Original Research

Elongation Patterns of the Superficial Medial Collateral Ligament and the Posterior Oblique Ligament

A 3-Dimensional, Weightbearing Computed Tomography Simulation

Sandro Hodel,*† MD, Julian Hasler,† MD, Philipp Fürnstahl,‡ Prof,
Sandro F. Fucentese,† Prof, MD, and Lazaros Vlachopoulos,† MD, PhD

Investigation performed at Balgrist University Hospital, University of Zurich, Zurich, Switzerland

---

Background: Although length change patterns of the medial knee structures have been reported, either the weightbearing state was not considered or quantitative radiographic landmarks that allow the identification of the insertion sites were not reported.

Purpose: To (1) analyze the length changes of the superficial medial collateral ligament (sMCL) and posterior oblique ligament (POL) under weightbearing conditions and (2) to identify the femoral sMCL insertion site that demonstrates the smallest length changes during knee flexion and report quantitative radiographic landmarks.

Study Design: Descriptive laboratory study.

Methods: The authors performed a 3-dimensional (3D) analysis of 10 healthy knees from 0° to 120° of knee flexion using weightbearing computed tomography (CT) scans. Ligament length changes of the sMCL and POL during knee flexion were analyzed using an automatic string generation algorithm. The most isometric femoral insertion of the sMCL that demonstrated the smallest length changes throughout the full range of motion (ROM) was identified. Radiographic landmarks were reported on an isometric grid defined by a true lateral view of the 3D CT model and transferred to a digitally reconstructed radiograph.

Results: The sMCL demonstrated small ligament length changes, and the POL demonstrated substantial shortening during knee flexion ($P = .005$). Shortening of the POL started from 30° of flexion. The most isometric femoral sMCL insertion was located 0.6 ± 1.7 mm posterior and 0.8 ± 1.2 mm inferior to the center of the sMCL insertion and prevented ligament length changes $>5\%$ during knee flexion in all participants. The insertion was located 47.8% ± 2.7% from the anterior femoral cortex and 46.3% ± 1.9% from the joint line on a true lateral 3D CT view.

Conclusion: The POL demonstrated substantial shortening starting from 30° of knee flexion and requires tightening near full extension to avoid overconstraint. Femoral sMCL graft placement directly posteroinferior to the center of the anatomical insertion of the sMCL demonstrated the most isometric behavior during knee flexion.

Clinical Relevance: The described elongation patterns of the sMCL and POL aid in guiding surgical medial knee reconstruction and preventing graft lengthening and overconstraint of the medial compartment. Repetitive graft lengthening is associated with graft failure, and overconstraint leads to increased compartment pressure, cartilage degeneration, and restricted ROM.

Keywords: medial knee reconstruction; isometry; medial collateral ligament; posterior oblique ligament

---

The anatomy of the medial collateral ligament (MCL) and the posteromedial corner has become of interest in the context of medial knee reconstruction techniques.[3,22,28,32] Despite the excellent healing potential of the MCL, patients with residual symptomatic valgus or anteromedial rotatory instability necessitate surgical reconstruction.[19] Furthermore, the role of the MCL as an anteromedial rotatory stabilizer has been recognized in combined anterior cruciate ligament injury.[4,31]

Repair or reconstruction of the MCL has proven to be effective in restoring valgus and rotatory instability, and various surgical techniques have been developed.[9] The

---

The Orthopaedic Journal of Sports Medicine, 10(5), 23259671221091264
DOI: 10.1177/23259671221091264

MCL and posteromedial corner consist of 3 main anatomical structures: the superficial MCL (sMCL), the deep MCL, and the posterior oblique ligament (POL).[23] While the MCL primarily resists valgus force,[4] the POL has been identified as an important restraint to tibial internal rotation near extension.[8,13,14,26] Modifications toward a more precise anatomical reconstruction of the 3 medial knee structures, compared with a nonanatomical single-bundle reconstruction,[33] intend to restore the anatomy of the sMCL and POL.[7] While restoration of valgus stability has been reported with the use of both techniques,[9] the importance of an additional POL reconstruction to restore native internal rotatory stability has been highlighted by LaPrade and Wijdicks.[24]

Previous research has mainly focused on the biomechanical behavior of these reconstruction techniques.[11,22,29] Although length changes of the native medial ligament complex and also reconstruction techniques have been described investigating the full range of motion (ROM),[21,32] we are only aware of 1 study investigating ligament elongation under in vivo weightbearing conditions.[18] Previous studies either have not considered the weightbearing state[21,32] or have not reported quantitative radiographic landmarks that allow the clear identification of the insertion sites that demonstrate the smallest length changes during flexion.[18] However, the axial rotation of the native knee joint during flexion under weightbearing load might influence ligament elongation patterns and therefore should be accounted for.

Understanding graft elongation patterns and accurate identification of the insertion sites is of clinical relevance, as an isometric graft placement may lead to overconstraint or slackening of the graft and can promote graft failure. A detailed understanding of the elongation patterns of the sMCL and POL throughout a full ROM and the femoral insertions that demonstrate the smallest length changes would be helpful to guide surgical reconstruction of the medial knee.

The primary aim of this study was to analyze the elongation patterns of the sMCL and POL during knee flexion in a weightbearing 3-dimensional (3D) computed tomography (CT) model. The secondary aim was to identify the femoral sMCL insertion that demonstrated the smallest length changes during knee flexion and to report its location with respect to quantitative radiographic landmarks. We hypothesized that (1) the sMCL would demonstrate decreased length changes compared with the POL during knee flexion and (2) a femoral sMCL insertion point could be identified that demonstrates isometric behavior throughout the full ROM.

METHODS

Weightbearing CT scans of 10 healthy volunteers, acquired for a previous study,[6] were analyzed in a 3D simulation. The mean age of the participants was 35 years (range, 25-42 years), the mean weight was 83 kg (range, 62-85 kg), and the mean height was 180 cm (range, 169-190 cm). No volunteer stated having had previous knee symptoms or surgery. High-resolution CT images were acquired in a standing position with increasing knee flexion (0°, 30°, 60°, and 120°) using an open extremity CT scanner (Verity, Planmed; slice thickness, 0.4 mm). The study protocol was approved by the local ethics committee, and written informed consent was obtained from all patients.

The 3D triangular surface models were generated with global threshold segmentation and region growing using Mimics software (Materialise). The models were imported into the in-house planning software CASPA (Balgrist Zurich). The femur remained static as a reference, and the tibial motion was described relative to the femur throughout flexion. The femoral model of each participant was superimposed using an iterative closest point (ICP) surface registration algorithm.[5] Five defined knee flexion angles (0°, 30°, 60°, 90°, and 120°) were interpolated to reduce the effect of variable degrees of flexion among the participants during CT scan. As the models were obtained for a previous study, the proximal tibia models did not include a minimum length of 7 cm in all cases. Therefore, a mean 3D model of a right tibia was superimposed onto the original tibial plateau of each candidate with the same ICP algorithm.[5] The model was generated from the CT data of 21 healthy participants using a statistical shape modeling (SSM) approach according to Albrecht et al[1] and was used for a previous study.[17] The mean absolute registration error of the SSM onto the original participants' tibial plateau was 1.1 mm (range, 0.9-1.6 mm).

A coordinate system was adjusted according to Grood and Suntay[15] with the proximal directing vector ($\vec{z}$) being the normal vector of the tibial joint plane, the anterior directing vector ($\vec{y}$) in the direction of the medial border of the tibial tuberosity, and ($\vec{x}$) toward lateral. The tibial joint plane was defined by standardized surface registration spheres at the medial and lateral tibial plateau as previously described.[16]

First, an analysis of the ligament length changes of the sMCL and POL was performed. Second, the most isometric femoral insertion point of the sMCL was defined and quantitative radiographic landmarks were reported. As the POL demonstrated significant lengthening during extension in previous studies[18,32] and its main role is to provide rotational and valgus stability near extension after anatomical

---

*Address correspondence to Sandro Hodel, MD, Department of Orthopedics, Balgrist University Hospital, University of Zurich, Forchstrasse 340, 8008 Zurich, Switzerland (email: andro.hodel1@gmail.com).

†Department of Orthopedics, Balgrist University Hospital, University of Zurich, Zurich, Switzerland.

‡Research in Orthopedic Computer Science (ROCS), Balgrist University Hospital, University of Zurich, Zurich, Switzerland.

Final revision submitted January 21, 2022; accepted February 8, 2022.

One or more of the authors has declared the following potential conflict of interest or source of funding: S.F.F. has received consulting fees from Medacta SA (Switzerland), Smith & Nephew (United Kingdom), and Karl Storz SE & Co KG (Germany). AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the regional ethics committee, Zurich, Switzerland (reference No. KEK-ZH-Nr 2013-0374).

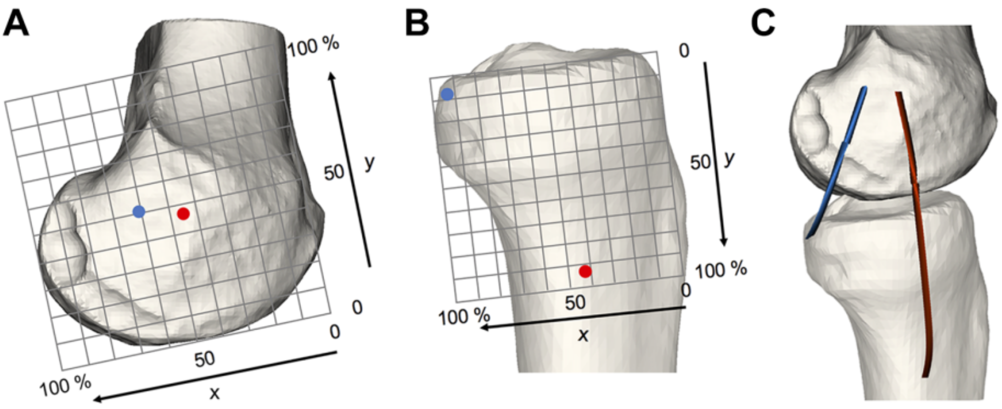

Figure 1. Definition of the superficial medial collateral ligament (sMCL) insertion (red) and posterior oblique ligament (POL) insertion (blue) at the (A) femur and (B) tibia. (C) The automatic string generation algorithm computed the graft strands of the sMCL (red) and POL (blue) from the defined femoral to the tibial insertion points.

reconstruction,[24] we did not attempt to compute an isometric point for this graft strand because of its limited clinical relevance.

Definition of the Anatomical Insertion Points, sMCL, and POL

Anatomical Insertion Points. The femoral and tibial insertion sites were defined as the center of insertion according to quantitative anatomical measurements as described by Saigo et al.[28] The quantitative anatomical insertion points of the sMCL and POL were computed according to a femoral and tibial grid in a true lateral view of the 3D CT model. The borders of the femoral grid were defined by the posterior medial condyle, the distal medial condyle, and the anterior femoral cortex. The femoral grid was defined as a square, and its proximodistal and anteroposterior length was defined by the distance from the posterior medial condyle to the anterior femoral cortex (Figure 1A). The borders of the tibial grid were defined by the posterior and anterior tibial cortex and the proximal medial tibial plateau. The tibial grid was defined as a square, and its proximodistal and anteroposterior length was defined by the distance from the posterior tibial cortex to the anterior tibial cortex (Figure 1B). The y axes of the femoral and tibial grids were identical to the plane normal of the tibial plateau ($\vec{z}$) of the previously described coordinate system. This allowed the simulation of the insertion points independent of height.

Superficial Medial Collateral Ligament. The sMCL was computed from the femoral insertion, located at 46.9% (x axis) and 47.5% (y axis) (Figure 1A), to the tibial insertion, located at 43.1% (x axis) and (92.9% y axis) (Figure 1B), as described by Saigo et al.[28]

Posterior Oblique Ligament. The POL was computed from the femoral insertion, located at 61.6% (x axis) and 51.2% (y axis) (Figure 1A), to the tibial insertion, located at 95.5% (x axis) and 7.0% (y axis) (Figure 1B), as described by Saigo et al.[28]

Definition of Ligament Length Changes and the Most Isometric Insertion of the sMCL on the Medial Femoral Surface

Ligament length change was defined as the maximum lengthening or shortening, compared with the initial length of the simulated ligament in extension, throughout the full ROM. Positive values indicated a ligament lengthening, and negative values a relative ligament shortening during knee flexion.

An automatic string generation algorithm according to Graf et al[12] computed the isometric score for the sMCL and POL graft strand throughout the full ROM (0°-120°). The sum of the relative mean square errors of all generated string lengths defined the isometric score (0 = perfect isometry; the higher the score, the more anisometric).[12] The isometric score (I_s) was calculated as the relative mean square error of a string (s) over all flexion positions as described by Graf et al[12]

$$I_s=\frac{1}{|P|}\sum_{p\epsilon P}^{c}\left(\frac{l_{p,s}-\bar{l}_s}{\bar{l}_s}\right)^2$$

where P is the set of all flexion positions, $l_{p,s}$ is the length of string s in flexion position p, l_s is the average length of the string over all flexion positions, and $|P|$ is the number of measured flexion positions.

We aimed to find the femoral insertion point close to the anatomical sMCL insertion that demonstrated the most isometric score throughout a full ROM while avoiding overconstraint or slackening in knee flexion. The most isometric femoral insertion point for the sMCL was calculated on the medial femoral surface and was limited within a sphere (10-mm radius) centered at the anatomical sMCL insertion. Additionally, the location of the most isometric point was reported within the femoral grid that was computed according to Saigo et al[28] (Figure 1). To allow the identification of the reported quantitative measurements in intraoperative fluoroscopy, we identified the anatomical landmarks that defined the femoral borders of the grid (ie, posterior medial condyle, inferior medial condyle, and anterior cortex) in the

TABLE 1
Relative Ligament Length Changes of the sMCL and POL Throughout Knee Flexion for Each Participant[a]

	Ligament Length Change Throughout Full ROM				
	<2%	2%-5%	5%-10%	>10%	Ligament Length Change During Flexion, mm[b]
sMCL	0	7	2	1	1.2 ± 5.1 (5.0 to–10.3)[c]
POL	0	0	0	10	–13.8 ± 2.8 (–9.3 to–19.8)[c]

[a] Values are presented as number or mean ± SD (range). POL, posterior oblique ligament; ROM, range of motion maximum; sMCL, superficial medial collateral ligament.

[b] Length changes are reported as maximum length change during knee flexion in relation to the original ligament length in extension. Positive values indicate relative lengthening, and negative values indicate relative shortening.

[c] Significant shortening of POL compared with sMCL during knee flexion ($P = .005$).

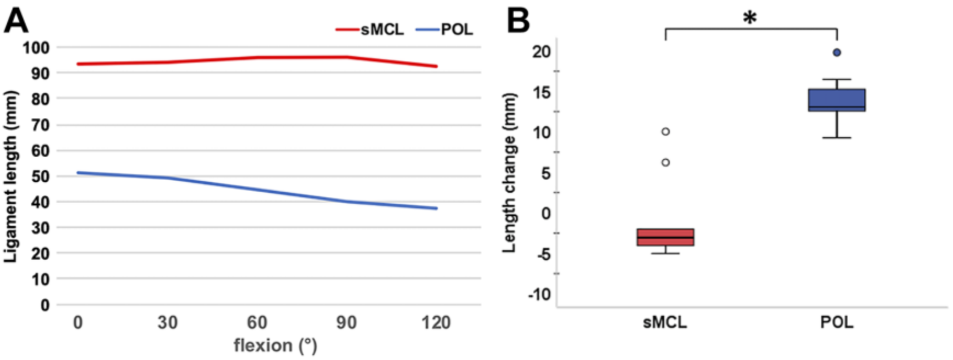

Figure 2. Ligament length changes of the superficial medial collateral ligament (sMCL) and posterior oblique ligament (POL) during knee flexion. (A) Average ligament length of the sMCL and POL throughout the full range of motion. (B) Average maximum length change during knee flexion in relation to the original ligament length in extension (positive values indicate relative lengthening, and negative values indicate relative shortening). *Significant shortening of the POL compared with the sMCL during knee flexion ($P = .005$).

3D CT model using manual annotation and created a digitally reconstructed radiograph as described by Esfandiari et al.[10] The quantitative radiographic landmarks were analyzed in a true lateral view confirmed by a congruent overlap of the posterior condyles.

Statistical Analysis

Normal distribution was assessed using the Shapiro-Wilk and Kolmogorov-Smirnov tests. Data were reported as means ± SDs and ranges. Differences between sMCL and POL ligament length changes and the isometric scores were assessed using the Wilcoxon test. Data were analyzed with SPSS Version 26 (IBM Corp).

RESULTS

Ligament Length Changes of the sMCL and POL

The sMCL demonstrated a mean ligament lengthening of 1.2 ± 5.1 mm (range, 5.0 to–10.3 mm) during knee flexion compared with a shortening of the POL of–13.8 ± 2.8 mm (range,–9.3 to–19.8 mm) in all participants ($P = .005$) (Table 1, Figure 2).

Lengthening of the sMCL occurred from 30° to 90° of knee flexion. Shortening of the POL occurred from 30° to 120° of knee flexion. The sMCL was longest in 60° to 90° of flexion, and the POL was longest in full extension (Figure 2).

Isometric Score and Most Isometric Femoral sMCL Insertion Point

The isometric score of the sMCL was 1.2 ± 1.8 ($\times 10^{-3}$) compared with 35.5 ± 15.2 ($\times 10^{-3}$) for the POL ($P = .005$). The femoral sMCL insertion with the most isometric score throughout the full ROM was located at 47.8% ± 2.7% (44.1%-52.1%) of the x axis and at 46.3% ± 1.9% (43.4%-49.3%) of the y axis (Figure 3A). The most isometric femoral sMCL insertion was located 0.6 ± 1.7 mm posterior and 0.8 ± 1.2 mm inferior to the center of the sMCL insertion. This point prevented ligament length changes >5% in all participants with a mean lengthening of 2.6% ± 1.1% (1.5%-5.0%) during knee flexion. In a true lateral view of the digitally reconstructed radiograph, the point could be identified directly anterosuperior of a crosshair defined by a line between the posterior femoral cortex and the most distal point of the medial condyle (in line with the posterior femoral cortex), and a perpendicular line through the most posterior point of the medial condyle (Figure 3B).

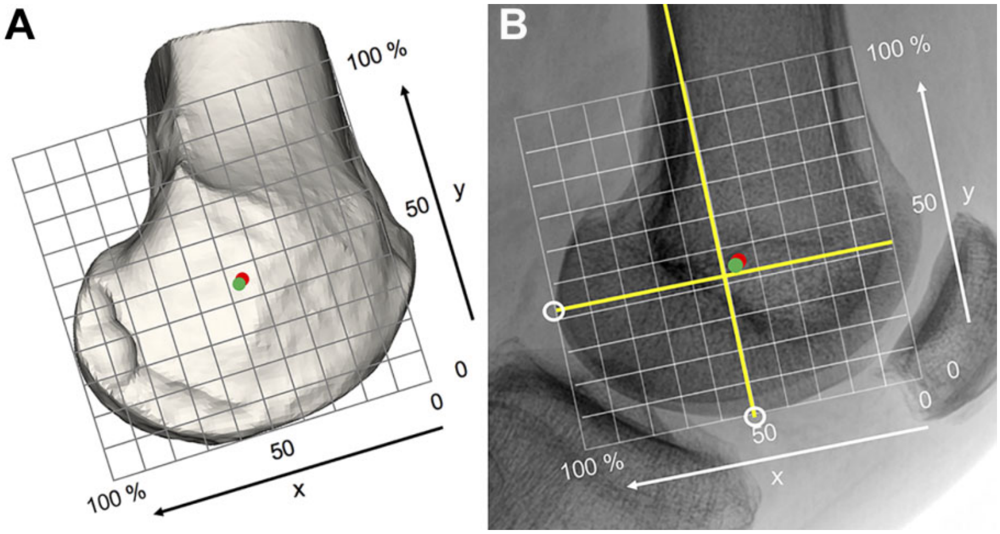

Figure 3. Quantitative radiographic landmarks to identify the most isometric superficial medial collateral ligament (sMCL) insertion point. (A) A close relationship was seen between the most isometric sMCL insertion point (green dot) and the anatomical insertion point (red dot). (B) In a true lateral fluoroscopy view, the most isometric point (green dot) can be identified in direct proximity anterosuperior to the center of a crosshair (yellow lines) that is defined by a line connecting the posterior femoral cortex and most inferior point of the medial condyle (white circle) and a perpendicular line passing through the most posterior point of the medial condyle (white circle). The red dot indicates the anatomical insertion point.

DISCUSSION

The most important finding of this study was that the sMCL, defined by the anatomical center of insertions, demonstrates only limited length changes throughout the full ROM compared with a significant shortening of the POL during knee flexion under weightbearing conditions. We were able to define the most isometric femoral sMCL insertion, which prevented ligament length changes $>5\%$ throughout the full ROM in each individual. The most isometric femoral insertion of the sMCL was identified in a true lateral view in direct proximity anterosuperior to the center of a crosshair, which was defined by a line connecting the posterior femoral cortex and the most inferior point of the medial condyle and a perpendicular line passing through the most posterior point of the medial condyle. These findings aid in guiding medial knee reconstruction to prevent repetitive stretching or slackening of the graft and eventual graft failure or overconstraint of the medial compartment.

We were able to confirm both our hypotheses. First, the sMCL demonstrated superior isometric characteristics and significantly smaller length changes during flexion compared with the POL. Second, we identified the most isometric sMCL insertion that demonstrated only limited length changes during knee flexion, with an average of less than 3% of the initial ligament length in extension. Because of the nearly isometric behavior of the native sMCL center, the computed most isometric point is located in direct proximity posteroinferior to the described anatomical insertion in accordance with previous studies.[21,32] While the elongation patterns of the center of the sMCL are in line with previous studies, it is important to consider the reciprocal behavior of tensioning of anterior fibers and slackening of posterior fibers of the MCL during flexion because of the fan-shaped wide anatomical structure.[2,21,30] However, most commonly performed MCL reconstruction techniques use a single graft strand for the sMCL,[24,25,33] and therefore guidance to reconstruct the sMCL and preventing lengthening or slackening of the graft strand is of high clinical relevance. The relatively small length changes of the sMCL during flexion support the role as a primary valgus stabilizer throughout the full ROM, whereas the slackening of the POL during flexion suggests that its primary role is to provide additional stability near full extension, as previously described.[28,31]

The reported quantitative radiographic landmarks aid in guiding surgical reconstruction using fluoroscopy. In the presence of chronic instability and scarring, the native anatomical insertions may not be identifiable and radiographic landmarks can be reproduced when using intraoperative fluoroscopy. As described by Saigo et al,[28] we could not reliably identify the medial epicondyle (ME) as a robust anatomical landmark and therefore purposely did not report the location with respect to the ME. Moreover, the relationship of the sMCL and the ME varies among previous studies,[23,27] which makes the ME a questionable anatomical landmark to guide medial knee reconstruction.

Regarding the POL graft strand, significant shortening occurred during knee flexion from 30° to 120°. As the main function is the constraint of tibial internal rotation near full extension[24] and ligament lengthening of the POL has been described toward knee extension in previous studies,[21,24] tightening of the POL graft strand in extension has been proposed.[24] This is supported by our results.

According to the described shortening in knee flexion (beyond 30°), the POL graft should be tensioned and fixed in less than 30° of knee flexion to reproduce its anatomical length and prevent overtightening in extension. Lind et al[25] have suggested tensioning the POL graft at 60° of knee flexion while using the same femoral insertion as for the sMCL graft strand.[20] This would result in restricted knee extension when respecting the anatomical femoral POL insertion and should be avoided.

Despite the inclusion of in vivo tibiofemoral kinematics by analyzing CT under weightbearing load, our findings are similar to those of previous studies that have not considered the weightbearing state.[21,32] This is most likely because the main anteroposterior translation as a result of weightbearing occurs at the lateral knee compartment and has only a limited effect on graft lengths at the medial side of the knee.

Limitations

Several limitations must be considered when interpreting our findings. The sample size of 10 participants is relatively small. Anatomical landmarks of the ligament insertion sites were computed on the 3D models according to described quantitative measurements,[28] and interindividual morphometric variances may not have been reproduced precisely. The use of a mean tibial model might have influenced our findings and potentially neglects interindividual differences. The decision to define the most isometric points at the femoral site is arbitrary and could also be analyzed on the tibial side. Changing the insertion site of the tibia will also affect the most isometric point on the femur. However, as we could confirm our hypothesis by computing the insertion point on the femoral side, we did not extend the analysis to the tibial side. Additionally, the femoral insertion site seems to have a bigger effect on the change of MCL elongation patterns.[18,21] The use of a single point of insertion for the sMCL and POL does not simulate the native behavior of the broad insertions of the sMCL and POL completely. Finally, the use of the described string generation algorithm simplifies the exact course of the ligaments, ignoring soft tissue (eg, the joint capsule), as well as biomechanical properties, including fiber orientation and stiffness of the graft.

CONCLUSION

The sMCL demonstrated small length changes during knee flexion. The POL demonstrated substantial shortening during knee flexion, starting from 30° of knee flexion, and requires tightening near full extension to avoid overconstraint. Femoral sMCL graft placement directly posteroinferior to the center of the anatomical insertion of the sMCL (0.6 ± 1.7 mm posterior and 0.8 ± 1.2 mm inferior) demonstrated the most isometric behavior during knee flexion and can be identified at 47.8% ± 2.7% from the anterior femoral cortex and at 46.3% ± 1.9% from the joint line in a true lateral view.

The described elongation patterns of the sMCL and POL aid in guiding surgical medial knee reconstruction and preventing graft lengthening and overconstraint of the medial compartment. Repetitive graft lengthening is associated with graft failure, and overconstraint leads to increased compartment pressure, cartilage degeneration, and restricted ROM.

REFERENCES

1. Albrecht T, Lüthi M, Gerig T, Vetter T. Posterior shape models. *Med Image Anal*. 2013;17(8):959-973.
2. Arms S, Boyle J, Johnson R, Pope M. Strain measurement in the medial collateral ligament of the human knee: an autopsy study. *J Biomech*. 1983;16(7):491-496.
3. Athwal KK, Willinger L, Shinohara S, et al. The bone attachments of the medial collateral and posterior oblique ligaments are defined anatomically and radiographically. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(12):3709-3719.
4. Ball S, Stephen JM, El-Daou H, Williams A, Amis AA. The medial ligaments and the ACL restrain anteromedial laxity of the knee. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(12):3700-3708.
5. Besl P, McKay N. *Method for Registration of 3-D Shapes*. Vol 1611. SPIE; 1992.
6. Blatter SC, Fürnstahl P, Hirschmann A, Graf M, Fucentese SF. Femoral insertion site in medial patellofemoral ligament reconstruction. *Knee*. 2016;23(3):456-459.
7. Coobs BR, Wijdicks CA, Armitage BM, et al. An in vitro analysis of an anatomical medial knee reconstruction. *Am J Sports Med*. 2010;38(2):339-347.
8. D'Ambrosi R, Corona K, Guerra G, et al. Biomechanics of the posterior oblique ligament of the knee. *Clin Biomech (Bristol, Avon)*. 2020;80:105205.
9. DeLong JM, Waterman BR. Surgical techniques for the reconstruction of medial collateral ligament and posteromedial corner injuries of the knee: a systematic review. *Arthroscopy*. 2015;31(11):2258-2272.e2251.
10. Esfandiari H, Anglin C, Guy P, et al. A comparative analysis of intensity-based 2D-3D registration for intraoperative use in pedicle screw insertion surgeries. *Int J Comput Assist Radiol Surg*. 2019;14(10):1725-1739.
11. Gilmer BB, Crall T, DeLong J, et al. Biomechanical analysis of internal bracing for treatment of medial knee injuries. *Orthopedics*. 2016;39(3):e532-e537.
12. Graf M, Diether S, Vlachopoulos L, Fucentese S, Fürnstahl P. Automatic string generation for estimating in vivo length changes of the medial patellofemoral ligament during knee flexion. *Med Biol Eng Comput*. 2014;52(6):511-520.
13. Griffith CJ, LaPrade RF, Johansen S, et al. Medial knee injury: part 1, static function of the individual components of the main medial knee structures. *Am J Sports Med*. 2009;37(9):1762-1770.
14. Griffith CJ, Wijdicks CA, LaPrade RF, et al. Force measurements on the posterior oblique ligament and superficial medial collateral ligament proximal and distal divisions to applied loads. *Am J Sports Med*. 2009;37(1):140-148.
15. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105(2):136-144.
16. Hodel S, Mania S, Vlachopoulos L, Fürnstahl P, Fucentese SF. Influence of femoral tunnel exit on the 3D graft bending angle in anterior cruciate ligament reconstruction. *J Exp Orthop*. 2021;8(1):44.
17. Hodel S, Zindel C, Jud L, et al. Influence of medial open wedge high tibial osteotomy on tibial tuberosity-trochlear groove distance. *Knee Surg Sports Traumatol Arthrosc*. *Published online April* 23, 2021. doi:10.1007/s00167-021-06574-z

18. Hosseini Nasab SH, Smith CR, Postolka B, et al. In vivo elongation patterns of the collateral ligaments in healthy knees during functional activities. *J Bone Joint Surg Am*. 2021;103(17):1620-1627.
19. Kannus P. Long-term results of conservatively treated medial collateral ligament injuries of the knee joint. *Clin Orthop Relat Res*. 1988;226:103-112.
20. Kim SJ, Lee DH, Kim TE, Choi NH. Concomitant reconstruction of the medial collateral and posterior oblique ligaments for medial instability of the knee. *J Bone Joint Surg Br*. 2008;90(10):1323-1327.
21. Kittl C, Robinson J, Raschke MJ, et al. Medial collateral ligament reconstruction graft isometry is effected by femoral position more than tibial position. *Knee Surg Sports Traumatol Arthrosc*. 2021; 29(11):3800-3808.
22. LaPrade MD, Kennedy MI, Wijdicks CA, LaPrade RF. Anatomy and biomechanics of the medial side of the knee and their surgical implications. *Sports Med Arthrosc Rev*. 2015;23(2):63-70.
23. LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg Am*. 2007;89(9):2000-2010.
24. LaPrade RF, Wijdicks CA. Surgical technique: development of an anatomic medial knee reconstruction. *Clin Orthop Relat Res*. 2012; 470(3):806-814.
25. Lind M, Jakobsen BW, Lund B, et al. Anatomical reconstruction of the medial collateral ligament and posteromedial corner of the knee in patients with chronic medial collateral ligament instability. *Am J Sports Med*. 2009;37(6):1116-1122.
26. Robinson JR, Bull AM, Thomas RR, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med*. 2006;34(11):1815-1823.
27. Robinson JR, Sanchez-Ballester J, Bull AM, Thomas RWM, Amis AA. The posteromedial corner revisited. An anatomical description of the passive restraining structures of the medial aspect of the human knee. *J Bone Joint Surg Br*. 2004;86(5):674-681.
28. Saigo T, Tajima G, Kikuchi S, et al. Morphology of the insertions of the superficial medial collateral ligament and posterior oblique ligament using 3-dimensional computed tomography: a cadaveric study. *Arthroscopy*. 2017;33(2):400-407.
29. Wang X, Liu H, Duan G, et al. A biomechanical analysis of triangular medial knee reconstruction. *BMC Musculoskelet Disord*. 2018;19(1):125.
30. Warren LA, Marshall JL, Girgis F. The prime static stabilizer of the medical side of the knee. *J Bone Joint Surg Am*. 1974;56(4):665-674.
31. Wierer G, Milinkovic D, Robinson JR, et al. The superficial medial collateral ligament is the major restraint to anteromedial instability of the knee. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(2):405-416.
32. Willinger L, Shinohara S, Athwal KK, et al. Length-change patterns of the medial collateral ligament and posterior oblique ligament in relation to their function and surgery. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(12):3720-3732.
33. Yoshiya S, Kuroda R, Mizuno K, Yamamoto T, Kurosaka M. Medial collateral ligament reconstruction using autogenous hamstring tendons: technique and results in initial cases. *Am J Sports Med*. 2005; 33(9):1380-1385.