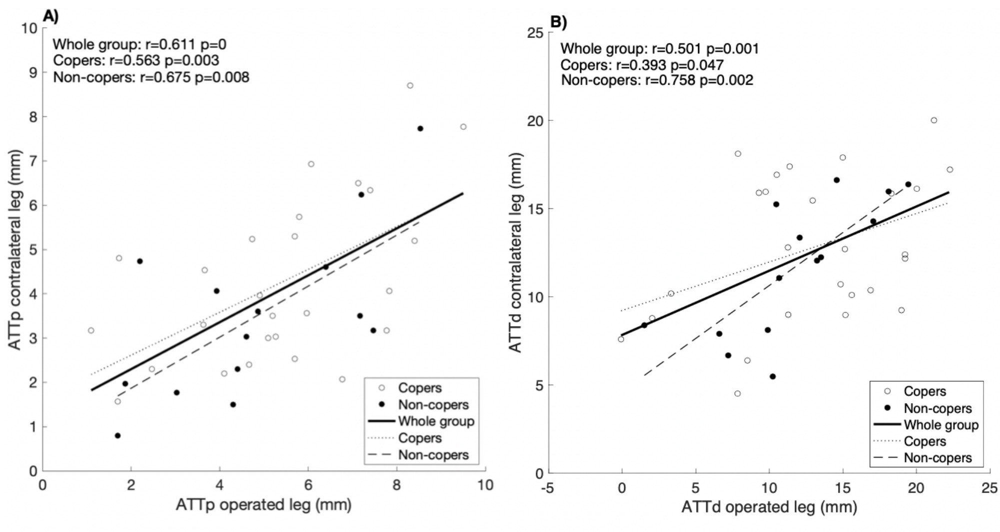


Fig. 6 A) Correlation between ATTp of the operated and contralateral leg. B) Correlation between the dynamic maximal ATTd of the operated and contralateral leg. For both legs, the data is divided in copers and non-copers.

IC (p = 0.028). A post-hoc SPMt regression analysis shows significant correlations of the vastus lateralis, gastrocnemius medialis, gastrocnemius lateralis and knee flexion angle on ATTd over some time sections. See Table 2 for only the significant sections of the variables. The SPM{x^2} CCA of the contralateral knee shows no significant correlations.

The SPM{x^2} analyses of the operated leg in copers shows a significant CCA between 0 ms and 3 ms after IC ($p = 0.049$). A post-hoc SPM{t} regression analysis shows significant correlations between the gastrocnemius medialis and lateralis on ATTd over some time sections. See Table 2 for only the significant sections of the variables. The SPM{x^2} CCA of the contralateral knee shows no significant correlations.

The SPM{x^2} analyses of the operated leg in non-copers show a significant CCA between 12 ms and 15 ms after IC ($p = 0.040$). The SPM{x^2} analyses of the contralateral knee shows a significant CCA between 4 ms and 6 ms after IC ($p = 0.049$) and between 16 and 19 ms after IC ($p=0.048$). For only the significant results of the a post-hoc SPM{t} regression analysis see Table 2.

Discussion

This research shows that after ACL reconstruction, patients who are able to return to sport and who have larger activation of the gastrocnemius muscles just after initial contact during a unilateral landing with the operated leg have less dynamic anterior tibia translation. Moreover, patients who are not able to return to sports have larger knee flexion moments during a unilateral landing with the operated leg and have greater dynamic anterior tibia translation. The dynamic anterior tibia translation of the operated knee was less in non-copers who had less passive anterior tibia translation, but there was no significant association present in copers.

Correlation of ATT between legs

In the current study we found a positive association between ATTp of the operated leg and the contralateral leg. We also found a positive association between maximal ATTd of the operated leg and the contralateral leg. This may suggest that surgeons are able to reconstruct the ACL at a comparable length of that in the native ACL of the contralateral knee or that during rehabilitation the length of the reconstructed ACL adapts to its use. Miura et al. also found that an ACLR could reduce knee laxity close to the level of that of the contralateral knee [30]. However, there is also a study that found higher ATTp in the operated leg compared to the contralateral leg [29].

Table 2 SPM{x^2} CCA analyses and post-hoc SPMt regression analysis for the whole group (A), only the copers (B) and the non-copers (C) for the operated and contralateral leg. For the post-hoc analysis, only the significant variables are shown. The variable name, time frame after IC in which the variable is significant, the p-value and the direction of the relation is given.

A. Whole group

Operated leg			Contralateral		
Variable	Time after IC (ms)	p-value (sign)	Variable	Time after IC (ms)	p-value (sign)
Vastus lateralis	0-6	0.04 (-)	N.S.	N.S.	N.S.
Gastrocnemius medialis	0-6	0.025 (-)	N.S.	N.S.	N.S.
Gastrocnemius lateralis	0-2	0.048 (-)	N.S.	N.S.	N.S.
Knee flexion angle	11-40	<0.001 (+)	N.S.	N.S.	N.S.
CCA	*2-3 & 11-17*	*0.049 & 0.028*	*CCA*	*N.S.*	*N.S.*

B. Copers

Operated leg			Contralateral		
Variable	Time after IC (ms)	p-value (sign)	Variable	Time after IC (ms)	p-value (sign)
Gastrocnemius medialis	0-5	0.027 (-)	N.S.	N.S.	N.S.
Gastrocnemius lateralis	0-1	0.049 (-)	N.S.	N.S.	N.S.
CCA	*0-3*	*0.049*	*CCA*	*N.S.*	*N.S.*

C. Non-copers

Operated leg			Contralateral		
Variable	Time after IC (ms)	p-value (sign)	Variable	Time after IC (ms)	p-value (sign)
Knee flexion moment	13-19	0.011 (+)	Gastrocnemius medialis	12-18	0.026 (-)
			Gastrocnemius lateralis	9-13	0.032 (-)
CCA	*12-15*	*0.040*	*CCA*	*4-6 & 16-19*	*0.049 & 0.048*

CCA canonical correspondence analysis; *IC* initial contact; *N.S* not significant.

6

General joint laxity and ATT

It is shown that general joint laxity is associated with a larger risk of ACL injury and increased risk of graft failure after reconstruction of the ACL and is more common in patients with an ACL injury [3, 42]. We found an association between the Beighton score and ATTp for the whole group, showing that persons with larger general joint laxity also have larger amounts of specific passive anterior tibia translation. In addition, our analysis shows that just before a unilateral landing with the operated leg, patients who have a higher Beighton score also have a larger amount of ATTd. These results imply that in passive situations ATTp, or in dynamic situations with no external forces ATTd, are associated with general joint laxity. After initial contact there was no association between general joint laxity and ATTd for copers or non-copers and this suggests that during jump landing ATTd is limited by joint kinetics and/or muscle activation. Indeed, we show that knee kinematics, kinetics and muscle activation probably contribute to the movements in the joint, limits ATTd during unilateral landing in the operated leg in copers and non-copers. Also, it is shown that girls with large general joint laxity, showed different muscle activation patterns during a static balance task without vision which supports our suggestion [21].

Relation between ATTp and ATTd

Previous studies showed no correlation between ATTp and ATTd during gait, active extension, heel raises, cycling, one-legged squat and chair squat in ACL deficient, ACLR and healthy knees [28, 40]. One previous study, using the same technique as the present study, showed a weak negative correlation between ATTp and ATTd in healthy subjects [23]. In contrary, the present study shows a positive association between ATTp and ATTd of the operated leg for non-copers but not for copers. This difference may be due to the injury. Non-copers with greater amounts of ATTp also have greater amounts of ATTd during unilateral landing in the operated leg and this suggests that non-copers rely more on the strain of the ACL during impact than copers. The absence of a significant association in copers support the hypothesis that those who are able to return to sport are able to control ATTd and developed an effective strategy during their rehabilitation to reduce ATTd during landing. Consequently, copers rely less on the strain of the ACL to limit ATTd. This is also shown in healthy subject who amended their knee flexion moment to reduce their ATTd [23].

In the following subsections we will discuss the underlying mechanisms of how joint kinematics, kinetics and/or muscle activation can contribute to an effective strategy that reduces ATTd during unilateral jump landing in ACLR patients.

Kinematics, kinetics and ATTd

We can divide a unilateral jump landing in different phases, i.e. preparation, loading response, and stabilization. The preparation phase is during flight and the knee is extending in order to prepare for initial contact. Our analysis shows that during this preparation phase there are no crucial differences in kinematics, kinetics and muscle activation between the operated and non-operated leg and/or between copers and non-copers. The second phase, loading response, is characterized by a rapid knee flexion movement that enables shock absorption and deceleration of the body center of mass. We found that larger knee flexion angles during loading response result in more ATTd. This finding is in line with previous findings in healthy subjects using the same measuring methods [23]. Previous cadaver studies using a strain transducer on the anteromedial bundle of the ACL showed that the ACL is most strained when the knee is flexed between 0 and 30 degrees and the strain becomes less by larger amounts of knee flexion [6, 34]. Similar results are shown in healthy knees using an MRI and fluoroscopy based modeled jump landings [41]. These studies show that when the knee is flexed more than 30 degrees, the ACL is less strained. Consequently, there is more room for ATT and this is thus in line with our findings on dynamic ATT.

More knee flexion during jump landing results in less strain on the ACL [6, 34] and physiotherapists usually instruct their patients to land with a more flexed knee to prevent re-ruptures [11, 45]. However, when the ACL is slack (in high knee flexion angles) a greater translational acceleration can occur of the tibia relative to the femur which subsequently is decelerated by the ACL, resulting in a greater peak stress of the ACL in uncontrolled sudden movements. Future studies should focus on the combination of knee flexion during landing and mechanical properties of the ACL to get more insight into the optimal and patient specific landing technique that lowers the strain on the ACL.

Only the non-copers, with their operated leg, decreased their knee flexion moment to reduce the ATTd. A decreased knee flexion moment is possible due to less knee flexion, which limits the energy absorption around the knee joint during landing.

Muscle activation and ATTd

Gastrocnemius activity limits passive ATT [7, 18, 26] and we, for the first time, showed that increased gastrocnemius activity also limits ATT during a dynamic hopping task. The reason for this may be due to the tibia plateau angle, posteriorly lower than anteriorly [22], which favours ATT. A future study could investigate the influence of the anatomy of the knee on ATTd. In healthy subjects, in contrast with the findings of the present study, there is no association between muscle activation and ATTd, also during a unilateral jump landing [23]. This difference may be explained by the injury. After an ACLR patients may learn to limit their ATTd in different ways than healthy subjects.

Vastus lateralis (VL) activity was negatively associated with ATTd. Indeed, patients with greater activation of the VL just after initial contact showed less ATTd. This negative correlation is not as expected as previous studies showed that the quadriceps cause an increase in ACL loading [43]. One previous study in healthy subjects, also found a negative weight coefficient between VL and ATTd, however, not significant. An increased vastus activity reduces further knee flexion and we found that the knee flexion angle is positively correlated with ATTd. The knee flexion angle may have a larger contribution to ATTd than the vastus activity, which may explain that at the moment that the vastus lateralis activity is increased (and knee extension flexion angle is smaller) the ATTd is smaller than with less vastus lateralis activity.

Because of the harvest of the medial hamstring tendon it is a self-evident hypothesis that the activity of the hamstrings is reduced shifting the balance towards the quadriceps group [36]. However, we did not find a difference in hamstring activity of the injured leg compared to the uninjured leg. This is in line with a previous study which showed that medial hamstring tendons regenerate and the strength returns [39]. Consequently, harvesting of that tendon may not have been the background of the observed differences.

Summary copers v.s. non-copers:

We found that copers and non-copers, in their operated and contralateral leg, showed differences in the association between muscle activity and ATTd and between kinetics and ATTd. Copers increase their gastrocnemius activation to reduce the ATTd of the knee in the operated leg. Non-copers amended their knee flexion moment of their operated leg to reduce the ATTd. Moreover, with their contralateral leg non-copers also used muscle activation of the gastrocnemius muscles to reduce the ATTd. These results may imply that copers use muscle activation of the gastrocnemius to limit ATTd whereas non-copers fail to do this. Instead non-copers limit their knee flexion moment in order to limit ATTd. Figure 7 summarizes the results of this study. Only the significant variables on ATTd are depicted.

Strong and weak points

A strong point of this study is the high statistical power. A limitation of this study may be that the measured ATTd is influenced by wobbling masses. In another ex-

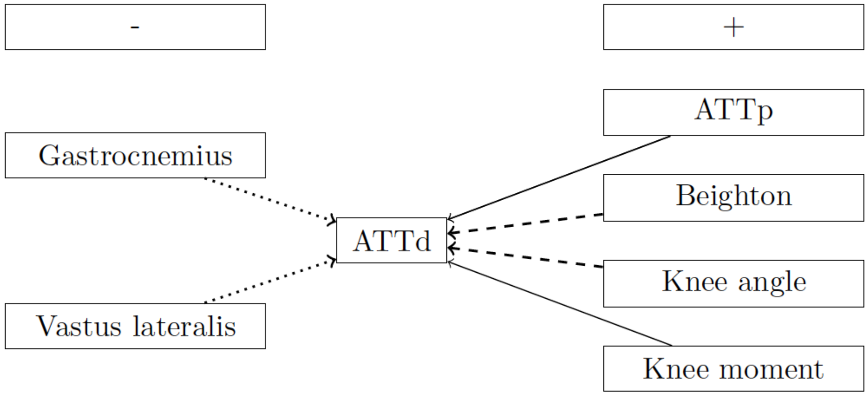


Fig. 7 Relation between significant variables and ATTd. Dashed line: whole group. Dotted line: only the copers. Continuous line: only the non-copers.

periment in which we identified the sensitivity of the method used to quantify ATTd on the marker placement (wobbling masses) and the Vicon's position error we found an error in measured ATTd of 2.32 mm [25]. All differences between patients or transients in one SLHD under 2.32 mm should be interpret with caution. This limitation is used to interpret the results of the current study. A second limitation is the method of normalization of muscle activity. We have chosen to normalize the muscle activity to the percentage of the mean muscle activity during the SLHD. This normalized muscle activity might be more comparable between participants than the non-normalized electrical muscle activity since the influence of variables like conductance and body fat are bypassed. We are using the muscle activation over a longer time window in the same task for normalization, which forms a background to detect peaks at certain moments in time.

6

Conclusion

Anterior tibia translation during unilateral jump landing is limited by knee flexion moments and gastrocnemius muscle activation but differs between copers and non-copers. Non-copers use a different landing technique from copers. Copers use increased gastrocnemius activity to limit ATTd of their operated leg, whereas non-copers limit their knee flexion moment to reduce ATTd.

References

[1] Abourezk, MN, Ithurburn, MP, McNally, MP, Thoma, LM, Briggs, MS, Hewett, TE, Spindler, KP, Kaeding, CC, Schmitt, LC Hamstring Strength Asymmetry at 3 Years after Anterior Cruciate Ligament Reconstruction Alters Knee Mechanics during Gait and Jogging. Am J Sports Med. 2017;45(1):97-105.

[2] Ahmad CS, Clark AM, Heilmann N, Schoeb JS, Gardner TR, Levine WN. Effect of Gender and Maturity on Quadriceps-to-Hamstring Strength Ratio and Anterior Cruciate Ligament Laxity. Am J Sports Med. 2006. 34(3):370-4.

[3] Akhtar MA, Bhattacharya R, Keating JF. Generalised ligamentous laxity and revision ACL surgery: Is there a relation? Knee. 2016;23(6):1148-53.

[4] Alkjær T, Henriksen M, Simonsen EB. Different knee joint loading patterns in ACL deficient copers and non-copers during walking. Knee Surgery, Sport Traumatol Arthrosc. 2011;19(4):615-21.

[5] Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: A systematic review and meta-analysis of the state of play. Br J Sports Med. 2011;45(7):596-606.

[6] Bakker R, Tomescu S, Brenneman E, Hangalur G, Laing A, Chandrashekar N. Effect of sagittal plane mechanics on ACL strain during jump landing. J Orthop Res. 2016;34(9):1636-44.

[7] Barcellona MG, Morrissey MC, Milligan P, Amis AA. The effect of thigh muscle activity on anterior knee laxity in the uninjured and anterior cruciate ligament-injured knee. Knee Surg Sports Traumatol Arthrosc. 2014;22(11):2821-9.

[8] Baumgart C, Gokeler A, Donath L, Hoppe MW, Freiwald J. Effects of Static Stretching and Playing Soccer on Knee Laxity. Clin J Sport Med. 2015;25(6):541-5.

[9] Begovic H, Zhou G-Q, Li T, Wang Y, Zheng Y-P. Detection of the electromechanical delay and its components during voluntary isometric contraction of the quadriceps femoris muscle. Front Physiol. 2014;5:494.

[10] Beighton P, Solomon L, Soskolnet CL. Articular Mobility in an African Population. Ann Rheum Dis. 1973;32(5):413-8.

[11] Benjaminse A, Gokeler A, Dowling AV, Faigenbaum A, Ford KR, Hewett TE, Onate JA, Otten B, Myer GD. Optimization of the anterior cruciate ligament injury prevention paradigm: Novel feedback techniques to enhance motor learning and reduce injury risk. J Orthop Sports Phys Ther. 2015;45(3):170-82.

[12] Berry J, Kramer K, Binkley J, et al. Error estimates in novice and expert raters for the KT-1000 arthrometer. J Orthop Sports Phys Ther. 1999;29(1):49-55.

[13] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, Moewis P, Scheffler S, Taylor WR. Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. Am J Sports Med. 2013;41(5):1051-7.

[14] Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. J Electromyogr Kinesiol. 2005;15(1):83-92.

[15] Ehrig RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining functional joint axes. J Biomech. 2007;40(10):2150-7.

[16] Ehrig RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining the centre of rotation of ball joints. J Biomech. 2006;39(15):2798-809.

[17] Eitzen I, Eitzen TJ, Holm I, Snyder-Mackler L, Risberg MA. Anterior Cruciate Ligament-Deficient Potential Copers and Noncopers Reveal Different Isokinetic Quadriceps Strength Profiles in the Early Stage after Injury. Am J Sports Med. 2010;38(3):586-593.

[18] Fleming BC, Renstrom PA, Ohlen G, Johnson RJ, Peura GD, Beynnon BD, Badger GJ. The Gastrocnemius Muscle Is an Antagonist of the Anterior Cruciate Ligament. J Orthop Res. 2001;19(6):1178-84.

[19] Gardinier ES, Di Stasi S, Manal K, Buchanan TS, Snyder-Mackler L. Knee contact force asymmetries in patients who failed return-to-sport readiness criteria 6 months after anterior cruciate ligament reconstruction. Am J Sports Med. 2014;42(12):2917-25.

[20] Cohen J. Statistical Power Analysis for the Behavioral Sciences. 1969. New York: Academic Press.

[21] Juul-Kristensen B, Johansen KL, Hendriksen P, Melcher P, Sandfeld J, Jensen BR. Girls with generalized joint hypermobility display changed muscle activity and postural sway during static balance tasks. Scand J Rheumatol. 2016;45(1):57-65.

[22] Kacmaz IE, Topkaya Y, Basa CD, Zhamilov V, Er A, Reisoglu A, Ekizoglu O. Posterior tibial slope of the knee measured on X-rays in a Turkish population. Surg Radiol Anat. 2020. [Epub ahead of print] PMID: 32052159.

[23] Keizer MNJ, Hijmans JM, Gokeler A, Benjaminse A, Otten E. Healthy subjects with lax knees use less knee flexion rather than muscle control to limit anterior tibia translation during landing. J Exp Orthop. 2020;15;7(1):32.

[24] Keizer MNJ, Otten E. Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review. Musculoskelet Surg. 2018;103(2):121-130.

[25] Keizer MNJ, Otten E. Technical note: sensitivity analysis of the SCoRE and SARA methods for determining rotational axes during tibiofemoral movements using optical motion capture. J Exp Orthop. 2020;7(1):6.

[26] Klyne DM, Keays SL, Bullock-Saxton JE, Newcombe PA. The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: A study of alterations in EMG measures and their relationship to knee joint stability. J Electromyogr Kinesiol. 2012;22(3):446-55.

[27] Kowalk DL, Wojtys EM, Disher J, Loubert P. Quantitative analysis of the measuring capabilities of the KT-1000 knee ligament arthrometer. Am J Sports Med. 1993;21(5):744-747.

[28] Kvist J. Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sports. 2005;15(3):148-58.

[29] Meyer CAG, Gette P, Mouton C, Seil R, Theisen D. Side-to-side asymmetries in landing mechanics from a drop vertical jump test are not related to asymmetries in knee joint laxity following anterior cruciate ligament reconstruction. Knee Surgery, Sport Traumatol Arthrosc. 2018;26(3):381-390.

[30] Miura K, Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, Toh S. Intraoperative comparison of knee laxity between anterior cruciate ligament-reconstructed knee and contralateral stable knee using navigation system. Arthrosc - J Arthrosc Relat Surg. 2010;26(9):1203-1211.

[31] Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43(7):1662-9.

[32] Project TS. Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles. SENIAM guidelines. 2016.

[33] Rangger C, Daniel DM, Stone ML, Kaufman K. Diagnosis of an ACL disruption with KT-1000 arthrometer measurements. Knee Surg Sport Traumatol Arthrosc. 1993;1(1):60-66.

[34] Renström P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med. 1986;14(1):83-7.

[35] Robertson G, Galdwell G, Hamill J, Kamen G, Whittlesey S. Research methods in biomechanics, 2E. Hum Kinet. 2013.

[36] Rogowski I, Vigne G, Blache Y, Thaunat M, Fayard JM, Monnot D, Sonnery-Cottet B. Does the Graft used for ACL Reconstruction Affect the Knee Muscular Strength Ration at Six Months Postoperatively? Int J Sports Phys Ther. 2019;14(4):546-53.

[37] Shelburne KB, Torry MR, Pandy MG. Effect of muscle compensation on knee instability during ACL-deficient gait. Med Sci Sports Exerc. 2005;37(4):642-8.

[38] Struzik A, Pietraszewski B. Relationships between Hamstrings-to-Quadriceps Ratio and Variables Describing Countermovement and Drop Jumps. Appl bionics Biomech. 2019;2019:4505481.

[39] Suijkerbuijk MAM, Reijman M, Lodewijks SJM, Punt J, Meuffels DE. Hamstring tendon regeneration after harvesting. Am J Sports Med. 2015;43(10):2591-2598.

[40] Tagesson S, Öberg B, Kvist J. Static and dynamic tibial translation before, 5 weeks after, and 5 years after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015;23(12):3691-7.

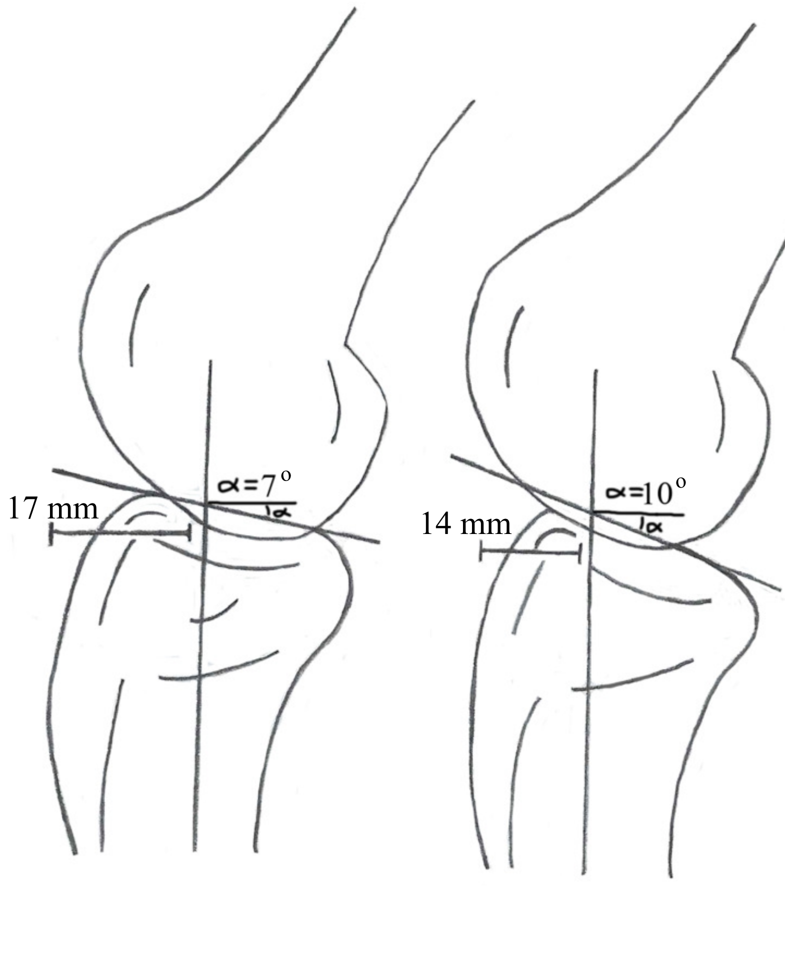
[41] Taylor KA, Terry ME, Utturkar GM, Spritzer CE, Queen RM, Irribarra LA, Garrett WE, DeFrate LE. Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. J Biomech. 2011;44(3):365-71.

[42] Vaishya R, Hasija R. Joint Hypermobility and Anterior Cruciate Ligament Injury. J Orthop Surg. 2013;21(2):182-4.

[43] Van Den Bogert AJ. Comment on “quadriceps protects the anterior cruciate ligament.” J Orthop Res. 2002;20(5):1133-4.

[44] van der Harst JJ, Gokeler A, Hof AL. Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg. Clin Biomech. 2007;22(6):674-80.

[45] Welling W, Benjaminse A, Gokeler A, Otten B. Retention of Movement Technique: Implications for Primary Prevention of ACL Injuries. Int J Sport Phys Ther. 2017;12(6):908–20.



17 mm
α=7°
α
14 mm
α=10°
α

Chapter 7

Sagittal Knee Kinematics in Relation with the Posterior Tibia Slope During Jump Landing After an Anterior Cruciate Ligament Reconstruction

Michèle N.J. Keizer · Juha M. Hijmans · Alli Gokeler · Egbert Otten · Reinoud. W. Brouwer

Journal of Experimental Orthopaedics 2020;21;7(1):69
http://dx.doi.org/10.1186/s40634-020-00289-9

Highlights

- Patients with larger Medial PTPA have lower ATT
- Patients with a smaller lateral PTPA show larger maximal knee flexion angle
- Patients with a larger lateral tibia plateau angle may automatically adapt their landing strategy (i.e. maximal knee flexion angle and muscle activity) to the anatomy of their knee

Abstract

Purpose: An increased posterior tibia plateau angle is associated with increased risk for anterior cruciate ligament injury and re-rupture after reconstruction. The aims of this study were to determine whether the tibia plateau angle correlates with dynamic anterior tibia translation (ATT) after an anterior cruciate ligament reconstruction and whether the tibia plateau angle correlates with aspects of knee kinematics and kinetics during jump landing.
Method: Thirty-seven patients after anterior cruciate ligament reconstruction with autograft hamstring tendon were included. Knee flexion angle and knee extension moment during single leg hops for distance were determined using a motion capture system and the dynamic ATT with its embedded method. The medial and lateral posterior tibia plateau angle were measured using MRI. Moreover, passive ATT was measured using the KT-1000 arthrometer.
Results: A weak negative correlation was found between the maximal dynamic ATT and the medial tibia plateau angle ($p=0.028$, $r=-0.36$) and between the maximal knee flexion angle and the lateral tibia plateau angle ($p=0.025$, $r=-0.37$) during landing. Patients with a smaller lateral tibia plateau angle show larger maximal knee flexion angle during landing than the patients with larger lateral tibia plateau angle. Also, the lateral tibia plateau angle is associated the amount of with muscle activity.
Conclusion: The posterior medical tibia plateau angle is associated with dynamic ATT. The maximal knee flexion angle and muscle activity are associated with the posterior lateral tibia plateau angle.

Level of evidence: III

Keywords Knee, Knee laxity, anatomy, tibia plateau

Introduction

The posterior tibia plateau angle (PTPA) is defined as the angle of the posterior tibia plateau relative to the plane orthogonal to the longitudinal axis of the tibia in the sagittal plane. The PTPA has a medial angle (MPTPA) and a lateral angle (LPTPA). On radiographs, the PTPA has shown to be increased in patients who have had an ACL injury compared to a group that had no injury [31]. Therefore, increased PTPA is a risk factor for anterior cruciate ligament (ACL) injury [17, 26, 30] and re-rupture after an ACL reconstruction [10, 14, 33].

A correlation between the PTPA and knee kinematics using cadaveric experiments (e.g.. [13]) and model studies (e.g. [20, 27, 29]) have been found. For example, it has been reported by using a biomechanical computational model that an increased PTPA, where the MPTPA and LPTPA was seen as one plateau, is associated with larger calculated anterior tibia translation (ATT) during the stance phase of gait in both healthy and ACL-deficient modelled knees [27]. It has also been shown that an increase in both the MPTPA and LPTPA correlates with an increased passive ATT in ACL injured [25], ACL reconstructed (ACLR) [5] and cadaveric knees [13]. The explanation for these results is that the tibiofemoral contact force on the tibia plateau with a large PTPA results in more ATT in a passive situation than when the PTPA is smaller. An increase in ATT consequently results in more load on the ACL: in cadaveric knees, 80% to 90% of the anteriorly applied tibial loads, using the drawer test, is supported by the ACL [4].

As a larger PTPA is associated with an increase in ATT, some orthopaedic surgeons consider and recommend a combined ACLR and anterior closing wedge tibial osteotomy in patients after an ACL injury in order to reduce the PTPA, especially in patients after an ACL re-rupture, when the PTPA is larger than a threshold of 12 degrees [6, 7, 13]. This is aimed at reducing the chance of re-rupture of the graft. It is shown that with an absence of applied internal moment, an anterior closing wedge tibial osteotomy in cadaveric knees alters knee kinematics, reduced the passive ATT, which results in a reduction of ACL load [13, 36]. However, neuromuscular control, kinematics and kinetics were not taken into account. The PTPA may play a significant role in the force load on the ACL. On biomechanical grounds patients who have a large PTPA may show different dynamics of the knee, due to a difference in direction of the condylar reaction force. Moreover, it is found that there is a correlation between the PTPA and the knee moment by using a model of a drop vertical jump [2]. As far as known to the authors it is not yet known if and how the PTPA correlates with dynamic in-vivo kinematics and kinetics during high demanding functional tasks, such as jump landing, after an ACLR.

This study sought to determine whether the PTPA (MPTPA and LPTPA) positively correlate with the dynamic ATT (ATTd) after an ACL reconstruction during a jump landing. The second aim was to determine how the MPTPA and LPTPA correlates with the knee flexion angle and knee internal extension moment during landing. We hypothesized that the PTPA is positively correlated with the maximal ATT during jump landing and that the PTPA does have a positive correlation with the knee flexion angle and internal extension moment of the knee.

Methods

The study was conducted at the University Medical Center Groningen (UMCG) in the period from April 2018 - November 2019. The study design, procedure, and protocol are approved by the Medical Ethical Committee of the UMCG (METC number: 2017.658). All participants were informed about the procedures and aim of the study by letter and they signed an informed consent before the start of the measurement.

Participants

Sample size estimations were performed a priori. Means and standard deviations from available data from the literature [18] were entered for the MPTPA in correlation with passive ATT (r=0.41). As no information about the correlation between dynamic ATT and PTPA is available in the literature, the correlation between passive ATT and MPTPA was used for the power analysis. Based on a statistical power set at $\alpha \leqslant 0.05$ and a power of 80% to detect a statistically significant correlation, 33 subjects were needed.

To be on the safe side of the statistical power, thirty-seven patients (13 woman and 24 men; age: 18-39) were included in the study. Inclusion criteria were one to two years post-surgery, age between 18 and 45 years and ACLR with autograft hamstring tendon. Exclusion criteria were patients with cartilage pathology that needed concomitant surgical treatment and changed the standard rehabilitation, who underwent a revision ACLR, osteotomy or contralateral ACLR. For baseline characteristics see Table 1.

Table 1 Baseline characteristics of the participants: allograft versus autograft.

	Mean	Range		Man	Woman
Age	25.9	18-39	Gender	24	13
Height (cm)	181.7	161-197.6			
Weight (kg)	78.2	51.7-111.6		Yes	No
Month post-surgery	16.4	12-14	RTS/not RTS	26	11
MPTPA (deg)	3.7	-21-8.8			
LPTPA (deg)	5.3	0.6-12.2			
Maximal ATTd (mm)	12.1	-0.1-22.3			
KT-1000 arthrometer (mm)	5.1	1.1-9.5			

MPTPA: medial posterior tibia plateau angle. *LPTPA*: lateral posterior tibia plateau angle. *ATT*: anterior tibia translation. *RTS*: return to sports.

Surgical technique

Subjects were included in this study after surgery, though in all patients the same surgical procedures were followed. For all surgical procedures, ipsilateral gracilis and semitendinosus autografts were used. If the graft diameter was less than 8 mm, one of the two grafts was tripled. After arthroscopic inspection of the patellofemoral joint and the cartilage and menisci of both compartments, the remaining ACL stumps were removed. First, the femoral socket was created through the anteromedial portal using a cannulated reamer 0.5 mm less than the diameter of the graft. Subsequently, the tibial tunnel was drilled using a cannulated reamer with the diameter of the graft. After introduction, the hamstring graft was fixated in the femoral socket with an endobutton (Endobutton CL Ultra; Smith & Nephew) and after 20 cycles the graft was fixated in the tibial tunnel with a plug and a peek interference screw (Biosure; Smith & Nephew) of one mm more than the diameter of the graft with the knee in 0-10 degrees of flexion.

Study parameters

The primary outcome measures were the maximal ATT during a single leg hop for distance (SLHD) landing determined using a passive motion capture system (VICON VERO; VICON Motion Systems Ltd, Oxford, UK) and its embedded methods and the MPTPA and LPTPA determined using MRI. The MRI's were taken as part of the care as usual. In addition, primary study parameters during the jumping task were the knee flexion angle, and internal knee extension moment measured using a Vicon system and force platform (AMTI; Watertown, MA). During the single leg hop for distance surface electromyographic (sEMG) data was captured using Cometa electrodes (Cometa Wave Plus Wirless sEMG system, Cisliano Milano, Italy) of the medial hamstring (MH), lateral hamstring (LH), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL). A secondary study parameter was passive ATT measured with the KT-1000 arthrometer (MEDmetric Corporation, San Diego, California, USA).

Procedure

Dynamic ATT

First, 42 retroreflective markers were attached to the participants. Markers were attached as shown in Fig. 1 (adapted from Boeth et al., 2013). The same investigator (MNJK) performed all marker and electrode placements. Marker positions were measured using the 10-camera three-dimensional motion capture system Vicon at a frequency of 200 Hz. After attaching the markers, calibration frames of a flexion-extension movement and a star-arc movement, as prescribed by the manual of VICON, were performed to be able to identify the joint hip and knee centres and axes of rotation of the knees [8, 9]. Then, the SLHD were performed as described previously [32]. For another study the SLHD was performed for both legs, for this study only data of the operated leg was of interest. First, three practice jumps were performed with both legs. The participants hopped forwards as far as possible starting from standing still on their tested leg. They were instructed to stand still for at least three seconds after landing to assure a controlled landing. The median distance of the practice jumps was used as the starting distance from a 40x60 cm force platform (AMTI; Watertown, Massachusetts). Next, twenty successful jumps, 10 with each leg. were performed where the participant landed on the force plate. The starting leg was randomised.

MPTPA and LPTPA using MRI

The MPTPA and LPTPA were measured by means of MRI using the circle method [12, 19] using a customized MATLAB script. See Fig. 2 for a description of this procedure. This procedure was repeated three times for each slope and each participant by the same researcher. The mean of the three calculated angles was taken.

Quantifications of ATT and knee angles

For quantification of ATTd and knee angles see Keizer and Otten (2020). In brief, two coordinate systems were reconstructed in the tested knee using a customized MATLAB script based on the method of Boeth et al. [3]. One system was reconstructed in

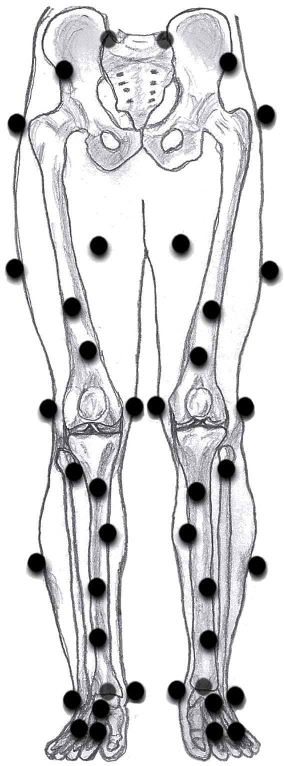


Fig. 1 Marker placement. Markers were attached on the right and left anterior and posterior superior iliac spine, the right and left iliac crest, the greater trochanter, the medial and lateral epicondyles of the knee, the medial and lateral malleoli of the ankle, the heel, anterior of the talus bone and the first and fifth metatarsophalangeal joints. Besides, two additional markers were attached to the pelvis, two to the thigh, and six additional markers were attached to the shank (adapted from Boeth et al. [3]).

the femoral segment (parent system) and one in the tibia segment (child system). The motion of each coordinate system is consistent with the movement of the respective segment. After reconstruction of the two coordinate systems, the femoral coordinate system was translated and rotated towards the local tibia coordinate system. Finally, the anterior tibia translation was quantified in millimeters using the relative movement of the joint centre of rotation of the tibia coordinate system relative to the joint centre of rotation of the femoral coordinate system in the local tibial coordinate system. The coefficient of variation of this procedure across 16 healthy knees is 5.2% +/- 1.2% and excellent reproducibility was observed (ICC(3,1) = 0.92). Moreover, Keizer and Otten [16] showed that ATTd larger than 2.32 millimeter (mm) is reliable in terms of wobbling masses and the Vicon marker position error. The knee flexion

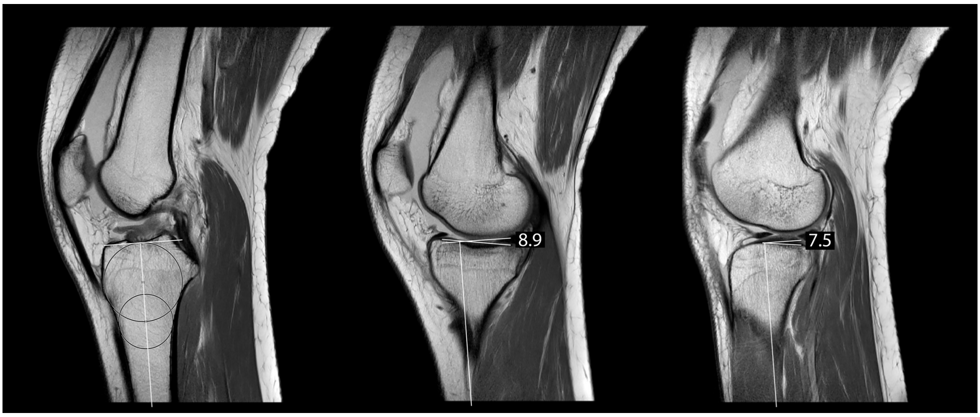


Fig. 2 Determination of the medial and lateral PTPA using MRI and the circle method [12, 19]. First, the central sagittal MRI image was found (left image). This image was determined using the following criteria: the anterior and posterior proximal tibia cortices were visible in concave shape and the intercondylar eminence and the posterior cruciate ligament attachment were visible in the image. In this image, a circle was fitted to the proximal tibia, tangential to the cortices. A second circle was fitted distally in the tibia with its centre placed on the first circle. The longitudinal axis was determined by the line connecting the centres of the two circles. Then, the mid-sagittal images of the medial and lateral femoral condyles were selected (middle and right image). The angle between the line connecting the anterior and posterior articular surface of the posterior tibia plateau and the line at right angles to the longitudinal axis of the tibia on both medial and lateral images were the MPTPA and LPTPA respectively.

angles, the rotations between both coordinate systems, tibia and femur, were calculated. The rotations are obtained using scalar products as in the equations explained in Robertson et al. [23].

Data analysis

Data were processed and analysed using the MATLAB version 9.4 (The MathWorks Inc., Natick, Massachusetts). The ATT, sagittal knee angle and knee extension moment during each jump were determined from the moment of first ground contact until 0.5 seconds after the moment of first ground contact. The moment of first ground contact was determent as the moment where the vertical ground reaction force measured by the force plate was at least five percent of the participants body weight expressed in N. Kinematic data were filtered using a convolution filter with low pass frequency of 10 Hz with zero lag. Using inverse dynamics, the ground reaction force vector and its lever arm to the centre of the knee of the stance leg where used to calculate the internal knee extension moment, which was normalized to body mass [35].

sEMG signals were recorded at 1000 Hz. The signals were rectify and a fourth-order low pass frequency Butterworth filter with a cut-off frequency of 6 Hz with zero lag was used to filter the muscle activity, taking into account an electromechanical delay of 50 milliseconds. The EMG signals were scaled to the mean muscle activity during 1 second before IC until 1.5 second after IC of the single leg hop for distance to minimize the effects of body fat and skin conductivity. We did not scale to the maximal muscle activity of an isometric contraction task as a large variation in peak activation of, especially the medial hamstrings muscle, during this task was observed.

Statistical analysis

For all statistical analysis the Statistics Toolbox from MATLAB version 9.4 was used. To assess the intertrial repeatability of the approach to measure the MPTPA and LPTPA the intraclass correlation coefficients ICC(3,1) was determined [22].

A Pearson correlation was performed between ATTp and maximal ATTd. A multi-regression analysis with intercept was performed for both the MPTPA and LTPA correlating with the maximal dynamic ATT, knee flexion angle and knee extension moment. A Pearson correlation was calculated between the maximal ATT during jump landing and the MPTPA and between the maximal ATT and the LPTPA. In addition, Pearson correlations were calculated between the MPTPA/LPTPA and the maximal knee moment, and between MPTPA/LPTPA plateau and the maximal knee flexion angle. An alpha of $\alpha \leqslant 0.05$ was considered to be significant. If a correlation was significant, a correlation coefficient of 0.2-0.49, 0.5-0.79 and 0.8-1 were considered to represent a weak, a moderate and a strong association, respectively [37].

A statistical parametric mapping (SPM) canonical correlation analysis (CCA) was performed to find the significance between muscle activity and the LPTPA or MPTPA over time. An open-source spm1d code (v.M.0.1, www.spm1d.org) in MATLAB version 9.7 was used to perform the SPM$\{X^2\}$. For this analysis, data from initial contact until 0.5 seconds after initial contact was used. Correlations were calculated between LTPTA or the MPTPA and the activities of the muscles. The null hypothesis was rejected when the original SPM$\{X^2\}$ analysis exceeded the calculated critical X2-value (threshold) based on an α of $\leqslant 0.05$, implying a correlation. When significant values were reached, a post-hoc regression analysis was performed over time for each muscle activity separately.

7

Results

MPTPA, LPTPA and passive ATT

The PTPA was measured three times for each participant by the same researcher. Excellent reproducibility was found between instances that the PTPA was calculated (MPTPA ICC(3,1) = 0.98, LPTPA ICC(3,1) = 0.98). For the mean and range of the MPTPA, LPTPA and ATT see Table 1. A non-significant correlation was found between ATTp and maximal ATTd ($p = 0.20$).

Correlation between PTPA and kinematics

A multi-regression analysis with intercept revealed a non-significant correlation for the MPTPA (r2=0.13, p=0.18) and LPTPA (r2=0.17, p=0.09). A weak significant negative correlation was found between the maximal ATT and the MPTPA (p=0.028, r=-0.36; Fig. 3A). A weak significant negative correlation was found between the maximal knee flexion angle and LPTPA (p=0.025, r=-0.37; Fig. 3D). No significant correlation was found between the maximal ATT and the LPTPA (p=0.88, r=-0.03; Fig. 3B), between the maximal knee flexion angle and MPTPA (p=0.28, r=-0.18; Fig. 3C), between the maximal knee extension moment and MPTPA (p=0.46, r=-0.12; Fig. 3E) and between the maximal knee extension moment and the LPTPA (p=0.15, r=-0.24; Fig. 3F). In addition, a weak significant positive correlation was found between the MPTPA and LPTPA (p=0.02, r=0.38).

Muscle activation and PTPA

The SPM$\{X^2\}$ analysis of the lateral tibia plateau angle with the muscle activity showed a significant CCA between 6 and 10 ms after initial contact ($p = 0.03$; Fig. 4A). The post-hoc SPM{t} regression analysis showed a significant negative correlation of the medial hamstrings muscle between 4.5 and 7 ms after IC (Fig. 4B). All other muscles did not show a significant correlation with the lateral tibia plateau angle (Fig. 4C-H). The SPM$\{X^2\}$ analysis of the medial tibia plateau angle with the muscle activity showed a non-significant CCA (Fig. 5).

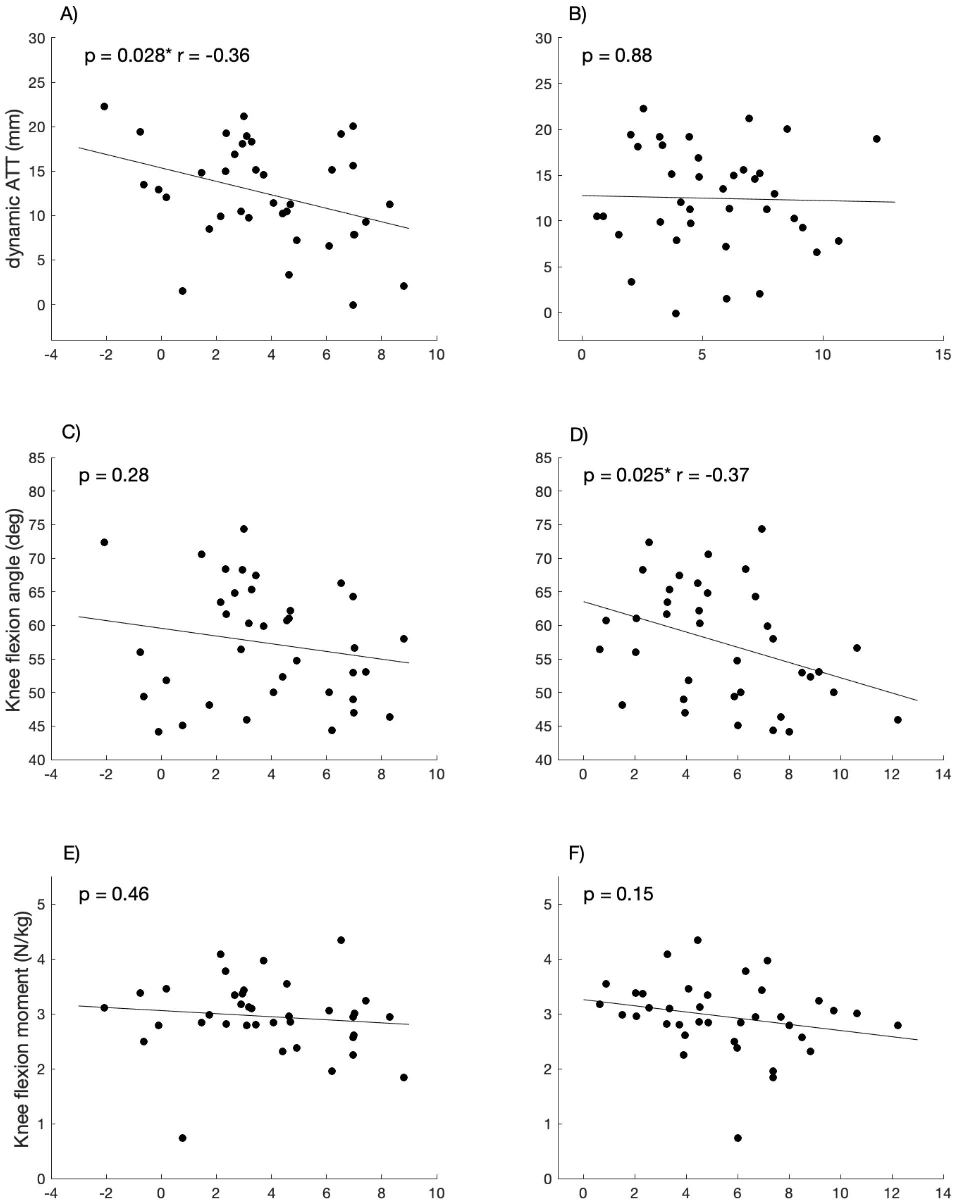


Fig. 3 Correlations between MPTPA and the maximal dynamic ATT (A), knee flexion angle (C) and knee extension moment (E), and between LPTPA and the maximal dynamic ATT (B), knee flexion angle (D) and knee extension moment (F). *: significant

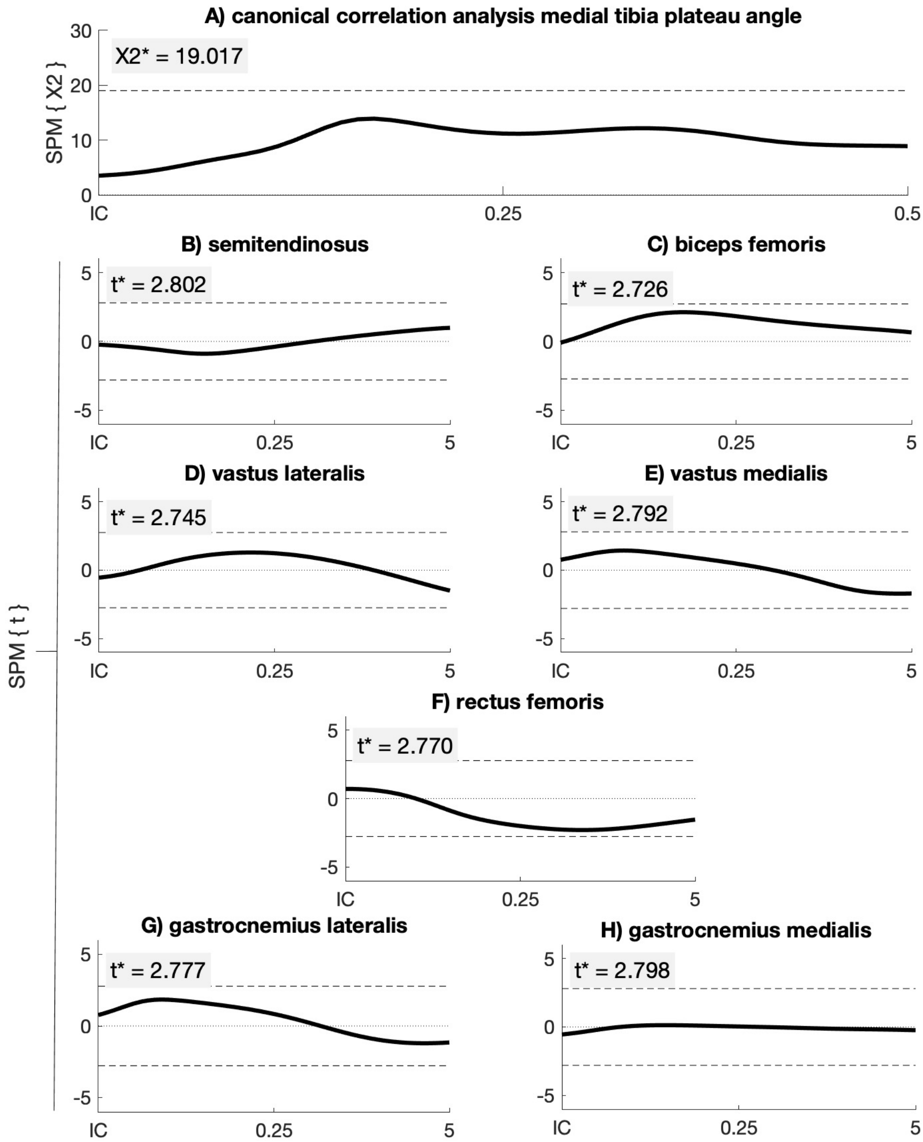


Fig. 4 SPM{X^2} canonical correlation analysis between muscle activity and the LPTPA (A). Pos-hoc SPM{t} regression analysis between LPTPA and the medial hamstrings (B), biceps femoris (C), vastus lateralis (D), vastus medialis (E), rectus femoris (F), gastrocnemius lateralis (G) and gastrocnemius medialis (H) activation. X2* and t* are the significant boundaries of the analysis.

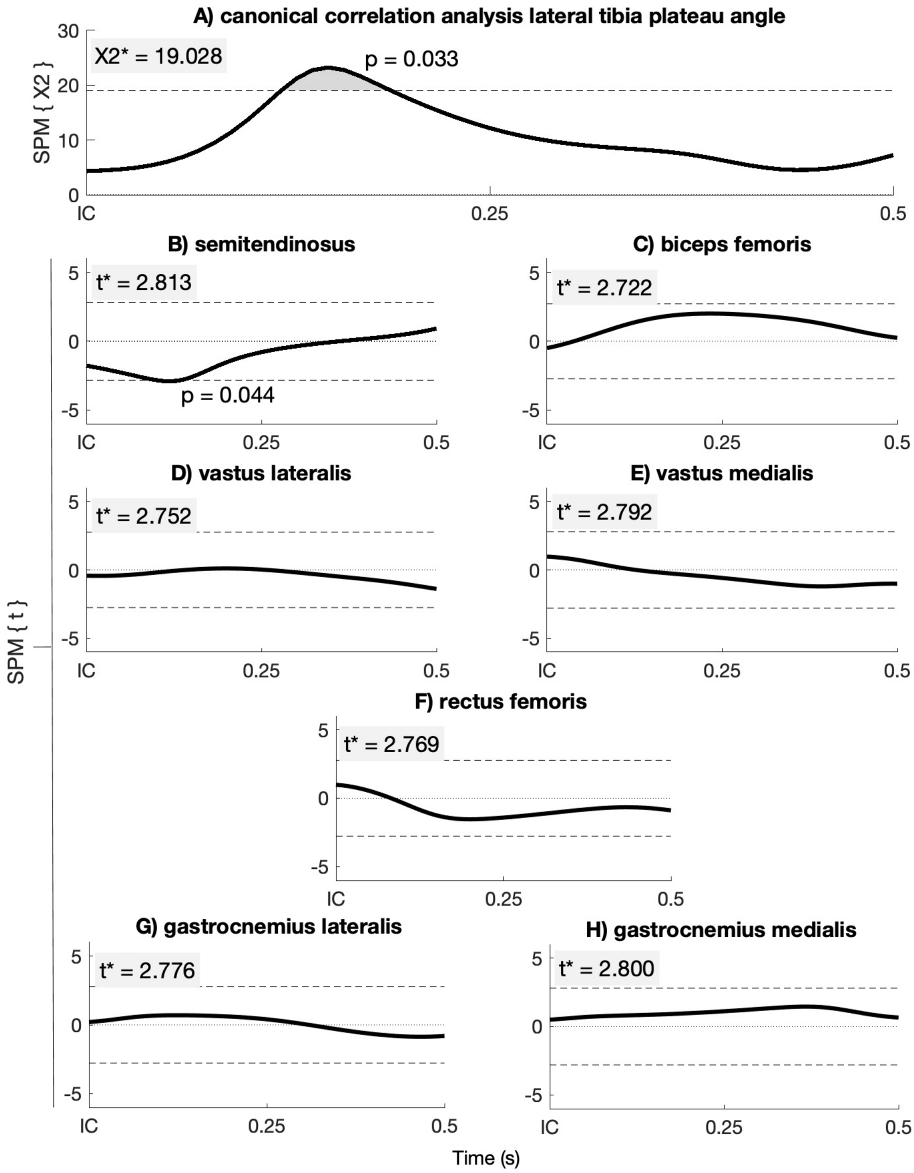


Fig. 5 SPM{X^2} canonical correlation analysis between muscle activity and the LPTPA (A). Pos-hoc SPM{t} regression analysis between LPTPA and the medial hamstrings (B), biceps femoris (C), vastus lateralis (D), vastus medialis (E), rectus femoris (F), gastrocnemius lateralis (G) and gastrocnemius medialis (H) activation. X2* and t* are the significant boundaries of the analysis.

Discussion

The most important findings of this study are that there is a weak significant negative correlation between ATTd and MPTPA and between the maximal knee flexion angle and LPTPA. Moreover, a significant correlation between muscle activation (especially a negative correlation of the medial hamstrings) and the LPTPA is found just after initial contact. This may imply that the slope of the PTPA is associated with the kinematics of ACL injured and reconstructed knees and that patients with a larger LPTPA automatically adapt their landing strategy (i.e. more knee flexion angle and medial hamstrings activity) to the anatomy of their knee.

Previous model studies showed that an increase in PTPA results in an increase in ATT (e.g. [27, 28]). Our study confirms that there is an association between ATTd during jump landing and the MPTPA. However, we found a negative correlation where the previous studies found a positive correlation: in our study, patients with larger MPTPA showed less maximal ATTd than patients with smaller MPTPA (r=-0.36). This is not as we hypothesized. In a passive situation tibiofemoral contact force on the tibia plateau in people with a larger PTPA results in more ATTp than when the PTPA is smaller. One possible explanation for the contradiction may be that during dynamic situations compensational muscle activation patterns play a significant role in limiting the ATTd. A non-significant correlation between ATTp and ATTd also implies this. During our study, patients may have compensated for increased dynamic ATTd or PTPA by using suitable muscle activation patterns or kinematics. A significant CCA between muscle activation and the LPTPA just after initial contact is indeed found. This is in line with previous studies who found adaptative muscle activation patterns in patients after an ACL reconstruction during gait [24] and suggested that neuromuscular compensation strategies enable patients after an ACL reconstruction to return to high demanding sports activities [21]. A 3D computer model study fed with real in vivo data could investigate the effect of the PTPA on kinematics, kinetics and muscle activity in further detail.

It has been shown that patients who have had an ACL injury compared to a group that had no ACL injury have larger LPTPA [31]. In our study we found that patients after an ACLR with larger MPTPA showed less ATTd and did not find a significant correlation between the LPTPA and ATTd. The results of Sonnery-Cottet et al. [31] and our results seems to contradict each other. However, as described in the previous paragraph, patients after an ACLR may compensate for larger PTPA by using muscle activation patterns in a way to reduce ATTd. When there is a loss of feedforward muscular activation control, for instance at foot positions that occur in a very short time span, an ACL (re)injury may occur in patients with a large PTPA because forces are not carried by the muscular components. This is in line with previous studies that showed that the PTPA correlates with an increased ATTp in ACL injured, ACL reconstructed and cadaveric knees [5, 13, 25]. We did find a significant CCA between the LPTPA and muscle activation, which suggests that patients indeed amend their muscle activation to the anatomy of their knee, especially by reducing their medial hamstring activity when the LPTPA is larger. This result is in line with our finding that patients with larger LPTPA showed smaller maximal knee flexion angle during jump landing than patients with smaller LPTPA. Patients with a larger LPTPA may automatically adapt their landing strategy (i.e. maximal knee flexion angle and hamstring activation) to their anatomy of the knee. Less knee flexion angle reduces ATTd. Further research could investigate if patients with larger PTPA use different muscle activation patterns than patients with smaller PTPA to reduce the ATTd.

The MPTPA and LPTPA have a low correlation: some patients with large MPTPA have small LPTPA (the difference between MPTPA and LPTPA is -9.1 to 3.7 (mean: -1.82) degrees in our study). Previous studies found asymmetry (a nonsignificant or weak correlation) between the LPTPA and MPTPA [11, 34]). A large LPTPA does not necessarily imply that these patients also have a large MPTPA. Our results showed, in most cases, a larger LPTPA than the MPTPA, which is also found in the study of Hashemi et al. [11]. Hashemi et al. [11] showed a range of MPTPA of -3 to 10 degrees (our study -2.1 to 8.8) and of LPTPA of 0 to 14 degrees (our study 0.6 to 12.2). We suggest that a larger LPTPA than the MPTPA is beneficial in terms of biomechanics because this combination provides a larger internal tibia rotation moment during walking. A larger internal tibia rotation moment (counteracted by a moment from the floor) helps to rotate the trunk in swinging the other leg forwards during walking. Also, our results showed a correlation between ATTd and MPTPA, however, not between ATTd and LPTPA.

Some orthopaedic surgeons even consider and recommend a combined ACLR and anterior closing wedge tibial osteotomy in patients after an ACL injury in order to reduce the PTPA [6, 7, 13]. It is shown that with an absence of applied internal moment, an anterior closing wedge tibial osteotomy in cadaveric knees alters knee kinematics, reduced the ATTp, which results in a reduction of ACL load [13, 36]. However, neuromuscular control, kinematics and kinetics were not taken into account. Future studies should investigate whether the ATTd is reduced, in situations with loss of muscular activation control, after an anterior closing wedge tibial osteotomy to confirm this suggestion.

Limitations

A limitation of this study that needs to be addressed is the potential influence of wobbling masses on the measured dynamic ATT. However, Keizer and Otten [16] have identified the sensitivity of the method to determine dynamic ATT on the marker placement (wobbling masses) and Vicon's position error. The error found in this sensitivity study was less than 2.32 mm [16]. The results of the current study were interpret using this error. A lack of golden standard makes it impossible to verify the outcomes of the methods used. When compared to previous studies the range of dynamic ATT is comparable. In previous studies the dynamic ATT range was 11.5 mm (-4.7 to 6.8 mm) [15] and 12 mm (-2 to 10 mm) [16] both using the same methods, 10 mm (8 to 18 mm) using bi-planar fluoroscopy model-based data during running [1]; all in healthy subjects. In our study the mean range of dynamic ATT was 13.42 (-2.96 to 10.46). A second limitation may be the method of normalization of muscle activity. We normalized muscle activation to the percentage of the mean muscle activity during the single leg hop for distance. This normalized muscle activation may be more comparable between patients than the absolute maximal electrical muscle activation. This was done because we observed large differences in the maximal muscle activation between legs during this task, especially in the medial hamstrings muscle. Since we are averaging over subjects in a group, this provides numerical more stable results. A third limitation is the absence of information about the tibia plateau slope of the contralateral knee. It would be very interesting for future study to investigate the contralateral tibia plateau slope in correlation with muscle activation and the difference between the contralateral and injured knee.

Conclusion

The dynamic ATT during a single leg hop for distance is negatively correlated with the MPTPA, however not with the LPTPA. Moreover, patients with a smaller LPTPA show larger maximal knee flexion angle during landing than the patients with larger LPTPA. Moreover, a correlation between the LPTPA and muscle activation was found.

References

[1] Anderst W, Zauel R, Bishop J, Demps E, Tashman S (2009) Validation of Three-Dimensional Model-Based Tibio-Femoral Tracking During Running. Med Eng Phys 31(1):10-6

[2] Bates NA, Nesbitt RJ, Shearn JT, Myer GD, Hewett TE, Hewett TE (2016) Posterior Tibial Slope Angle Correlates with Peak Sagittal and Frontal Plane Knee Joint Loading during Robotic Simulations of Athletic Tasks. Am J Sports Med 44(7):1762–70

[3] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, Moewis P, Scheffler S, Taylor WR (2013) Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. Am J Sports Med 41(5):1051–7

[4] Butler DL, Noyes FR, Grood ES (1980) Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg Am 62(2):259–70

[5] Dejour D, Pungitore M, Valluy J, Nover L, Saffarini M, Demey G (2019) Tibial slope and medial meniscectomy significantly influence short-term knee laxity following ACL reconstruction. Knee Surg Sport Traumatol Arthrosc 27(11):3481-3489

[6] Dejour D, Saffarini M, Demey G, Baverel L (2015) Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. Knee Surg Sports Traumatol Arthrosc 23(10):2846–52

[7] DePhillipo NN, Kennedy MI, Dekker TJ, Aman ZS, Grantham WJ, LaPrade RF (2019) Anterior Closing Wedge Proximal Tibial Osteotomy for Slope Correction in Failed ACL Reconstructions. Arthrosc Tech 8(5):e451–e457

[8] Ehrig RM, Taylor WR, Duda GN, Heller MO (2006) A survey of formal methods for determining the centre of rotation of ball joints. J Biomech 39(15):2798–809

[9] Ehrig RM, Taylor WR, Duda GN, Heller MO (2007) A survey of formal methods for determining functional joint axes. J Biomech 40(10):2150–7

[10] Grassi A, Signorelli C, Urrizola F, Macchiarola L, Raggi F, Mosca M, Samuelsson K, Zaffagnini S (2019) Patients With Failed Anterior Cruciate Ligament Reconstruction Have an Increased Posterior Lateral Tibial Plateau Slope: A Case-Controlled Study. Arthroscopy 35(4):1172–1182

[11] Hashemi J, Chandrashekar N, Gill B, Beynnon BD, Slauterbeck JR, Schutt RC, Mansouri H, Dabezies E (2008) The Geometry of the Tibial Plateau and Its Influence on the Biomechanics of the Tibiofemoral Joint. J Bone Joint Surg Am 90(12):2724-34

[12] Hudek R, Schmutz S, Regenfelder F, Fuchs B, Koch PP (2009) Novel measurement technique of the tibial slope on conventional MRI. Clin Orthop Relat Res 467(8):2066–2072

[13] Imhoff FB, Mehl J, Comer BJ, Obopilwe E, Cote MP, Feucht MJ, Wylie JD, Imhoff AB, Arciero RA, Beitzel K (2019) Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load. Knee Surg Sports Traumatol Arthrosc 27(10):3381-3389

[14] Jaecker V, Drouven S, Naendrup JH, Kanakamedala AC, Pfeiffer T, Shafizadeh S (2018) Increased medial and lateral tibial posterior slopes are independent risk factors for graft failure following ACL reconstruction. Arch Orthop Trauma Surg 138(10):1423–1431

[15] Keizer MNJ, Hijmans JM, Gokeler A, Benjaminse A, Otten E (2020) Healthy subjects with lax knees use less knee flexion rather than muscle control to limit anterior tibia translation during landing. J Exp Orthop 15;7(1):32

[16] Keizer MNJ, Otten E (2020) Technical note: sensitivity analysis of the SCoRE and SARA methods for determining rotational axes during tibiofemoral movements using optical motion capture. J Exp Orthop 7(1):6

[17] Kızılgoz V, Sivrioglu AK, Ulusoy GR, Yıldız K, Aydın H, Çetin T (2019) Posterior tibial slope measurement on lateral knee radiographs as a risk factor of anterior cruciate ligament injury: A cross-sectional study. Radiography 25(1):33–38

[18] Li Y, Hong L, Feng H, Wang Q, Zhang J, Song G, Chen X, Zhuo H (2014) Posterior tibial slope influences static anterior tibial translation in anterior cruciate ligament reconstruction: A minimum 2-year follow-up study. Am J Sports Med 42(4):927–33

[19] Lipps DB, Wilson AM, Ashton-Miller JA, Wojtys EM (2012) Evaluation of Different Methods for Measuring Lateral Tibial Slope Using Magnetic Resonance Imaging. Am J Sports Med 40(12):2731–2736

[20] Navacchia A, Bates NA, Schilaty ND, Krych AJ, Hewett TE (2019) Knee Abduction and Internal Rotation Moments Increase ACL Force During Landing Through the Posterior Slope of the Tibia. J Orthop Res 37(8):1730–1742

[21] Nyland J, Mauser N, Caborn DNM (2013) Sports involvement following ACL reconstruction is related to lower extremity neuromuscular adaptations, subjective knee function and health locus of control. Knee Surg Sports Traumatol Arthrosc 21(9):2019–28

[22] Portney, LG, Watkins MP (2009) Foundations of clinical research: applications to practice. Pearson/Prentice Hall, Saddle River, NJ

[23] Robertson G, Galdwell G, Hamill J, Kamen G, Whittlesey S (2013) Research methods in biomechanics, 2E. Hum Kinet

[24] Roper JA, Terza MJ, Tillman MD, Hass CJ (2016) Adaptation Strategies of Individuals With Anterior Cruciate Ligament Reconstruction. Orthop J Sports Med 4(2):2325967115627611.

[25] Sauer S, Clatworthy M (2018) The Effect of Medial Tibial Slope on Anterior Tibial Translation and Short-Term ACL Reconstruction Outcome. Surg J (N Y) 4(3):e160–e163

[26] Sayit E, Sayit AT, Terzi Y (2017) Evaluation of the posterior Tibial slope in noncontact ACL injuries using magnetic resonance imaging. Acta Orthop Belg 83(2):245–250

[27] Shao Q, MacLeod TD, Manal K, Buchanan TS (2011) Estimation of ligament loading and anterior tibial translation in healthy and ACL-deficient knees during gait and the influence of increasing tibial slope using EMG-driven approach. Ann Biomed Eng 39(1):110–121

[28] Shelburne KB, Kim HJ, Sterett WI, Pandy MG (2011) Effect of posterior tibial slope on knee biomechanics during functional activity. J Orthop Res 29(2):223–231

[29] Shelburne KB, Pandy MG (2010) A Dynamic Model of the Knee and Lower Limb for Simulating Rising Movements. Comput Methods Biomech Biomed Engin 5(2):149-59.

[30] Shen X, Xiao J, Yang Y, Liu T, Chen S, Gao Z, Zuo J (2019) Multivariable analysis of anatomic risk factors for anterior cruciate ligament injury in active individuals. Arch Orthop Trauma Surg 139(9):1277-1285

[31] Sonnery-Cottet B, Archbold P, Cucurulo T, Fayard J-M, Bortolletto J, Thaunat M, Prost T, Chambat P (2011) The influence of the tibial slope and the size of the intercondylar notch on rupture of the anterior cruciate ligament. J Bone Jt Surg Br 93(11):93–1475

[32] VDHarst JJ, Gokeler A, Hof AL (2007) Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg. Clin Biomech 22(6):674–80

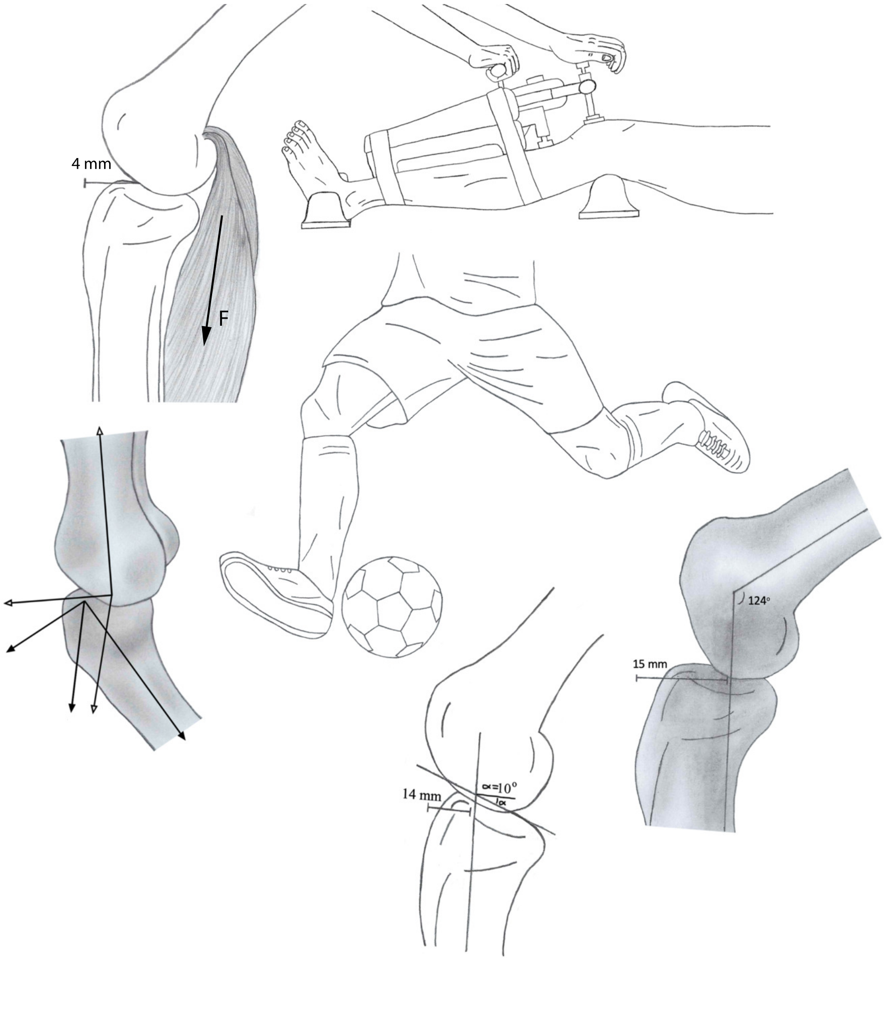
[33] Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP (2013) Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament-reconstructed patient. Am J Sports Med 41(12):2800–4

[34] Weinberg DS, Williamson DF, Gebhart JJ, Knapik DM, Voos JE Differences in Medial and Lateral Posterior Tibial Slope An Osteological Review of 1090 Tibiae Comparing Age, Sex, and Race. Am J Sports Med 45(1):106-113

[35] Winter, D.A. (2009) Biomechanics and Motor Control of Human Movement. 4th Edition, John Wiley & Sons, Hoboken.

[36] Yamaguchi KT, Cheung E, Mathew J, Boguszewski D V, Markolf K, Mcallister DR, Petrigliano FA (2019) ACL Force and Knee Kinematics After Posterior Tibial Slope-Reducing Osteotomy. Knee Surg Sports Traumatol Arthrosc 27(10):3381-3389

[37] Cohen J. Statistical Power Analysis for the Behavioral Sciences. 1969. New York: Academic Press.



4 mm
F
124°
15 mm
α=10°
14 mm

Chapter 8

Discussion and conclusion

General discussion

Around one third of the patients after an ACL reconstruction (ACLR) is not able to return to their pre-injured level of sports [4]. Moreover, around 20% of the patients are not able to return to any sports at all [4]. Copers (those who are able to return to their pre-injured type of sports) may be differentiated from non-copers (those who are not able to return to their pre-injured type of sports) by the strategy they use to control their knee laxity, i.e. anterior tibia translation (ATT), during dynamic situations, such as in jump landings. Kvist et al. [14] showed that there is no correlation between passive ATT (ATTp) and dynamic ATT (ATTd). This suggests that ATTd is controlled by other factors than the movement limiting force of the ACL, such as muscle activation patterns. In this thesis, we hypothesised that copers can compensate for dynamic ATTd by developing effective muscle strategies while non-copers fail to do this. Moreover, we hypothesised that a steeper tibia plateau angle increases the ATTd. The aim of this thesis was to uncover possible strategies to control ATTd after an ACLR consisting of muscle activation patterns and kinematics.

The most important result of this thesis is that we, indeed, found a difference in the control of ATTd between copers and non-copers. Copers reduce their gastrocnemius activity to limit ATTd. Non-copers decrease their knee flexion moment in such a way that ATTd was smaller. Moreover, patients with a larger medial posterior tibia plateau angle showed less ATTd than patients with a smaller medial posterior tibia plateau angle. Also, we have shown that ATTd can reliably be measured when transients in movements are higher than 2.3 mm. Measuring ATTd in a valid way is important to answer the research questions of this thesis.

Measurement devices for ATT

Measuring ATT in patients after an ACLR can be used to compare ATT after different operation techniques or to compare the ATT in copers v.s. non-copers, as the ACL (graft) limits ATT. ATTp tests are commonly used to diagnose an ACL injury and to select patients for an ACLR [3]. A number of devices has been developed to measure ATTp (The KT-1000 arthrometer, Kneelax, Rolimeter, Telos Stress Device, electromagnetic measurement system, fluoroscopic measurement and navigation systems; see Chapter 3). We showed that ATTp measured using these devices is not very consistent. Therefore, the outcomes of studies using different measurement devices cannot be compared. More consistency in ATTp measuring devices should be introduced. The golden standard, the most frequently used device to measure ATTp and the device we used to collect the data presented in this thesis, is the KT-1000 arthrometer (Medmetric Corp., San Diego, CA, USA) [27]. Fair intra-rater reproducibility was reported for the KT-1000 arthrometer [27]. The Rolimeter may be a better device to use for research to measure ATTp as the intra-rater reproducibility is shown to be reliable [18]. Moreover, this device is cheap, easy to sterilize and easy to use [18, 11]. In this thesis, the KT-1000 arthrometer was used as this is the golden standard to measure ATTp and is relatively easy to use. The device was used by one examiner for all participants. For future research we recommend to use the Rolimeter or KT-1000 arthrometer by two or three examiners for each participant to average out errors.

Measuring ATTd is more difficult than ATTp and no golden standard is available. Therein this thesis we showed that there is no correlation between ATTp and ATTd and, therefore, ATTd may give interesting information in addition to ATTp when measured after an ACLR as an ACLR aims to improve ATTd. The ability to measure ATTd is of high interest to be able to evaluate highly significant functional movements. Since 2013, the methods of Ehrig et al. [7, 8], the symmetrical centre of rotation estimation (SCoRE) and the symmetrical axes of rotation approach (SARA), are easily available when using the optical motion capture system Vicon (see Chapter 4). These methods can be used to measure ATTd. Both methods use the optimal common shape technique (OCST) for their estimations. The OCST virtually replaces the actual markers so that the virtual markers of each segment act as a rigid body [29]. The SCoRE method calculates joint centres and the SARA method calculates knee rotation axes. Both methods use dynamic calibration frames to calculate these data. SARA can calculate one rotation axis placed in the rigid body of the tibia and one in the rigid body of the femur. Those two axes, and the knee centre calculated with the SCoRE method, can be used to measure ATTd and dynamic tibia rotation (see Chapter 4 for the calculations). These methods are a great development in the ability to measure tibiofemoral movements, i.e. ATTd and dynamic external tibia rotation, during movements. We found that ATTd of 2.3 mm or more and external tibia rotation of 1.7 degrees or more during jump landing are reliable when taking into account the marker setup and Vicon position errors (Chapter 4). To compare this result with the total range of ATTd during jump landing: 2.3 mm is 19.42% of the total ATTd range and 1.7 degrees is 13.51% of the total external tibia rotation range. These results are better than expected as wobbling masses are a great concern when measuring ATTd [22]. The use of OCST may be able to minimize the errors due to wobbling masses in such a way that results using the SCoRE and SARA methods are reliable.

One big disadvantage of the SCoRE and SARA technique is that there is a motion capture (MoCap) system, like Vicon, needed to perform the tests. This MoCap system is not (easily) available for everyone, such as for physiotherapists, coaches and some researchers. Also, optical MoCap systems are not able to measure in real sports situations on the field, which may be interesting for future research. For future research it may be interesting to develop devices that can measure tibiofemoral movements (ATTd and external tibia rotation), for example using accelerometers, in field situations and in ADL situations, outside the lab. This data may be of interest as we showed that ATTd and ATTp can be very different from each other in one participant. When excessive ATTd is detected, physiotherapists or coaches may recommend their patients or athletes to do ACL injury prevention exercises [17, 12] and may be more careful with those patients or athletes. Clinical assessment tools that help identify athletes at high risk for ACL injury, helps personalise prevention training and may reduce ACL injury incidence. When such measurements can be performed, physiotherapists and coaches are able to monitor their patients or athletes in uncontrolled situations as well, and be able to identify players who are at risk for second injury after return to sports.

For now, the technique and application of Ehrig and Boeth et al. [7, 8, 5] is a great improvement in dynamic knee measurement and can be used to 1) monitor progression after an ACL injury or reconstruction, 2) compare results after an ACL reconstruction using different operation techniques, 3) compare results after different rehabilitation protocols, 4) compare copers and non-copers, 5) and in the future, using the right protocol, this technique may be able to predict which patients would be copers and non-copers before return to sports, early in the rehabilitation. There are many indicators which could predict copers and non-copers.

Graft choice on ATT

Graft choice is an important aspect which could influence functional results after an ACLR. Using an allograft v.s. autograft and patellar tendon v.s. hamstring tendon has advantages and disadvantages (see Chapter 2). An important difference between a hamstring tendon and patellar tendon is that a hamstring tendon becomes longer during rehabilitation which is not the case with a patellar tendon [13]. This is because the hamstring tendon creeps more under static load, the graft is longer and the fixation is between bone and tendon instead of between bone and bone. This can be an advantage or a disadvantage. When using a patellar tendon, the tendon will keep approximately the length as when it was placed during surgery, the hamstring tendon will lengthen a bit. The slack length, unstrained length, of the ACL graft is very important. A graft which is placed too tight may result in knee extension deficits. A graft which is placed too loose may result in large ATT ranges. In Chapter 6 we described that, for copers and non-copers, using a hamstring tendon ATTp and ATTd of the operated knee were comparable with those values of the contralateral knee. This suggests that surgeons are able to reconstruct the ACL at a comparable length of that in the contralateral knee, or that during rehabilitation the length of the reconstructed ACL adapts to its use.

In Chapter 2 we showed that using an autograft patellar tendon for revision (second) ACLR had superior return to sports results at a minimum of two years after surgery than an allograft patellar tendon (75% v.s. 43.3%). There are several reasons to explain the difference in return to sports rate using an autograft and allograft tendon. One possible explanation is that, as we reported in Chapter 3 (a systematic review), an autograft ACLR may give better return to sports results than an allograft ACLR because ATTp remains larger when using an allograft tendon. Unfortunately, in Chapter 2, we did not perform clinical tests, such as to assess ATT to confirm this suggestion. When choosing between allograft and autograft, we recommend using an autograft tendon as we found better return to sports results using this type of graft.

One major disadvantage of using an autograft patellar tendon is that the harvest of the middle 1/3 of the patellar tendon can result in knee extension moment deficits [1]. The same holds true for using the quadriceps tendon [1]. When using a hamstring tendon, the harvest of this tendon results in knee flexion moment deficits [28, 20]. Both can result in a disbalance in the quadriceps-hamstrings force ratio or quadriceps-hamstrings activation ratio which may not be ideal for the functional results after an ACLR. On the other hand, a disbalance towards hamstring activation, may protect the ACL. We hypothesize that using the patellar or quadriceps tendon, which reduces the quadriceps strength, will protect the ACL. When the quadriceps-hamstrings activation ratio is shifted towards the hamstrings, the tibia is pulled posteriorly relative to the femur [6], which protects the ACL graft. When a hamstring graft is used, the quadriceps-hamstrings activation ratio shifts more towards the quadriceps, which in theory pulls the tibia anteriorly, which in turn strains the ACL [6]. Hence, it would be very interesting to do knee ATT tests, passive and dynamic, in patients who underwent an ACLR with different types of grafts (i.e. patella tendon autograft v.s. quadriceps tendon autograft v.s. hamstring tendon autograft).

This will give information about whether the harvest of the graft (i.e. chancing the quadriceps-hamstrings activation ratio) influences ATTd after an ACLR. An RCT, using the measuring methods of Ering and Boeth et al. [7, 8, 5] to measure ATTd is needed. This study should include EMG signals from the hamstrings and quadriceps to measure the quadriceps-hamstring activation ratio. Comparing patients after an ACLR using a hamstring tendon, using a patellar tendon and using a quadriceps tendon would be an opportunity for future research.

Control of ATTd in healthy people, copers and non-copers after an ACL reconstruction

Another very important factor after an ACLR which could make functional results of patients favourable is adapting their motor control. As is stated before, it is found that there is no relation between ATTp and ATTd [14] and our results of Chapter 5 showed that healthy subjects with large ATTp showed low ATTd and vice versa (a negative correlation between ATTp and ATTd). This implies that people with a large amount of ATTp are able to compensate their ATTd by using effective motor control or kinematics which limits ATTd. We found that during one-leg jump landing:

- healthy subjects with more ATTp showed less ATTd;
- copers after an ACLR with more ATTp did not necessarily show less or more ATTd;
- non-copers after an ACLR with more ATTp showed more ATTd.

Also, we showed that during one-leg jump landing, ATTd is limited by:

- using less knee flexion rather than muscle control in healthy subjects;
- by modulating gastrocnemius activation in copers after an ACLR;
- by amending the knee extension moment in non-copers after an ACLR.

Healthy people without knee problems and with large ATTp may have learned to use strategies to reduce ATTd. A possible explanation is that those people may have learned this from strained conditions from their ACL in which sensory feedback is provided. People with low ATTp may not have learned this as they do not often receive feedback from a sudden transient load which results in sudden forces on the native ACL. The ability to reduce ATTd using muscle activation patterns protects the native ACL and after an ACLR the ACL graft, particularly against transient loads.

When the native ACL is torn, ATT is not limited by the ACL. Patients who are not able to compensate for the increased ATT will have problems with stability (i.e. increased knee laxity). In that case, an ACLR will increase the stability of the knee (Chapter 2).

After an ACLR, ATTp and ATTd are not correlated in copers, however, they are positively correlated in non-copers (see Chapter 6). Many copers may have learned to reduce ATTd with muscle activation, by increasing their gastrocnemius activity (Chapter 6). A possible explanation is that patients may have received more signals from the native ACL and have learned to compensate for excessive ATTd before tearing the ACL. This can be concluded from our results presented in Chapter 6: both the ATTp and ATTd measured in both the operated knee and contralateral knee were larger in copers than non-copers. Note that this has to be performed in controlled situations where no external forces are applied to the tibia and femur other than the ground reaction force and without unpredicted movements. In uncontrolled situations with external forces to the tibia or femur, or during unpredicted movements, when forces are too large for the ACL to handle, the ACL tears in 45 ms whereas muscles are producing force 80 ms after neural activation [10]. The finding that non-copers showed a positive correlation between ATTp and ATTd where copers did not show this correlation, supports the suggestion that copers are able to compensate for ATTd. Moreover, there is no correlation between ATTp and subjective instability of the knee [16]. Patients with large ATTp do not always experience knee instability, which may be because those patients limit their ATTd by muscle activation in such a way that dynamic knee instability is reduced. Indeed, we found that copers increase their gastrocnemius activity to decrease ATTd when they have a large amount of ATTp (Chapter 6).

Non-copers, however, limit ATTd by decreasing their knee flexion moment (Chapter 6). By decreasing the knee flexion moment, anterior directed forces on the tibia decrease. Note that ATTd and ACL strain are not the same, there is more room for ATTd when the ACL is allowed to be strained more. Patients who control their knee flexion moment (landing with a less flexed knee) and do not use muscle activation patterns to limit ATTd, may not be able to return to sports, as muscle control is much more adaptive.

A clinical implication may be to incorporate exercises during rehabilitation that strain the ACL in a controlled way to allow patients to find solutions in terms of muscle activation patterns to limit ATTd.

Anatomy of the knee

Some aspects of the anatomy of the knee, such as a steep posterior tibia plateau angle (PTPA), a deep posterior lateral femoral condyle, and a narrow intercondylar notch, are indicators for graft failure [9, 26]. We have investigated the influence of the PTPA on in vivo ATTd (Chapter 7), because model studies showed a correlation between the PTPA and ATT [21, 23, 25]. The PTPA is defined as the angle of the posterior tibia plateau relative to the plane orthogonal to the longitudinal axis of the tibia in the sagittal plane (see figure 2 in Chapter 7). We found that patients after an ACLR with a larger medial PTPA showed less ATTd than patients with a smaller medial PTPA. Moreover, patients with a larger PTPA showed less knee flexion during jump landing. This result was not as expected, as previous research showed that a steeper PTPA results in more ATTp (KT-1000) [24]. However, we measured ATT during a jump landing task during which motor control and kinematics also influence the ATT. As also highlighted in the previous subsection about the control of ATTd, we showed that excessive ATTd is compensated by increasing gastrocnemius activity and smaller knee flexion moments. We showed that healthy subjects with large ATTp showed low ATTd (Chapter 5) and that there is no correlation between ATTp and ATTd in patients after an ACLR (Chapter 6). Therefore, our result of Chapter 7, that a larger PTPA is positively correlated with a decreased ATTd may be due to compensation strategies. Patients with a larger PTPA use more gastrocnemius activity or smaller knee flexion angles during jump landing to compensate for their large PTPA. The results of Chapter 6 showed that smaller knee flexion angles during jump landings result in less ATTd. Since a more extended leg places the tibia plateau more perpendicular to the ground force, this might be a strategy to limit the ATTd. This is in line with our finding that patients with a steeper lateral PTPA showed less knee flexion during jump landing. However, when there is bad feedforward muscle activation control at unfavourable foot positions, an ACL (re)injury may occur easier in patients with a large PTPA and, therefore, a large PTPA may be a risk factor for (re)injury.

A longitudinal study where the slope of the tibia plateau, ATTd, knee flexion angles and moment and muscle activation during the rehabilitation will be measured and used to monitor patients while returning to sports will be an opportunity for future research. Moreover, developing a dynamic knee computer simulation model based on in vivo data can give insight in the relationship between muscle activation patterns, PTPA and ground reaction forces on the one hand, and the dynamics of the knee joint (ATTd and external tibia rotation) and the strain on the ACL on the other. Such a model can confirm the results of our research described in this thesis.

Limitations of the studies presented in this thesis

Some limitations of the studies presented in this thesis should be addressed. In Chapter 2 a retrospective cohort study is presented in which patients one to two years after surgery and patients more than two years after surgery are included. A prospective study could confirm the results presented in this chapter. The papers included in the review presented in Chapter 3 were assessed and appraised only by one researcher. The quality of the review may have been increased when two or more researchers appraised the papers. More risks of bias may have been detected in that case. For Chapter 3 only one subject was measured. This was sufficient for the purpose of this study. Such a study with more participants may give more insight in the reliability of the method. Measuring the reliability of the method used in this thesis to measure ATTd is of high importance.

A major limitation of the results presented in Chapters 3 to 6 is that there is no golden standard to measure ATTd and, therefore, no way to confirm the results. However, the consistency of the data presented in the figures of ATTd in chapters 4 (figure 4), 5 (figure 2) and 6 (figure 2 and 3) gave us more trust in the method. No large fluctuations are present in the figures. In most figures, there is a small negative peak just before IC, however, the duration of this negative peaks is too short to be caused by wobbling masses. Those negative peaks may be a form of feedforward control. In addition, previous studies found an absolute range of ATT comparable to the studies presented in this thesis: using bi-planar fluoroscopy model-based data during running of +/- 10 mm [2] and +/- 25 mm [15]. Future studies could test the between-day reliability of the method. The reliability of the results of the measuring method for ATTd can also be increased by a study where a patient after a total knee replacement without ATT or a known ATT is measured using this method. A limitation of Chapter 5 and 6 is the method of normalization of muscle activity. We normalized muscle activity to the percentage of the mean muscle activity during the single leg jump for distance. We wanted to normalize the EMG signals to maximal voluntary contractions and did record this data. When we assessed the maximal voluntary contractions for the injured and uninjured leg, we saw large differences between the legs, especially for the hamstrings force. As we did not trust these results, we chose to normalize to the percentage of the mean muscle activity during the jumping task, highlighting the differences in activation peaks.

General conclusion

There are many factors that can influence ATT after an ACLR. For example, in passive situations, graft choice, intra-articular injuries and whether the injury is chronic or acute can affect ATTp (Chapter 2). In dynamic situations this is far more complicated. Graft choice, muscle activation of the gastrocnemius muscles, knee flexion angle and moment and the slope of the tibia plateau are associated with the amount of ATTd. In copers after an ACLR, ATTd is controlled by gastrocnemius activity. In non-copers ATTd is controlled by choosing the knee flexion moment in such a way that ATTd is limited. A neuromechanical importance of our studies is an increased insight in the control of laxity in the human knee joints in functional tasks. A clinical importance of our studies is that we can differentiate between copers and non-copers in control of that laxity.

References

[1] Adams DJ, Mazzocca AD, Fulkerson JP (2006) Residual Strength of the Quadriceps Versus Patellar Tendon After Harvesting a Central Free Tendon Graft. Arthroscopy 22(1):76-9

[2] Anderst W, Zauel R, Bishop J, Demps E, Tashman S (2009) Validation of three-dimensional model-based tibio-femoral tracking during running. Med Eng Phys 31(1):10-16

[3] Arbes S, Resinger C, Vécsei V, Nau T (2007) The functional outcome of total tears of the anterior cruciate ligament (ACL) in the skeletally immature patient. Int Orthop 31(4):471–475

[4] Ardern, CL, Webster, KE, Taylor, NF, Feller, JA (2011) Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med 45(7):596-606

[5] Boeth H, Duda GN, Heller MO, Ehrig RM, Doyscher R, Jung T, et al. (2013) Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. Am J Sports Med 41(5):1051-7

[6] Van Den Bogert AJ (2002) Comment on "quadriceps protects the anterior cruciate ligament." J Orthop Res. 20(5):1133-4

[7] Ehrig RM, Taylor WR, Duda GN, Heller MO (2006) A survey of formal methods for determining the centre of rotation of ball joints. J Biomech 39(15):2798-809

[8] Ehrig RM, Taylor WR, Duda GN, Heller MO (2007) A survey of formal methods for determining functional joint axes. J Biomech 40(10):2150-7

[9] Grassi A, Macchiarola L, Urrizola Barrientos F, Zicaro JP, Costa Paz M, Adravanti P, Dini F, Zaffagnini S (2019) Steep Posterior Tibial Slope, Anterior Tibial Subluxation, Deep Posterior Lateral Femoral Condyle, and Meniscal Deficiency Are Common Findings in Multiple Anterior Cruciate Ligament Failures: An MRI Case-Control Study. Am J Sports Med;47(2):285-295

[10] C.P. van der Hart (accesed: 06-2020) http://kniechirurgie.nl/de-voorste-kruisband

[11] Hatcher J, Hatcher A, Arbuthnot J, McNicholas M (2005) An Investigation to Examine the Inter-Tester and Intra-Tester Reliability of the Rolimeter Knee Tester, and Its Sensitivity in Identifying Knee Joint Laxity. J Orthop Res 23(6):1399-403

[12] Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE (2016) Mechanisms, Prediction, and Prevention of ACL Injuries: Cut Risk With Three Sharpened and Validated Tools J Orthop Res 34(11):1843-1855

[13] M. Jagodzinski, V. Behfar, C. Hurschler, K. Albrecht, C. Krettek, U. Bosch (2004) Femoral Press-Fit Fixation of the Hamstring Tendons for Anterior Cruciate Ligament Reconstruction. Am J Sports Med 32(7):1723-30

[14] Kvist J (2005) Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. Scand J Med Sci Sports 15(3):148–158

[15] Lin CC. Li JD. Lu TW. Kuo MY. Kuo CC. Hsu HC (2018) A model-based tracking method for measuring 3D dynamic joint motion using an alternating biplane x-ray imaging system. Med phy 45(8):3637-3649

[16] R. Magnussen, E.K. Reink, L.J.Huston, MOON Knee Group; J.T. Andrish, C.L. Cox, W.R. Dunn, D.C. Flanigan, T. Hewett, M.H. Jones, C.C. Kaeding (2019) Anterior and Rotational Knee Laxity Does Not Affect Patient-Reported Knee Function 2 Years After Anterior Cruciate Ligament Reconstruction Am J Sports Med 47(9):2077-2085

[17] Mehl, J, Diermeier, T, Herbst, E, Imhoff, AB, Stoffels, T, Zantop, T. Petersen W, Achtnich A (2018) Evidence-based concepts for prevention of knee and ACL injuries. 2017 guidelines of the ligament committee of the German Knee Society (DKG). Arch Orthop Trauma Surg 138(1):51-61

[18] Muellner T, Bugge W, Johansen S, Holtan C, Engebretsen L (2001) Inter- And Intratester Comparison of the Rolimeter Knee Tester: Effect of Tester's Experience and the Examination Technique. Knee Surg Sports Traumatol Arthrosc 9(5):302-6

[19] Myrer JW, Schulthies SS, Fellingham GW (1996) Relative and absolute reliability of the KT-2000 arthrometer for uninjured knees. Am J Sports Med 24(1):104–108

[20] N. Nakamura, S. Horibe, S. Sasaki, T. Kitaguchi, M. Tagami, T. Mitsuoka, Y. Toritsuka, M. Hamada, K. Shino (2002) Evaluation of Active Knee Flexion and Hamstring Strength After Anterior Cruciate Ligament Reconstruction Using Hamstring Tendons. Arthroscopy 18(6):598-602

[21] Navacchia A, Bates NA, Schilaty ND, Krych AJ, Hewett TE (2019) Knee Abduction and Internal Rotation Moments Increase ACL Force During Landing Through the Posterior Slope of the Tibia. J Orthop Res 37(8):1730-1742

[22] M. Sangeux, A. Barré, K. Aminian (2017) Evaluation of Knee Functional Calibration With and Without the Effect of Soft Tissue Artefact. J Biomech 62:53-59

[23] Shao Q, MacLeod TD, Manal K, Buchanan TS (2011) Estimation of ligament loading and anterior tibial translation in healthy and ACL-deficient knees during gait and the influence of increasing tibial slope using EMG-driven approach. Ann Biomed Eng 39(1):110–121

[24] S. Sauer, M. Clatworthy (2018) The Effect of Medial Tibial Slope on Anterior Tibial Translation and Short-Term ACL Reconstruction Outcome. Surg J (N Y) 4(3):e160-e163.

[25] Shelburne KB, Kim HJ, Sterett WI, Pandy MG (2011) Effect of posterior tibial slope on knee biomechanics during functional activity. J Orthop Res 29(2):223–231

[26] Shen L, Jin ZG, Dong QR, Li LB (2018) Anatomical Risk Factors of Anterior Cruciate Ligament Injury. Chin Med J (Engl) 131(24):2960-2967

[27] Sernert N, Kartus J, Kohler K, Ejerhed L, Karlsson J (2001) Evaluation of the reproducibility of the KT-1000 arthrometer. Scand J Med Sci Sport 11(2):120–125

[28] K. Tadokoro, N. Matsui, M. Yagi, R. Kuroda, M. Kurosaka, S. Yoshiya (2004) Evaluation of Hamstring Strength and Tendon Regrowth After Harvesting for Anterior Cruciate Ligament Reconstruction. Am J Sports Med 32(7):1644-50

[29] Taylor WR, Ehrig RM, Duda GN, Schell H, Seebeck P, Heller MO (2005) On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res 23(4):726-34.

Chapter 9

Appendices

- Summary (ENG)
- Samenvatting (NL)
- Dankwoord
- About the author
- List of publications

Summary (ENG)

To provide stability of the knee (a decrease of knee laxity, i.e. tibiofemoral translations), the tibia and femur are connected by ligaments. One of these ligaments, the anterior cruciate ligament (ACL), prevents both anterior tibia translation relative to the femur (ATT) and internal tibial rotation. The quadriceps muscle group is a dynamic antagonist to an intact ACL. The hamstrings muscle group and gracilis muscle are antagonists to an intact posterior cruciate ligament. Annually around 0.2-4 percent of the athletes injure their ACL. An ACL injury results in increased ATT at the same anterior force on the tibia. In order to improve stability of the knee and to reduce the chance of cartilage damage, an ACL reconstruction (ACLR) is commonly indicated as treatment, especially when aiming at a return to sports. Despite functional improvements after an ACLR one year after ACLR one-third of the patients do not manage to return to their pre-injured level of sports and only 44% of the patients return to competitive sports. In our study presented in **Chapter 2** we found that percentage of return to the pre-injured type of sports is higher using an ipsilateral patellar tendon autograft for ACLR compared to a patellar tendon allograft. This may be due to the fact that knee laxity, or ATT, is greater when using an allograft tendon compared to an autograft tendon (**Chapter 3**). Instability due to an increase in ATT may be an explanation for the lower percentage of return to sports. In this thesis we aimed to investigate whether copers (patients who return to sports) are able to develop more effective strategies to compensate for the increased dynamic ATT (ATTd), (i.e. by using a specific muscle activation pattern) whereas non-copers (patients who do not return to sports) rely more on the movement limiting force produced by the ACL. We also investigated whether the anatomy of the knee plays an important role in controlling the ATTd.

First, presented in **Chapter 3**, we reviewed the possible factors determining the passive ATT (ATTp). We found that comparisons of ATTp between studies should be taken with caution as many different measurement methods are used with different results. The factors that could affect the ATTp are: graft choice, ACL injury or reconstruction, intra-articular injuries and whether an ACL injury is chronic or acute. Other possible factors such as fixation techniques gave inconclusive results. The main clinical relevance of this study was that using an autograft ACLR may give better results then using an allograft tendon for ACLR as knee laxity is greater when using an allograft tendon.

To measure ATTd for the research presented in **Chapters 5, 6 and 7** we used the

symmetrical center of rotation estimation (SCoRE) and the symmetrical axes of rotation approach (SARA) introduced by Boeth and colleagues. The combination of these two methods can be used to calculate tibiofemoral movements and is implemented in the software of the motion capture system Vicon. For this we first investigated the sensitivity of this method to determine ATTd, as reported in **Chapter 4**. Two experiments were performed. In the first experiment we determined the sensitivity of the calculated tibiofemoral movements for the position of the set of femoral markers. In the second experiment we determined the sensitivity of the calculated tibiofemoral movements for the errors in the captured positions of the reflective markers found in previous research. We found that variations in ATTd less than 2.32 mm and external tibia rotations less that 1.70 degrees should be taken with caution. Moreover, a marker set with markers spread over the whole femur gives better results than when markers are clustered. The reason for this is mutual cancelation of movements of soft tissue relative to the bone when applying markers over the whole femur.

In **Chapter 5** our research with healthy participants is presented. The aims of this study were to investigate whether there is a correlation between ATTd and ATTp; whether quadriceps, hamstrings and gastrocnemius activity are correlated with ATTd; and whether the knee flexion angle and knee flexion moment are correlated with ATTd. In contradiction to our hypothesis that there was no significant correlation between ATTd and ATTp, we found a negative correlation between ATTp and ATTd. This means that participants with large ATTp showed small ATTd, which provides us information that ATTd is indeed limited. A negative correlation suggests that there is a contribution of muscle activity or a modification of kinematics or kinetics to limit ATTd. In this study we found that there was no clear relationship between muscle activation and ATTd. We did however find a relation between knee flexion angle and ATTd. Participants with a large ATTp land with less knee flexion and have less ATTd during jump landing.

In our study with patients after an ACLR, presented in **Chapter 6**, we investigated whether there is a relationship between both the ATTp and general joint laxity with ATTd during jump landing; whether ATTd in ACLR patients can be moderated by muscle activation patterns; and whether there is a difference in ATTd between copers and non-copers. Only in non-copers in their operated leg there was a positive correlation between ATTd and ATTp. This suggests that this group of patients is not able to limit the ATTd. We showed that copers adapt their gastrocnemius activation and non-copers adapt their knee flexion moment to limit their ATTd. Adapting the knee flexion moment may not be the best solution as more non-copers use this technique than copers

In our last study, **Chapter 7**, we investigated whether the anatomy of the knee, the angle of the posterior tibia plateau relative to the plane orthogonal to the longitudinal axis of the tibia, influences the ATTd during a unilateral landing; whether this angle influences knee kinematics and kinetics; and whether this angle is associated with muscle activation. We indeed found that patients with a larger medial posterior tibia plateau angle showed less ATTd than patients with a small angle. Patients with a larger lateral posterior tibia plateau angle showed smaller knee flexion angles. Moreover, a significant association between muscle activation and the lateral tibia plateau angle just after initial contact was found. This was especially true for the medial hamstrings activation which proves to have a negative correlation. This suggests that patients after an ACLR automatically adapt their landing strategy (i.e. knee flexion angles and medial hamstring activity) to the anatomy of their knee.

In **Chapter 8** we discuss the results of the above mentioned studies. To measure ATTp more consistency should be introduced. The golden standard is the KT1000 arthrometer, however, the Rolimeter may be a better device to measure ATTp. No golden standard is available to measure ATTd. The method of Ehring et al. (2013) is easily available relatively and valid to measure ATTd. This method is a great development in the ability to measure tibiofemoral movements in functional tasks.

The choice of graft for an ACLR is very important for the results after an ACLR. For example, ATTp remains larger when using an allograft compared to an autograft. Also, a hamstring tendon creeps more under static load than a patellar tendon and is fixed between bone and tendon. A graft which is placed too tight may result in knee extension deficits. A graft which is placed too loose may result in larger ATT ranges. We found that surgeons are able to repair a hamstrings autograft at a comparable length of that in the contralateral knee or that during rehabilitation the length of the reconstructed ACL adapts to its use. When choosing between allograft and autograft we recommend using an autograft tendon. When choosing between hamstring and patellar tendon we recommend using a patellar tendon.

Healthy people without knee problems and with large ATTp may have learned to use strategies from strained conditions form the ACL in which sensory feedback is provided to reduce ATTd. Copers after an ACLR may use these compensational techniques to be able to return to sports whereas non-copers fail to do this. In both the ACL reconstructed and contralateral knee ATTp and ATTd is larger in copers than non-copers. Therefore, copers may have been more often in situations where ATTd should have been compensated. Copers limit their ATTd by using their gastrocnemius activity whereas non-copers adapt their knee flexion moment. Patients who adapt their knee flexion moment and do not use muscle activation patterns to limit ATTd, may not be able to return to sports, as muscle control is much more adaptive. Patients with a large posterior tibia plateau angle may use more gastrocnemius activity or smaller knee flexion angles during jump landing to compensate for their large posterior tibia plateau angle.

For future study, developing a dynamic knee computer simulation model based on in vivo data can give insight in the relationship between muscle activation patterns, the posterior tibia plateau angle and ground reaction forces on the one hand, and the dynamics of the knee joint (i.e. ATTd) and the strain on the ACL on the other.

Samenvatting (NL)

Om stabiliteit van de knie te bieden (een afname van knielaxiteit, d.w.z. tibiofemorale translaties), zijn de tibia en het femur verbonden met ligamenten. Eén van deze ligamenten, de voorste kruisband (VKB), voorkomt zowel de translatie van de tibia ten opzichte van het femur naar voren (ATT) als de interne rotatie van de tibia. De quadriceps spiergroep is een dynamische antagonist voor een intacte VKB. De hamstrings spiergroep en gracilis spier zijn antagonisten voor een intacte achterste kruisband. Jaarlijks scheurt ongeveer 0,2-4 procent van alle sporters hun VKB. Een VKB-blessure resulteert in vergrote ATT bij dezelfde kracht op het scheenbeen naar voren. Om de stabiliteit van de knie te verbeteren en de kans op kraakbeenschade te verkleinen, is een VKB reconstructie (VKBR) vaak geïndiceerd als behandeling, vooral als het gaat om terugkeer naar sport. Ondanks functionele verbeteringen na een VKBR slaagt een jaar na de reconstructie een derde van de patiënten er niet in om terug te keren naar hun sportniveau van voor de operatie en slechts 44% van de patiënten keert terug naar competitieve sporten. In ons onderzoek gepresenteerd in **Hoofdstuk 2** hebben wij gevonden dat het percentage terugkeer naar het sporttype van voor de operatie hoger is wanneer er gebruik wordt gemaakt van een eigen ipsilaterale patellapees in vergelijking met een donor patellapees. Dit kan te wijten zijn aan het feit dat de knielaxiteit, of ATT, groter is bij het gebruik van een donorpees in vergelijking met een eigen pees (**Hoofdstuk 3**). Instabiliteit door een toename van ATT kan een verklaring zijn voor het lagere percentage van terugkeer naar de sport. In dit proefschrift hebben wij onderzocht of copers, patiënten die wel terugkeren naar de sport, in staat zijn om effectievere strategieën te ontwikkelen om de vergrote dynamische ATT (ATTd) te compenseren (d.w.z. door een specifiek spieractiveringspatroon te gebruiken), terwijl non-copers, patiënten die niet terugkeren naar de sport, meer vertrouwen op de bewegingsbeperkende kracht vanuit de VKB. Ook hebben we onderzocht of de anatomie van de knie een belangrijke rol speelt bij het begrenzen van de ATTd.

Ten eerste, gepresenteerd in **Hoofdstuk 3**, hebben wij de mogelijke factoren besproken die de passieve ATT (ATTp) bepalen. We hebben gevonden dat vergelijkingen van ATTp tussen onderzoeken met de nodige voorzichtigheid moeten worden geïnterpreteerd, aangezien er een groot aantal verschillende meetmethoden wordt gebruikt met verschillende resultaten. De factoren die de ATTp kunnen beïnvloeden zijn: transplantaatkeuze, VKB-letsel, VKB reconstructie, intra-articulaire letsel en of een VKB-letsel chronisch of acuut is. Over andere mogelijke factoren, zoals fixatietechnieken, waren de resultaten verdeeld. De belangrijkste klinische relevantie

van deze studie was dat het gebruik van een eigen pees als VKB transplantaat betere resultaten geeft dan het gebruik van een donorpees, aangezien de knielaxiteit groter is bij gebruik van een donorpees.

Om ATTd te kunnen meten voor het onderzoek dat in **Hoofdstukken 5 t/m 7** wordt gepresenteerd, hebben we de 'symmetrical center of rotation estimation' (SCoRE) en de 'symmetrical axes of rotation approach' (SARA) gebruikt die zijn geïntroduceerd door Boeth en collega's. De combinatie van deze twee methoden kan worden gebruikt om tibiofemorale bewegingen te bepalen en is geïmplementeerd in de software van Vicon. Hiervoor hebben we eerst, zoals gerapporteerd in **Hoofdstuk 4**, de gevoeligheid van deze methode om ATTd te bepalen, onderzocht. Hiervoor hebben wij twee experimenten gedaan. In het eerste experiment bepaalden wij de gevoeligheid van de berekende tibiofemorale bewegingen voor de keuze van plaatsing van de set femorale markers. In het tweede experiment bepaalden we de gevoeligheid van de berekende tibiofemorale bewegingen voor de fouten in de vastgelegde posities van de Vicon-markers gevonden in eerder onderzoek. Variaties in ATTd van minder dan 2,32 mm en externe tibia rotaties van minder dan 1,70 graden moeten met voorzichtigheid worden geïnterpreteerd. Bovendien geeft een markerset met markers verspreid over de hele femur betere resultaten dan wanneer markers worden geclusterd. De reden hiervoor is dat bij het aanbrengen van markers over het hele femur ongelijke bewegingen van zacht weefsel ten opzichte van het bot onderling wordt gecompenseerd.

In **Hoofdstuk 5** wordt ons onderzoek met gezonde deelnemers gepresenteerd. Het doel van deze studie was om te onderzoeken of er een verband bestaat tussen ATTd en ATTp; of quadriceps, hamstrings en gastrocnemius activiteit gecorreleerd zijn met ATTd; en of de knie flexie hoek en het knie flexie moment gecorreleerd zijn met ATTd. In tegenstelling tot onze hypothese dat er geen significante correlatie zou zijn tussen ATTd en ATTp, vonden wij een negatieve correlatie tussen ATTp en ATTd. Dit betekent dat onder andere deelnemers met een grote ATTp een kleine ATTd lieten zien, wat betekent dat ATTd inderdaad wordt beperkt. De negatieve correlatie suggereert dat er een bijdrage is van spieractiviteit, kinematica of kinetica om ATTd te beperken. In deze studie vonden wij dat er geen duidelijke relatie was tussen spieractivatie en ATTd. Wel vonden wij een verband tussen de knie flexie hoek en ATTd. Deelnemers met een grote ATTp landen met minder knie flexie en hebben minder ATTd tijdens de landing.

In onze studie met patiënten na een VKBR, gepresenteerd in **Hoofdstuk 6**, hebben wij onderzocht of er een verband bestaat tussen zowel de ATTp als de algemene gewrichtslaxiteit en ATTd tijdens een landing; of ATTd bij VKBR-patiënten kan worden begrensd door spieractiveringspatronen; en of er een verschil is in ATTd tussen copers en non-copers. Alleen van het geopereerde been van non-copers was er een positieve correlatie te zien tussen ATTd en ATTp. Dit suggereert dat deze groep patiënten de ATTd niet goed kan beperken; de passieve translatie is gelijk aan de dynamische translatie. Copers verminderen hun gastrocnemius-activering en non-copers verkleinen hun knie flexie moment om de ATTd te beperken. Het aanpassen van het knie flexie moment is misschien niet de beste oplossing, aangezien meer non-copers deze techniek gebruiken dan copers.

In onze laatste studie, **Hoofdstuk 7**, hebben wij onderzocht of de anatomie van de knie en de hoek van het tibia plateau aan de achterkant ten opzichte van het vlak orthogonaal op de lengte-as van de tibia, de ATTd beïnvloeden bij het landen na een eenbenige sprong; of deze hoek de kinematica en kinetica van de knie beïnvloedt; en of deze hoek verband houdt met spieractivaties. Wij vonden inderdaad dat patiënten met een grotere mediale tibia plateau hoek minder ATTd vertoonden dan patiënten met een kleine hoek. Patiënten met een grotere laterale tibia plateau hoek vertoonden kleinere knie flexie hoeken. Bovendien hebben wij een significant verband gevonden tussen spieractivatie (vooral een negatieve correlatie van de mediale hamstrings) en de laterale tibia plateau hoek net na het eerste contact met de grond. Dit suggereert dat patiënten na een VKBR hun landingsstrategie (d.w.z. knie flexie hoeken en mediale hamstringactiviteit) automatisch aanpassen aan de anatomie van hun knie.

In **Hoofdstuk 8** bediscussiëren we de resultaten van de bovengenoemde onderzoeken. Er moet meer consistentie worden geïntroduceerd om ATTp te meten. De gouden standaard is de KT1000-artrometer, maar de Rolimeter is mogelijk een beter apparaat om ATTp te meten. Er is geen gouden standaard beschikbaar om ATTd te meten. De methode van Ehring et al. (2013) is relatief gemakkelijk beschikbaar en valide om ATTd te meten. Deze methode is een goede ontwikkeling in het meten van tibiofemorale bewegingen tijdens functionele taken.

De keuze van het transplantaat voor een ACLR is erg belangrijk voor de resultaten na een ACLR. ATTp blijft bijvoorbeeld groter bij gebruik van een allograft in vergelijking met een autograft. Ook rekt een hamstringpees meer uit onder statische belasting dan een patellapees en zit hij vast tussen bot en pees. Een te strak geplaatst transplantaat kan leiden tot moeilijkheden met het strekken van de knie. Een te los geplaatst transplantaat kan resulteren in grotere ATT uitslagen. Uit ons onderzoek blijkt dat chirurgen in staat zijn om een autograft van een hamstringpees te plaatsen op een vergelijkbare lengte als die in de contralaterale knie of dat tijdens revalidatie de lengte van de gereconstrueerde ACL zich aanpast aan het gebruik ervan. Bij de keuze tussen allograft en autograft raden we het gebruik van een autograft aan. Bij het kiezen tussen hamstring en patellapees raden we het gebruik van een patellapees aan.

Gezonde mensen zonder knieproblemen en met een grote ATTp hebben mogelijk geleerd strategieën te gebruiken op basis van sensorische feedback van de ACL in situaties waarin de ACL op spanning staat om zo ATTd te verminderen. Copers na een ACLR kunnen deze compensatietechnieken gebruiken om terug te kunnen keren naar sport, terwijl non-copers dit niet doen. In zowel de ACL gereconstrueerde als de contralaterale knie zijn ATTp en ATTd groter in copers dan non-copers. Copers zijn mogelijk vaker in situaties geweest waarin zij ATTd hebben moeten compenseren. Copers beperken hun ATTd door hun gastrocnemiusactiviteit te veranderen, terwijl non-copers hun knie flexie moment aanpassen. Patiënten die hun knie flexie moment aanpassen en geen spieractiveringspatronen gebruiken om ATTd te beperken, kunnen mogelijk niet terugkeren naar sport, omdat spiercontrole veel adaptiever is. Patiënten met een grote plateau hoek van de tibia gebruiken tijdens de spronglanding meer gastrocnemiusactiviteit of een kleinere knie flexie hoek om de grote plateau hoek te compenseren.

Voor toekomstig onderzoek kan de ontwikkeling van een dynamisch knie-computersimulatiemodel op basis van in-vivo-gegevens inzicht geven in de relatie tussen spieractiveringspatronen, de tibia plateau hoek en grondreactiekrachten enerzijds, en de dynamiek van het kniegewricht (d.w.z. ATTd) en de spanning op de ACL anderzijds.

Dankwoord

Graag wil ik iedereen bedanken die er voor heeft gezorgd dat dit proefschift tot stand is gekomen. In het bijzonder mijn begeleidingsteam: Reinoud Brouwer, Juha Hijmans en Bert Otten. Jullie hebben er voor gezorgd dat ik een mooi proefschrift en wij uitstekende publicaties hebben kunnen schrijven. Jullie waren altijd bereikbaar voor discussies en feedback. Dank voor het vertrouwen en de vele dingen die ik van jullie geleerd heb, niet alleen over mijn onderwerp, maar ook over onderzoek in het algemeen, operaties (Reinoud) en veel andere dingen in het leven zoals onder andere over kwantummechanica (Bert). Ik heb de tijd met jullie als bijzonder fijn ervaren en had deze tijd voor geen goud willen missen! Ook wil ik de andere co-auteurs, Roy Hoogslag, Jos van Raay, Alli Gokeler, Anne Benjaminse en Chantal Beijersbergen, bedanken voor jullie bijdrage aan verschillende hoofdstukken. De leden van de leescommissie, Han Houdijk, Bart Koopman en Gino Kerkhoffs, hartelijk dank voor het beoordelen van mijn proefschift. Als laatste wil ik graag de proefpersonen die hebben deelgenomen aan de onderzoeken en alle anderen die hebben bijgedragen aan mijn professionele en wetenschappelijke ontwikkeling bedanken.

About the author

Michèle Keizer was born on 28 december 1993 in Haren (Groningen, the Netherlands). In her last year of high school she decided she wanted to study Medicine. Her interest in this field started when she was 13 years old and injured her anterior cruciate ligament. However, the study Medicine in the Netherlands has a numerus fixus and she was not selected. Therefore, she decided to study Human Movement Sciences in Groningen. After one year of studies she was convinced Human Movement Sciences was the right field of studies for her. A third years Bachelors Academic Assignment formed the basis for her first publication published in a high-impact journal. This research was performed in collaboration with the Orthopedic departement of the Martini hospital in Groningen (Dr. Reinoud Brouwer) and the Orthopedic departement of the 'Orthopedisch Centrum Oost Nederland' in Hengelo (Roy Hoogslag). The publication put her on the fast-track for the Master-PhD trajectory at the University Medical Center Groningen. In 2017 she received her Masters diploma specialised in rehabilitation. In the following 3 years she worked on her PhD-project and successfully received her University Teaching Qualification. She finalized the research for this dissertation in 2020. She is currently working as a junior teacher at the department of Human Movement Sciences at the University of Groningen since 1 September 2020.

List of publications

Keizer MNJ, Hoogeslag RAG, van Raay JJAM, Otten E, Brouwer RW (2018) Superior return to sports rate after patellar tendon autograft over patellar tendon allograft in revision anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 26(2):574-581

Keizer MNJ, Otten E (2019) Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review. Musculoskelet Surg 103(2):121-130

Keizer MNJ, Otten E (2020) Technical note: sensitivity analysis of the SCoRE and SARA methods for determining rotational axes during tibiofemoral movements using optical motion capture. J Exp Orthop 7(1):6

Keizer MNJ, Hijmans JM, Gokeler A, Benjaminse A, Otten E (2020) Healthy subjects with lax knees use less knee flexion rather than muscle control to limit anterior tibia translation during landing. J Exp Orthop 7(1):32

Keizer MNJ, Hijmans JM, Gokeler A, Otten E, Brouwer RW (2020) Sagittal knee kinematics in relation with the posterior tibia slope during jump landing after an anterior cruciate ligament reconstruction. J Exp Orthop 7(1):69

Keizer MNJ, Brouwer RW, Beijersbergen CMI, Otten E, Hijmans JM (accepted). Copers and Non-copers use Different Landing Techniques to Limit Anterior Tibia Translation after an ACL Reconstruction. Orthop J Sports Med

Research Institute
SHARE