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Isometry of anteromedial reconstructions mimicking the deep medial collateral ligament depends on the femoral insertion

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Abstract

Purpose: This study aimed to investigate the length change patterns of the native deep medial collateral ligament (dMCL) and potential anteromedial reconstructions (AMs) that might be added to a reconstruction of the superficial MCL (sMCL) to better understand the control of anteromedial rotatory instability (AMRI).

Methods: Insertion points of the dMCL and potential AM reconstructions were marked with pins (tibial) and eyelets (femoral) in 11 cadaveric knee specimens. Length changes between the pins and eyelets were then tested using threads in a validated kinematics rig with muscle loading of the quadriceps and iliotibial tract. Between 0° and 100° knee flexion, length change pattern of the anterior, middle and posterior part of the dMCL and simulated AM reconstructions were analysed using a rotary encoder. Isometry was tested using the total strain range (TSR).

Results: The tibiofemoral distance of the anterior dMCL part lengthened with flexion (+12.7% at 100°), whereas the posterior part slackened with flexion (−12.9% at 100°). The middle part behaved almost isometrically (maximum length: +2.8% at 100°). Depending on the femoral position within the sMCL footprint, AM reconstructions resulted in an increase in length as the knee flexed when a more centred position was used, irrespective of the tibial attachment position. Femoral positioning in the posterior aspect of the sMCL footprint exhibited <4% length change and was slightly less tight in flexion (min TSR = 3.6 ± 1.5%), irrespective of the tibial attachment position.

Conclusion: The length change behaviour of potential AM reconstructions in a functionally intact knee is mainly influenced by the position of the femoral attachment, with different tibial attachments having a minimal effect on length change. Surgeons performing AM reconstructions to control AMRI would be advised to choose a femoral graft position in the posterior part of the native sMCL attachment to optimise graft length change behaviour.

Abbreviations: ACL, anterior cruciate ligament; AM, anteromedial; AMRI, anteromedial rotatory instability; dMCL, deep (prefix a anterior, m middle, p posterior); ER, external rotation; F1–2, femoral pin point; MCL, medial collateral ligament; POL, posterior oblique ligament; sMCL, superficial MCL; T1–5, tibial pin point; TSR, total strain range.

Given the high frequency of MCL injuries, sufficient restoration of AMRI is essential in isolated and combined ligamentous knee injuries.

Level of Evidence: There is no level of evidence as this study was an experimental laboratory study.

KEYWORDS

anteromedial rotatory instability, deep medial collateral ligament, isometry, length change, reconstruction

INTRODUCTION

The medial collateral ligament (MCL) is commonly injured and is an associated injury in 40% of all knee injuries and 8% of injuries in athletes [10, 27]. Importantly, it is the most frequent, concomitant ligament injury to occur with anterior cruciate ligament (ACL) rupture, with the superficial MCL (sMCL) and deep MCL (dMCL) being the parts of the MCL ligament complex most commonly involved [27, 41, 43]. The dMCL may be injured by forced valgus and tibial external rotation (ER) [32]. This mechanism of injury has also been identified by video analyses, to be the most frequent in ACL injury [5, 35]. It is common for the MCL component of combined ACL/MCL injuries to be conservatively managed [43], yet it is increasingly recognised that some patients will exhibit residual laxity [26, 31]. This has been revealed as a significant risk factor for ACL graft failure, with a reported 13-fold higher failure rate in primary ACL reconstruction and a 17-fold higher rate for revision cases [2, 3, 40]. Chronic dMCL injuries can also cause persistent pain and disability with sports activities that involve forced tibial ER [5, 19, 32]. In light of these clinical findings, the pioneering work on anteromedial rotatory instability (AMRI) by Slocum and Larson [37] has been revisited. Recent biomechanical studies have highlighted that not only is the reciprocal length change behaviour of the different fibre bundles of the sMCL important in controlling AMRI at different angles of knee flexion [18, 20, 44] but also that the dMCL is also an important restraint to tibial ER, particularly when the knee is in extensio [5, 18].

MCL reconstruction techniques focus on the reconstruction of the sMCL and the posterior oblique ligament (POL), which is well aligned to restrain tibial internal rotation and posteromedial rotatory instability, but not to control tibia ER. Indeed, clinical studies [24] have shown residual valgus laxity following 30% of combined MCL + ACL reconstructions, and inferior clinical results compared to isolated ACL reconstruction. Four recent biomechanical studies [6, 8, 29, 30] have questioned the efficacy of clinically established MCL reconstructions to control AMRI and restore native knee kinematics. However, they found that the addition of an anteromedial (AM) reconstruction to sMCL reconstruction significantly improved the control of AMRI. This effect was achieved with either an anatomical [29, 30] or extra-anatomical [8] reconstruction reproducing the function of the dMCL. It is important to note that due to the numerous distinct fibre bundles within the MCL complex, all reconstructions aim solely to approximate the complex anatomical structure of the MCL. The anatomical reconstructions utilised grafts for the sMCL and dMCL with individual femoral and tibial tunnels. The extra-anatomical reconstruction proposed a single femoral attachment for the sMCL and AM reconstruction (mimicking the dMCL) to simplify the surgical procedure [8]. However, the optimal femoral and tibial attachment positions and resultant length change patterns of these AM reconstructions are not understood. This is important in order to understand how to avoid overconstraint or graft elongation [20].

The aim of this study was to examine the length change pattern of both the native dMCL and related reconstructions. Previous studies investigating the length change behaviour of sMCL reconstructions [20] led us to hypothesise that changing the tibial attachment point would have less effect on the length change pattern compared to changing the femoral attachment point. Furthermore, it was hypothesised that the length change pattern of extra-anatomical AM reconstruction would not differ significantly from that of the native dMCL.

MATERIALS AND METHODS

Eleven unpaired, fresh-frozen human cadaveric knees (mean age: 81.8; range: 73–90) with no history of prior injury, no fixed flexion deformity or joint disease were used in this study. The specimens were dissected and tested by a single senior orthopaedic surgeon investigator (initials blinded for review). After testing, specimens were carefully examined to ensure the integrity of the menisci and cruciate ligaments and to ensure that no advanced cartilage erosions were present. Intra-articular pathology like severe osteoarthritis was excluded at the end of testing through a trans patella approach.

Specimen preparation

Specimens were stored at −20°C and thawed for 24 h before testing. The tibia and femur were transected 200 mm above and below the joint line. The skin and subcutaneous tissue were removed, but the fascia and muscles were left intact. After preparation, the quadriceps muscle and iliotibial band were divided into six different anatomical parts as described previously [20]. Sutures (No.2 Fiberwire; Arthrex Inc.) were placed at the musculotendinous junction to allow load application. All specimens were flexed and extended 10 times to minimise tissue hysteresis.

On the medial side, the layer 1 fascia was divided to reveal the proximal and distal attachment sites of the sMCL. To expose the dMCL, the distal tibial sMCL attachment was osteotomised, with the sMCL left attached, as described previously [44]. The sMCL was then elevated from the underlying tissue and reflected proximally to expose the dMCL as far posterior as the merging of layers 2 and 3 [36, 42]. The femoral and tibial dMCL attachments were delineated into anterior, middle and posterior parts and marked with small metal pins. The middle was defined as being equidistant between the anterior and most posterior fibres. The tibial bone block, with attached sMCL, was then fixed back in the original place as described previously, resulting in a functionally intact dMCL and sMCL throughout the length change testing [44].

To analyse length change patterns of potential AM reconstructions, additional tibial attachment points were marked with small metal pins (Figure 1 and Table 1). Previous studies have shown that isometric sMCL reconstruction may be best achieved when the femoral graft attachment is positioned in the middle or posterior part of the native sMCL femoral attachment site [20]. Behrendt et al. [8] suggested that AMRI could be better controlled by adding an extra-anatomical AM reconstruction to a sMCL graft. To simplify the surgical procedure, a single femoral attachment position was used for both grafts. To test the optimal position for the AM reconstruction, pins were placed in the middle of the femoral sMCL attachment (pin 'F1') and into the posterior part of the sMCL femoral attachment (pin 'F2').

Length change measurements

Specimens were mounted into a custom-made kinematic rig with the posterior femoral condyle line parallel to the ground by fixing an intramedullary rod into the femur and leaving the tibia hanging vertically and unrestrained. This setup has been previously described and shown to have a high test–retest reliability [39]. Dynamic muscle forces were mimicked by loading the quadriceps muscle parts and iliotibial band using

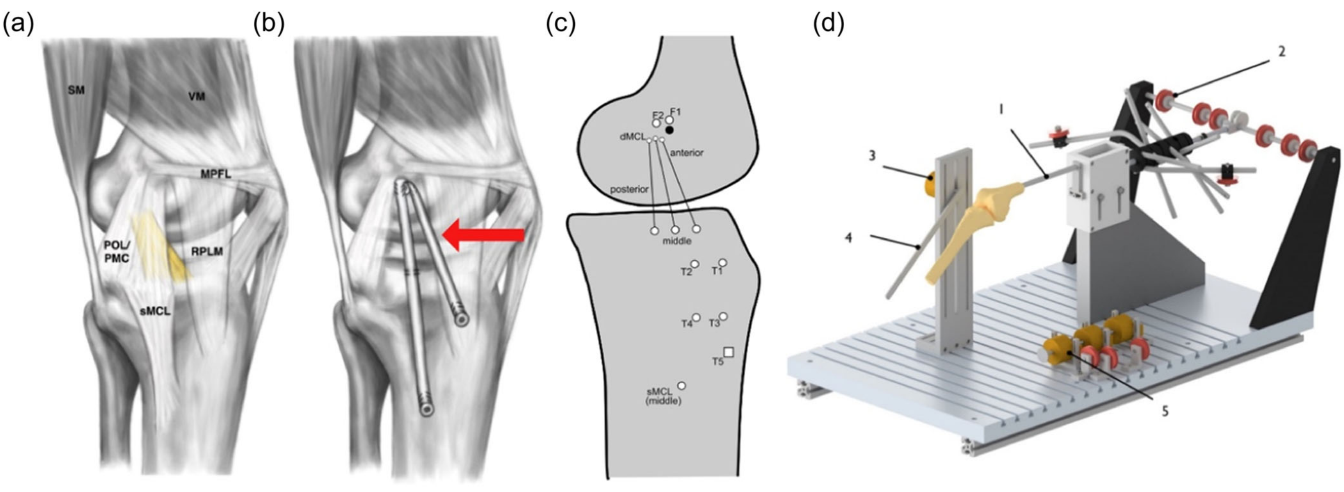

FIGURE 1 Length change patterns of the deep medial collateral ligament (dMCL) and related reconstructions. (a) Anatomy of the medial collateral complex (dMCL highlighted in yellow). (b) V-shaped anteromedial reconstruction including a dMCL reconstruction (red arrow). (c) Different tibiofemoral combinations were examined representing three different fibre orientations of the dMCL (anterior, middle, posterior) and extra-anatomical reconstructions (femoral: F1, F2; tibial T1–5). (d) Testing was performed using an open chain muscle extension rig as described by Ghosh et al. [16] and modified by Kittl et al. [20] with the femur being fixed with an intramedullary femoral rod (1). Muscle loads were applied using a pully system (2) and free-hanging weights. Flexion of the femur was recorded by a rotatory encoder connected to a metal bar (4) that paralleled the tibia shaft axis; tibiofemoral length changes were recorded by a second rotatory encoder (5), which was connected to a monofilament suture combining different tibial and femoral pin positions. MPFL, medial patellofemoral ligament; POL/PMC, posterior oblique ligament/posteromedial capsule; RPLM, medial longitudinal patellar retinaculum; SM, semimembranosus muscle; sMCL, superficial medial collateral ligament; VM, vastus medialis muscle.

TABLE 1 Attachment position of the femoral and tibial pins and related tibiofemoral combinations.

Tibiofemoral combination	Femoral pin position	Tibial pin position
Native deep MCL		
Anterior dMCL	Anterior position of the femoral dMCL attachment	Anterior position of the tibial dMCL attachment
Middle dMCL	Midpoint between the anterior and posterior femoral dMCL attachment	Midpoint between the anterior and posterior tibial dMCL attachment
Posterior dMCL	Posterior position of the femoral dMCL attachment	Posterior position of the tibial dMCL attachment
Extra-anatomical anteromedial reconstructions		
Femoral pin position	**Tibial pin position**	
Central femoral attachment of the sMCL (F1)	T1–T5	T1: 2 cm distal to the tibial joint line and 1 cm posterior to the anterior tibial margin
		T2: 2 cm distal to the tibial joint line and 2 cm posterior to the anterior tibial margin
Posterior femoral attachment of the sMCL (F2)	T1–T5	T3: 4 cm distal to the tibial joint line and 1 cm posterior to the anterior tibial margin
		T4: 4 cm distal to the tibial joint line and 2 cm posterior to the anterior tibial margin
		T5: The attachment of the semitendinosus

Abbreviations: dMCL, deep medial collateral ligament; sMCL, superficial medial collateral ligament.

hanging weights (total of 205 N) according to their cross-sectional areas and fibre orientation [12, 21].

To measure the length changes between tibiofemoral pin combinations, an established method was used [20]. A No.2 Fiberwire (Arthrex Inc.) suture was tied to a tibial pin, passed through the eyelet of a femoral marking pin and led to an optical rotary incremental encoder (PRID 58H8; Opkon), attached to a small weight (0.3 N) to hold the suture tight. Opening of the eyelet pin was standardised pointing towards the encoder, which was in an identical position for all tested specimens. The accuracy of the optical rotary encoder was ±0.08°, allowing length changes to be calculated to the nearest 0.1 mm (accuracy ±0.02 mm). Tibiofemoral distances, for each pin combination tested, were measured at full extension using a digital caliper (accuracy ±0.01 mm). The knee was then flexed between 0° and 100° three times. Data were collected using custom-made software [20] from the rotary encoder measuring suture length change (mm) and from another rotatory encoder, fixed to a metal bar aligned with the flexion/extension axis, measuring knee flexion angle (°) [20]. A data point was taken at increments of 10° of knee flexion and a script (Python Software Foundation) averaged the three repetitions.

Data analysis

Length change patterns of the native dMCL and related tibiofemoral reconstructions were plotted and expressed as strain [(length change/absolute length at 0° × 100%)]. In addition, the total strain range (TSR) was calculated (TSR = maximum strain − minimum strain), with low values indicating near-isometric behaviour and high values indicating nonisometric behaviour.

Statistical analysis

Statistical analysis was performed using GraphPad Prism 8 (GraphPad). Two-way repeated-measures analysis of variances were conducted to determine the effect of changing the femoral or tibial attachment sites and to compare TSR for the native fibres and reconstructions. Significance was set at $p < 0.05$ divided by the number of tests (Bonferroni correction). Based on previous work [20, 43], an a priori power analysis was performed to detect a difference of 1% strain (effect size: 0.78; power: 0.8) and 3% TSR (effect size: 0.73; power: 0.8) using G*Power (Universität Düsseldorf, Germany). For this, an estimated total sample size of six was calculated.

RESULTS

Native dMCL

The three fibre regions of the native dMCL, anterior, middle and posterior demonstrated different length change patterns with knee flexion (Figure 2). The anterior part tightened from 20° of flexion, with the distance between femoral and tibial pins lengthening

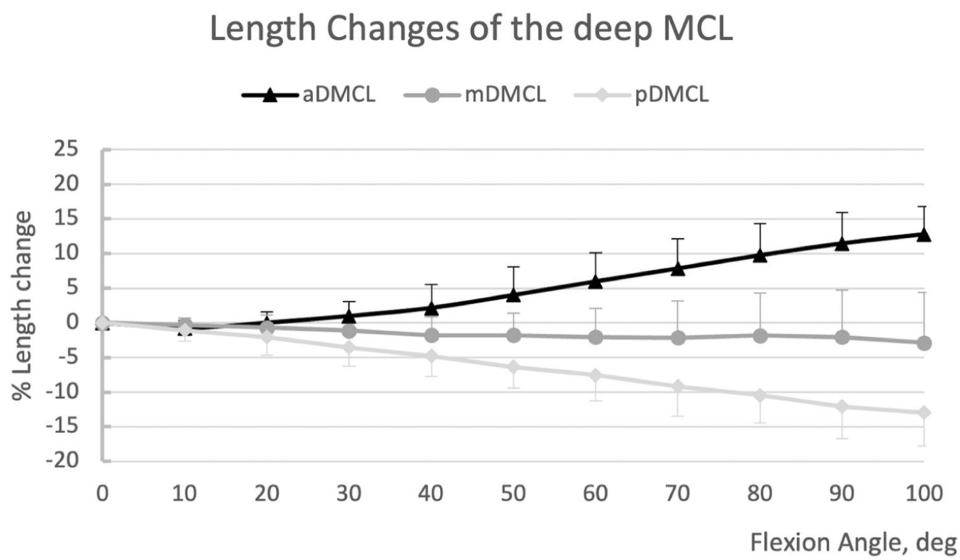

FIGURE 2 Length change pattern of the anterior, middle and posterior fibre regions of the deep medial collateral ligament across knee flexion. Displayed as mean ± SD; $n = 11$. Significances are stated in the text.

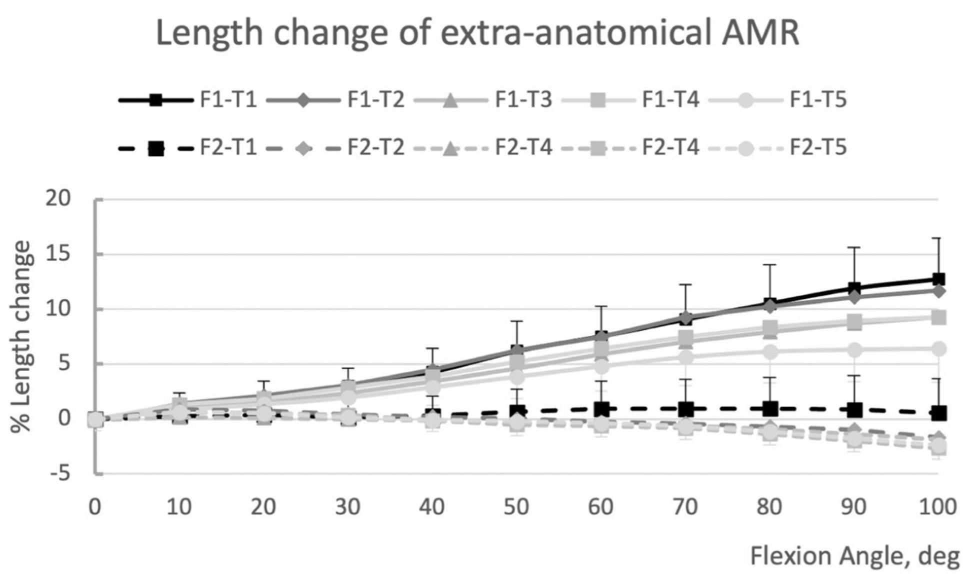

FIGURE 3 Length change pattern of the different tibiofemoral combinations connecting the tibial attachment points T1–T5 and femoral F1 and F2 points, across knee flexion. Displayed as mean ± SD; $n = 11$. Significances are stated in the text. AMR, anteromedial rotatory.

to a maximum of 12.7 ± 4.0% at 100° knee flexion. Conversely, the posterior fibres slackened with flexion, with the distance between pins reducing by −12.9 ± 4.8% ($p < 0.05$ at ≥30° of flexion compared to the anterior dMCL). The middle fibre region was almost isometric and slackened by a maximum of 2.8% at 100° knee flexion with an overall TSR of 6.8 ± 1.5% ($p < 0.01$) compared to TSR = 14.2 ± 3.7% for the anterior part and TSR = 13.3 ± 4.6% for the posterior part.

Extra-anatomic anteromedial reconstruction

Changes between the femoral position F1 and F2 had a more pronounced effect on length change behaviour than changes in tibial pin position (Figure 3). Length changes only became significantly different for changes in tibial position beyond 80° of flexion ($p < 0.05$) for F1 combinations and after 90° of flexion for F2 combinations. Pin combination F2–T1 was the

TABLE 2 Total strain range of each tested tibiofemoral combination (in %).

Tibiofemoral combination	Total strain range
Native dMCL	
Anterior fibres of the dMCL	14.2 ± 3.7
Middle fibres of the dMCL	6.8 ± 1.5
Posterior fibres of the dMCL	13.3 ± 4.6
Potential anteromedial reconstructions	
F1–T1	13.0 ± 3.7
F1–T2	12.2 ± 3.8
F1–T3	9.9 ± 3.1
F4–T4	9.8 ± 3.7
F4–T5	6.8 ± 3.1
F2–T1	3.6 ± 1.5
F2–T2	3.9 ± 1.7
F2–T3	3.9 ± 1.5
F2–T4	4.2 ± 1.6
F2–T5	3.7 ± 1.7

Abbreviation: dMCL, deep medial collateral ligament.

most isometric (TSR = 3.6 ± 1.5%) with other tibial positions also showing little length change variation (Table 2). The behaviours of all the F2-based tibiofemoral combinations were not significantly different from the fibre length change behaviours of the middle portion of the native dMCL.

In comparison, the F1 pin tibiofemoral combinations exhibited a wider range of length change behaviours (T1, 13.0 ± 3.7%; T2, 12.2 ± 3.8%; T3, 9.8 ± 3.1%; T4, 9.8 ± 3.7%; T5, 6.8 ± 3.1%), with increased length at higher flexion angles (6%–12% at 100°). TSR for tibiofemoral combinations (Table 2) using the F1 attachment site varied (maximum F1–T1, 13.0 ± 3.7%; minimum F1–T5, 6.8 ± 3.1%).

DISCUSSION

The main finding of this study was that the length change behaviours of potential extra-anatomic AM reconstructions in a functionally intact knee joint were similar to that of the native mid-portion of the dMCL when the femoral attachment of the AM reconstruction was placed in the posterior part of the native sMCL attachment. AM reconstructions, using this femoral position, were close to isometric between 0° and 100° of knee flexion, irrespective of the tibial attachment site.

The reciprocal length change pattern of the anterior and posterior fibres of the dMCL has been previously investigated [4, 43] and is mainly dependent on the femoral attachment site. The posterior dMCL fibres attach posterior to the medial epicondyle and slacken with knee flexion, while the anterior fibres are attached anteriorly to the axis of flexion [4, 43]. Our study confirmed this behaviour. We found that the anterior part of the dMCL slackened <5% in the first 30° of flexion, reaching approximately 10% length increase at 100° flexion. The posterior part slackened uniformly, with the distance between tibial and femoral attachments decreasing in length by 13% at 100° knee flexion. A similar pattern of length change was found by Willinger et al. [43], although they found a decrease in length of 7%. The difference may be related due to different testing setups. Whilst Willinger et al. [43] assessed the anterior and posterior parts of the dMCL, they did not assess the midportion fibres, which we found to demonstrate nearly isometric length change behaviours.

Recently, biomechanical studies have shown the potential of an AM in restraining ER and combined anterior tibial translation and external rotation (AMRI) [8, 29, 30]. Miyaji et al. performed an anatomical dMCL reconstruction by using the native femoral insertion site of the dMCL and its tibial footprint in the centre of the broad tibial dMCL attachment [29, 30]. This tibiofemoral combination showed isometric length changes, similar to the behaviours of the mid-dMCL fibres that we found in the present study. However, reconstructing the sMCL and dMCL, with separate grafts and tunnels, would necessitate the drilling of two separate femoral tunnels and two tibial tunnels. This might present issues with tunnel conflict, particularly on the femoral side due to the close proximity of the two tunnels. Previous studies have suggested that AMRI might be controlled by a combined sMCL and extra-anatomic AM reconstruction, simulating the role of the dMCL [8, 13]. However, the optimal tunnel position and length change behaviours of this extra-anatomic AM reconstruction were not elucidated. The optimal position and behaviours of such a reconstruction were investigated in this study. We found that the AM reconstruction as suggested by Behrendt et al. [8] (represented by the F1–T1 pin positions) would tighten by 12.7% as the knee flexed to 100°. Thus, if a graft using these tibial and femoral attachment sites was tensioned in extension, it would likely result in excessive graft forces that could cause graft elongation or compromise healing in the early postoperative period.

Graft isometry has been advocated as an important goal in knee ligament reconstruction [14, 17, 33], and the optimal femoral attachment would be in the F2 position as suggested by this study, located in the posterior part of the native femoral sMCL attachment site. When the femoral attachment was placed in this position, tibiofemoral length change was minimal, exhibiting near-isometric length change behaviours, irrespective of the tibial attachment used. All the tibial attachments tested using the F2 femoral attachment position resulted in <4% tibiofemoral length change. In addition, an AM reconstruction graft positioned using the F2 femoral attachment site and T2, T3 and T4 tibial attachments demonstrated length change patterns similar to the native mid-portion of the dMCL and would be slightly tighter in extension. These behaviours would be favourable to restrain anteromedial rotation in lower angles of knee flexion without possibly over-constraining the knee in deeper flexion angles. Associated ideas involving the use of flat tendons may display greater leniency concerning isometry. Described techniques and previous single-bundle reconstructions also target a relatively posterior placement of the femoral sMCL insertion and achieve excellent clinical outcomes [1, 7, 28].

Despite showing that the different tibial attachment points had a minimal influence on the length change patterns when using the F2 position, the use of a more distal tibial attachment position resulted in slightly more slackening as the knee flexed (T1 = 0.5% vs. T5 = −2.4% at 100° knee flexion). A more proximal tibial graft attachment might be advantageous in that it would shorten the working length of the graft and theoretically improve the stiffness of the construct. Taking into account the different structural properties of the dMCL and sMCL [34], further investigations building upon the results of this study should investigate these effects in a kinematic robotics design, also considering the influence of rotatory loads on the kinematics. This aspect becomes even more important when using synthetic graft materials with very low elasticity. Posterior F2 positioning allows for almost isometric graft behaviour, which may be important to augment primary repair allowing the healing of the deep MCL [9].

This study has some limitations due to the experimental setup. Length change behaviours were assessed with functionally intact knees to 100° flexion, without axial loading or involvement of the hamstring muscles. Additionally, the resulting tensile strain from length changes could not be directly measured, because the transition of the tested structures of becoming tight from a slack state was not known. This could be important in defining graft pretensioning and optimal knee flexion angle for fixation. This study did not evaluate the capability of AM reconstructions to restore knee kinematics; therefore, functionally intact knees were used to assess the length change pattern.

Previous studies have shown that an AM can restore intact knee kinematics after a simulated sMCL/dMCL injury [8], supporting our confidence in the model as a fair approximation. We focused on length change behaviour to reveal optimal AM graft position with regard to isometry in a similar manner to studies that have recommended optimal positioning of sMCL and POL reconstructions [20]. The length change behaviour in response to rotatory loads, like the study of Willinger et al. [44], was not tested, because the capacity of this reconstruction in restraining combined loads would be best evaluated in a robotic testing setup.

The femoral attachment of the sMCL has been described differently in the literature. Some authors have described it as attaching posterior and proximal to the medial epicondyle [14, 22], while others described it as enveloping the epicondyle [4, 11, 20, 23, 25, 36, 38, 42, 44, 45]. We found the latter description in the dissection of the sMCL in this study. The central sMCL fibres are attached in the midportion of the medial epicondyle, but slightly more proximally than the anterior and posterior parts. The way in which the native fibres envelope the epicondyle may lead to subtle length change differences [15], but cannot be reproduced by sutures or small diameter grafts that have a linear course. In light of the high frequency of MCL complex injuries and their significant impact on the increased failure rate in ACL reconstruction, an ideal AM reconstruction with a low tension profile holds a lot of promise for future MCL reconstruction.

CONCLUSION

The length change behaviours of simulated AM reconstructions in an intact knee are mainly influenced by the position of the femoral attachment, with different tibial attachments having a minimal effect on length change across 0°–100° of flexion. Using a femoral attachment in the posterior part of the native sMCL minimised graft length changes with knee flexion. Surgeons performing AM reconstructions to control AMRI are advised to choose a femoral graft position in the posterior part of the native sMCL attachment to optimise graft length change behaviour.

AUTHOR CONTRIBUTIONS

Conceptualisation: Peter Behrendt, Bodo Kurz and Christoph Kittl. *Methodology*: Peter Behrendt, Elmar Herbst and Christoph Kittl. *Validation*: Peter Behrendt, James R. Robinson, Florian Gellhaus, Mirco Herbort, Bodo Kurz and Christoph Kittl. *Formal analysis*: Peter Behrendt, James R. Robinson and Christoph Kittl. *Investigation*: Peter Behrendt, Florian Gellhaus and Bodo Kurz. *Writing—original draft preparation*: Peter Behrendt, James R. Robinson and Christoph Kittl. *Writing—review and editing*: All authors. *Visualisation*: Peter Behrendt and Christoph Kittl. *Supervision*: Michael J. Raschke and Andreas Seekamp. *Project administration*: Peter Behrendt, Michael J. Raschke, Andreas Seekamp and Christoph Kittl. *Funding acquisition*: Peter Behrendt and Andreas Seekamp. All authors have read and agreed to the final version of this manuscript.

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CONFLICT OF INTEREST STATEMENT

Elmar Herbst and Christoph Kittl both declare that they are part of the KSSTA Editorial Team and Board, respectively.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the institutional Ethics Committee of the University of Kiel. The body donors were recruited from the local body donation programme provided by the Institute of Anatomy, Christian-Albrechts-University Kiel, Germany, after previous informed written consent to be used for medical research and educational purposes in accordance with the regulatory guidelines ('Law on the Handling, Burial and Cemetery Management (Burial Act) of the State of Schleswig-Holstein dated 04/02/2005, Section II, §9: anatomical dissection').

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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