Effect of Nearly Isometric ACL Reconstruction on Graft-Tunnel Motion

A Quantitative Clinical Study

Fang Wan,[*†] MD, PhD, Tianwu Chen,[*†] MD, Yunshen Ge,[*†] MD, Peng Zhang,[*†] MD, PhD, and Shiyi Chen,[*†‡] MD, PhD

Investigation performed at the Department of Orthopedic Sports Medicine, Huashan Hospital, Shanghai, China

Background: In anterior cruciate ligament (ACL) reconstruction, minimizing the graft-tunnel motion (GTM) will promote graft-to-bone healing and avoid graft loosening or tearing as well as potential bone tunnel enlargement. A nearly isometric state of the graft can be achieved by placing the tunnel properly to theoretically gain better graft-to-bone healing. However, little clinical evidence is available to quantify the relation between GTM and tunnel position.

Purpose: To find the proper zones for the femoral and tibial tunnel apertures that minimize the GTM, referred to as the "nearly isometric zone," through use of intraoperative GTM measurement and 3-dimensional computed tomography (3D-CT).

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: A total of 100 patients were enrolled in this study. Nearly isometric ACL reconstruction was performed, and an intra-articular GTM measuring device was designed to measure and record the amplitude of GTM while the knee was flexed from 0° to 120°. Postoperatively, the patients underwent multislice CT, and the images were used to create 3D-CT models. After tibial aperture examination, 5 patients were excluded due to the divergence of tibial aperture, and therefore 95 patients remained in the study. Patients were divided into 2 groups according to whether the lateral intercondylar ridge was absent or present. The Bernard-Hertel grid coordinates (*h, t*) of the femoral tunnel were then quantified.

Results: The maximal GTM (mGTM) was a mean ± SD of 1.06 ± 0.66 mm (range, 0.0-3.0 mm). The mGTM in patients with a lateral intercondylar ridge was significantly lower than that in patients without a lateral intercondylar ridge (0.81 ± 0.39 vs 1.59 ± 0.73 mm, respectively; $P < .0001$). The average *h* and *t* were 0.227 ± 0.079 and 0.429 ± 0.770, respectively. Notably, in 1 patient, the mGTM was 0 mm whereas the coordinates (*h, t*) of the femoral tunnel were 0.250 and 0.255. The overall GTM slowly increased before 90° but increased significantly after the knee was bent 105° ($P = .010$). Correlation analysis showed that the *t* coordiinate had significant correlation with mGTM ($R = 0.581$; $P < .001$). A gradient pattern was created to show the nearly isometric blue zone (mGTM <0.5 mm), which was found to overlap with the IDEAL (isometric, direct insertion, eccentric, anatomic, low tension-flexion pattern) position.

Conclusion: A method of measuring intraoperative GTM and quantifying femoral tunnel position on postoperative 3D-CT was successfully developed. The presence of a lateral condylar ridge can significantly reduce mGTM. A nearly isometric zone was described that was consistent with the IDEAL concept.

Keywords: anterior cruciate ligament reconstruction; near isometry; nearly isometric zone; graft-tunnel motion

During the past 20 years, anterior cruciate ligament (ACL) reconstruction has undergone enormous development in aspects such as bone tunnel positioning, graft choice, and return to sports.[15] Bone tunnel positioning is one of the most crucial technical factors affecting outcomes. Inappropriate locations of the bone tunnel will leave the graft in a nonisometric state[24] that may result in abnormal tensile and relative movement between the graft and the tunnel during knee flexion (see Supplementary Video). This kind of motion between graft and tunnel is called graft-tunnel motion (GTM).[10] The phenomenon leading to GTM was described in the late 1990s.[11] Some scholars believe that GTM can affect the graft-to-bone interface[10,11]; that is, GTM will impair graft and bone tunnel healing by changing the local mechanical environment. Others consider that GTM is the expression of a "windshield wiper effect" and

The Orthopaedic Journal of Sports Medicine, 7(12), 2325967119890382
DOI: 10.1177/2325967119890382

"bungee effect" that will increase bone absorption activity around the bone tunnel, resulting in bone tunnel enlargement.[18] In our clinical practice, we find that nonisometric reconstruction overstressing the graft may limit the range of motion and result in graft failure, cartilage damage, and osteoarthritis. We have directed our attention to the kinematic and mechanical influence of nonisometric reconstruction of the knee since we began to use artificial ligament grafts more than 10 years ago.[4]

Rodeo et al[18] used animal experiments to prove the existence of GTM, reporting that the amplitude of GTM had a positive correlation with the width of graft-bone interface and a negative correlation with the healing progress. Nakase et al,[16] using magnetic resonance imaging (MRI) for follow-up of patients who received ACL reconstruction, found differences in healing for different portions of the graft not only longitudinally but also transversally. These investigators suggested that the windshield wiper effect caused anterior-posterior GTM that impaired the healing process.

Pearle et al[17] suggested a femoral tunnel position that they called IDEAL (isometric, direct insertion, eccentric, anatomic, low tension-flexion pattern). Such a position reproduces the isometry of the native ACL, covers the fibers of the direct insertion histologically, is eccentrically located in the anterior (high) and proximal (deep) region of the footprint, is anatomic (within the footprint), and replicates the low tension-flexion pattern of the native ACL throughout the range of flexion and extension.

Most of the previous studies have been performed on animals and cadavers; the question remained how GTM could be observed clinically. In a small sample clinical study, investigators proved the existence of GTM in vivo by marking the intra-articular portion of the graft with a titanium suture.[2] After the surgery, GTM could be directly observed and measured under fluoroscopy. Despite the effectiveness of this technique, it is not suitable for large-scale application because of ethical issues. Until now, no technique has been available that can be used clinically to observe GTM directly in vivo or postoperatively.

Theoretically, an absolutely isometric ACL reconstruction can minimize GTM. However, native ACL has been considered "nonisometric" from a biomechanical perspective. The concept of *clinical isometry* refers to tunnel placement such that the distance between the femoral and tibial tunnel apertures remains constant as the knee moves in the plane of flexion and extension.[1] However, surgeons have found that it is almost impossible to achieve absolute isometry during surgery.[6,9,20] Nonetheless, nearly isometric reconstruction can be achieved occasionally by holding GTM to a minimum, about 1.0 to 2.0 mm.

Thus, we use the term *near isometry* to describe the condition mentioned above that can be confirmed by direct measurement of the GTM during knee flexion intraoperatively. We hypothesized that (1) GTM correlates with femoral tunnel position, and (2) not only a point but also a zone exists for an ACL graft to be reconstructed at a nearly isometric state throughout the range of motion. Once the tunnel is positioned at this specific, nearly isometric zone, the GTM will be minimized. To prove our hypotheses, we conducted a prospective clinical study. In this study, we performed the nearly isometric ACL reconstruction on a series of patients with ACL deficiency. Using a custom-made measurement tool, we were able to measure GTM intraoperatively. Postoperative 3-dimensional computed tomography (3D-CT) was applied to quantify the coordinates of tunnel apertures in order to study the correlation between apertures and GTM. We sought to investigate the nearly isometric zone of the femoral tunnel aperture and confirm its effect on minimize GTM. We found that we can place the tunnels optimally by using GTM as a reference.

METHODS

Patient Selection

Institutional review board approval was obtained before the study began. The study included all patients who received ACL reconstruction from September 2014 to March 2018 in our center. The inclusion criteria were (1) age 20 to 50 years and (2) sole initial ACL tear or rupture. The exclusion criteria were (1) fracture, (2) revision, (3) concomitant knee injuries such as posterior cruciate ligament and meniscal injury, (4) medical conditions such as metabolic and rheumatoid diseases, (5) osteoarthritis, and (6) tibial aperture beyond 42% to 50% anterior-posterior of the plateau (described later). All patients provided informed consent, and their demographic data were collected.

ACL Reconstruction

The same senior chief surgeon (S.C.) performed all surgeries. The type of the graft was chosen based on the agreement between surgeon and patients. The selection consisted of quadruple hamstring autograft, allograft, or synthetic graft. When hamstring autograft and allograft were used, the femoral side was fixed with suspensory ACL

‡Address correspondence to Shiyi Chen, MD, PhD, No. 12 Middle Wulumuqi Road, Shanghai, China (email: cshiyi@163.com).
*Department of Orthopedic Sports Medicine, Huashan Hospital, Shanghai, China.
†Fudan University Sports Medicine Institute, Shanghai, China.

One or more of the authors has declared the following potential conflict of interest or source of funding: This work was supported by the National Key R&D Program of China (2016YFC1100300, 2017YFC0840100, and 2017YFC0840106), the National Natural Science Foundation of China (81572108, 8191101103, and 81772339), the Key Clinical Medicine Center of Shanghai (2017ZZ01006), the Sanming Project of Medicine in Shenzhen (SZSM201612078), the Shanghai Rising-Star Project (18QB1400500), the Introduction Project of Clinical Medicine Expert Team for Suzhou (SZYJTD201714), the Development Project of Shanghai Peak Disciplines-Integrative Medicine (20180101), and Shanghai Committee of Science and Technology (19441901600 and 19441902000). 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 medical ethics committee of Huashan Hospital.

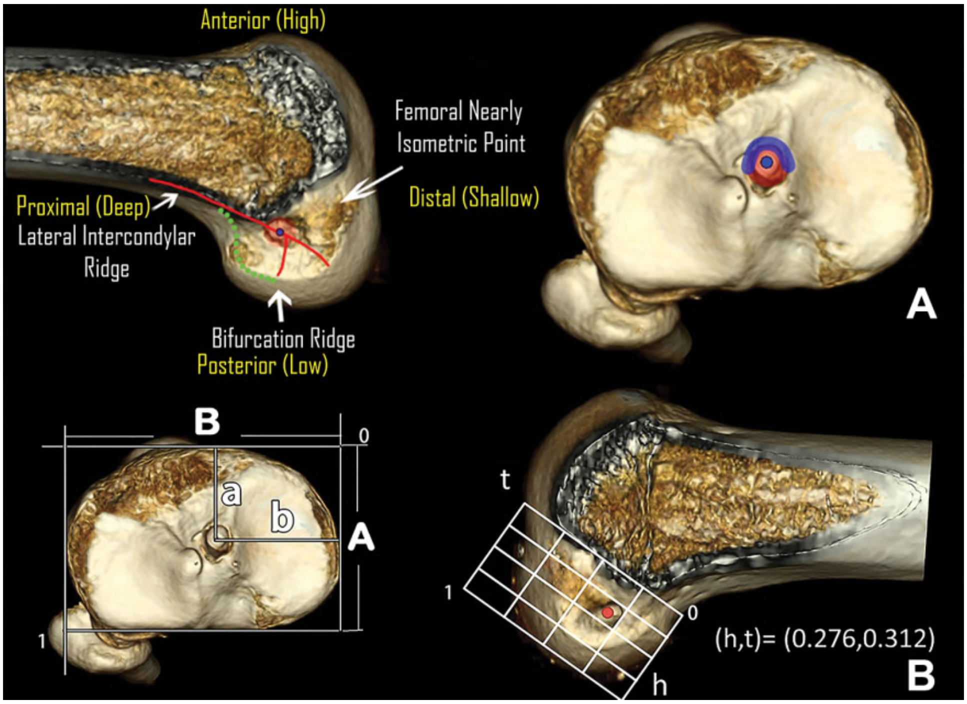

Figure 1. (A) Designated femoral and tibial tunnel position. (Left) On the medial aspect view of the lateral femoral condyle, the anterior (high), posterior (low), distal (shallow), and proximal (deep) directions are shown. The long red line is the femoral posterior cortex line and the lateral condylar ridge. The short red line is the bifurcation ridge. The red oval is the designated "nearly isometric" femoral tunnel. The green dotted line is the femoral posterior cortex wall. The blue dot is the center of the designated tunnel. (Right) On the overlook view of the tibial plateau, the blue arc is the anterior cruciate ligament tibial remnant (usually C-shaped). The red oval is the designated tunnel. The blue dot is the center of the designated tunnel. (B) (Left) Quantification of the tibial tunnel position with coordinates (*a, b*). Two tangent vertical lines are drawn along medial and lateral edges of the tibial plateau. Two additional tangent lines are drawn along the anterior and posterior edges at right angles to the previous 2 lines. The anteroposterior position of the tunnel is defined relative to a rectangular grid with origin (0,0) at the anteromedial corner of the rectangle. The anteroposterior position is determined by the ratio *a:A*, and the mediolateral position is given as the ratio *b:B*. This yields coordinates (*a, b*), where both *a* and *b* have values between 0 and 1, to define the location of the tunnel relative to the tibial surface. (Right) A Bernard-Hertel grid is used to calculate the coordinates (*h, t*) to quantify the femoral tunnel position.

TightRope (Arthrex) and the tibial side was fixed with bioabsorbable interference screw with sheath (BioIntrafix; Mitek). Both femoral and tibial side were fixed with titanium interference screw when a synthetic graft was used. The tunnel diameter was 8 mm on autograft and allograft and 7.5 mm on synthetic graft (LARS; Surgical Implants and Devices).

In addition to the regular medial and lateral portals for knee arthroscopy, a midpatellar tendon portal was made to visualize the medial aspect of the lateral condyle. After the torn ACL was confirmed, debridement of the femoral insertion was confirmed to expose the intercondylar ridge and bifurcation ridge on the medial aspect of the lateral condyle. The tibial ACL remnant should be maximally preserved according to the senior surgeon's personal technique.

Nearly Isometric Zone Positioning

Femoral Tunnel Position. The direction of the medial femoral condyle is shown in Figure 1A. The intersection of the lateral intercondylar ridge and bifurcation ridge is a crucial landmark to localize the aperture of the femoral tunnel. The nearly isometric femoral tunnel was positioned on the lateral intercondylar ridge, 2 mm proximal (deep) to the bifurcation ridge. If the lateral intercondylar ridge was missing, the nearly isometric femoral tunnel was positioned on the extension of the femoral posterior cortex line (long red line on Figure 1A), 5 mm distal (shallow) to the femoral posterior cortex wall (green dotted line on Figure 1A).

Tibial Tunnel Position. Unlike the situation with the femoral ACL footprint, a major residual of the ACL is often visible on the tibial ACL footprint medial to the anterior horn of the lateral meniscus. It is often difficult to identify the bare tibial footprint without debriding the remnant. Whether the remnant should be preserved remains controversial. Our preference is to preserve the remnant as much as possible in order to promote healing, which is also crucial for the synthetic graft because it is designed for augmentation. We prefer to split the remnant into halves from the middle line and point the tip of a 55° tibial ACL aimer (pointing toward the elbow) 3 to 4 mm posterior to the middle point of the remnant (Figure 1A).

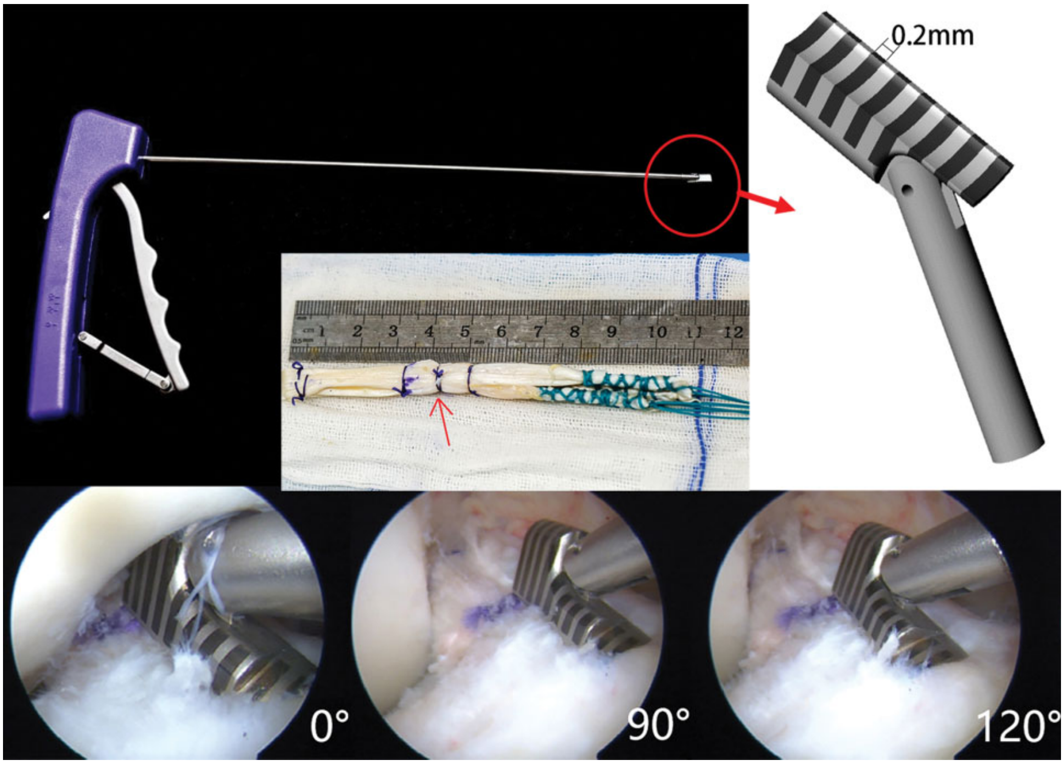

Figure 2. A custom-made intra-articular graft-tunnel motion (GTM) measuring device is used to measure GTM arthroscopically according to pre-embedded sutures (red arrow) on the graft. An enlarged detail of the tip of the device (red circle) shows that each black block is 0.2 mm in width, as validated by a digital Vernier caliper (Appendix Figure A1).

GTM Measurement

According to the length of the femoral tunnel, the intra-articular portion of the graft was marked with 3 absorbable suture knots on the femoral and tibial apertures and middle site, 1 cm away from each other. After the graft was placed in the tunnel, femoral fixation was completed. Then, the knee was flexed 20 times passively with 200 N of tension with a graft tensioning device applied on the tibial side. Keeping the tension on the tibial side, we placed a custom-made intra-articular GTM measuring device (0.2-mm precision; patent No. CN105078467B) into the joint. We adjusted the angle of the device so that the tip was anchored on the tibial aperture and so the device and graft were parallel with each other (Figure 2). The maximal amplitude of GTM (mGTM) was measured, and a video recording was made while the knee was flexed from 0° to 120°. The GTM data were recorded at 0°, 15°, 30°, 60°, 90°, 105°, and 120°.

Multislice CT and 3D Reconstruction

All of the patients underwent multislice CT scanning (Toshiba Aquilion Prime) on the surgical knee 1 day post-operatively. The scan used the default factory preset (voltage, 140 kV; baseline, B40S) of knee CT with 0.5 mm thickness per slice in 5 seconds. All of the raw data were processed and reconstructed by use of a Vitrea imaging workstation (Vital Images Inc). The 3D volume-rendering model of the knee was split into a femoral part and a tibial part, which were analyzed separately (Figure 1B) in the following 2 steps. First, the distribution of the aperture of the tibial tunnel was confirmed by comparing the overlook view of tibial plateau. A rectangular coordinate system was used to quantify the coordinates (a, b) of the tibial tunnel. The tibial aperture was required to be in a position 42% to 50% anterior-posterior of the plateau ($0.42 \leq a \leq 0.56$), which was considered a "constant," in order that the femoral aperture was a single variant. Otherwise, the case was excluded. Through tibial aperture examination, 5 patients were excluded due to the divergence of tibial aperture ($a > 0.58$ or $a < 0.5$). The a and b (mean ± SD) for the excluded patients were 0.461 ± 0.075 and 0.491 ± 0.062, respectively.

Second, a sagittal cut was made on the femoral part along the top point of the intercondylar notch parallel to the femoral axis to expose the aperture of femoral tunnel. Then, the aperture point was coordinated by use of a Bernard-Hertel grid,[6] with the coordinates (h, t) of each case recorded. The presence or absence of the lateral intercondylar ridge was recorded.

Statistical Analysis

The patients were divided into groups according to sex, graft type, and the presence or absence of a lateral intercondylar ridge. Statistical analysis included 1-way

TABLE 1
Demographic Information of Study Participants

Parameter	Result
Sex, male:female, n	78:17
Age, y, mean ± SD	27.08 ± 8.39
Left side affected, n	45
Interval from injury to surgery, wk, median (range)	78.1 (2.1-521.5)
Graft type, n	
Allograft	21
Autograft	50
Synthetic	24
Graft size, n	
7.5 mm	24
8 mm	71
Maximal graft-tunnel motion, mm, mean ± SD (range)	1.06 ± 0.66 (0-3)
Lateral intercondylar ridge, n	
Absent	20
Present	75

analyses of variance (ANOVAs) for comparison of GTM results from different groups. The Pearson correlation coefficient was used to calculate the correlation between the h coordinate of the femoral aperture and the mGTM and between the t coordinate and the mGTM, respectively. All statistical analysis was performed with MedCalc Statistical Software version 18.2.1 (MedCalc Software bvba). The significance level was set at $P < .05$.

RESULTS

For our clinical study, we enrolled 100 patients who had nearly isometric ACL reconstruction. After tibial aperture exclusion, 95 patients were involved. Demographic information is listed in Table 1.

The mGTM (mean ± SD) was 1.06 ± 0.66 mm (range, 0-3.0 mm). No significant differences were found between mGTM and sex ($P = .233$), side ($P = .572$), or graft type ($P = .526$). The lateral intercondylar ridge was present in 78.9% of the patients and absent in 21.1%. Interestingly, the mGTM in the group who had a lateral intercondylar ridge was significantly lower than that in the group without a lateral intercondylar ridge (0.81 ± 0.39 vs 1.59 ± 0.73 mm; $P < .0001$) (Figure 3).

The mean h and t in the total sample were 0.227 ± 0.079 and 0.429 ± 0.770, respectively. The mean h and t were 0.218 ± 0.074 and 0.408 ± 0.064 in patients who had a lateral intercondylar ridge compared with 0.123 ± 0.085 and 0.458 ± 0.084 in patients without a lateral intercondylar ridge. Notably, in 1 patient, the mGTM was 0 mm while the coordinates (h, t) of the femoral tunnel were (0.250, 0.255). The femoral tunnel was approximately on the lateral intercondylar ridge and 2 mm proximal (deep) to the bifurcation ridge.

We further classified the patients according to their mGTM, or isometric level, as: (1) blue, 0 mm $\leq$ mGTM $\leq$ 0.5 mm (n = 22); (2) green, 0.5 mm < mGTM $\leq$ 1 mm (n = 39); (3) yellow, 1 mm < mGTM $\leq$ 2 mm (n = 28); (4) red, 2 mm < mGTM $\leq$ 3 mm (n = 6). The tendency for GTM with different knee angles was also analyzed. We discovered that the overall GTM was slight and increased slowly before 90° but increased significantly after the knee was bent at 105° ($P = .010$) (Figure 4A).

Through correlation analysis, the t coordinate showed significant correlation with mGTM ($R = 0.581$; $P < .001$). All of the femoral aperture coordinates were projected onto the same medial aspect of the lateral condyle according to their color group: blue, green, yellow, or red (Figure 4B). A gradient pattern was made on the medial aspect of the lateral condyle to show the nearly isometric zone (Figure 4C). The blue zone had minimal GTM, the green zone was nearly isometric, and the yellow and red zones were nonisometric with more GTM.

DISCUSSION

The GTM in ACL reconstruction merits more attention. It is crucial to achieve nearly isometric ACL reconstruction to improve outcomes. According to the current study, whether an ACL reconstruction can be considered nearly isometric can be determined as follows: Once the femoral graft fixation is completed, tension is applied on the tibial side and the intra-articular graft is observed with the method described above. If GTM is less than 2.0 mm while the knee is flexed from 0° to 120°, this is considered nearly isometric reconstruction. Although GTM may still exist at a microscopic level, the adverse effect of GTM on the graft-tunnel interface will be greatly reduced.

While reviewing previous articles, we found that the concept of near isometry has been occasionally used but with varied definitions.[1,5,13,19] Sidles et al[19] defined near isometry as “length change less than 0.4 mm for 0° to 110° knee flexion.” Rodeo et al[18] referred to the concept as “less than 2.0 mm during 0° to 90° knee flexion.” Dabirrahmani et al[5] defined it as “±3.0 mm length change during 0° to 90° knee flexion.” Others thought it acceptable if the distance change was less than 2.0 mm from 0° to 120° of flexion.[9,19,25] In our study, the mean mGTM was 1.06 ± 0.66 mm, and our criterion for near isometry was that that length should change less than 2.0 mm for 0° to 120° of knee flexion.

Take et al[21] compared the excursion of bone–patellar tendon–bone grafts during flexion-extension movement between isometric and anatomic reconstruction techniques in ACL reconstruction. The mean length change of the grafts in total was 1.0 ± 0.7 mm in the isometric technique and 3.4 ± 0.9 mm in the anatomic technique, quite similar to our results. However, the properties of bone–patellar tendon–bone graft are quite different from those of soft tissue graft and synthetic graft. Also, the measuring method was extra-articular and indirect.

We believe that there must be an isometric zone located on the medial surface of the lateral femoral condyle compatible with a certain tibial tunnel aperture. An ideal nearly isometric reconstruction must meet the following 2 requirements: (1) After the nearly isometric reconstruction, the mGTM of the graft should be less than 2.0 mm, and (2) there should

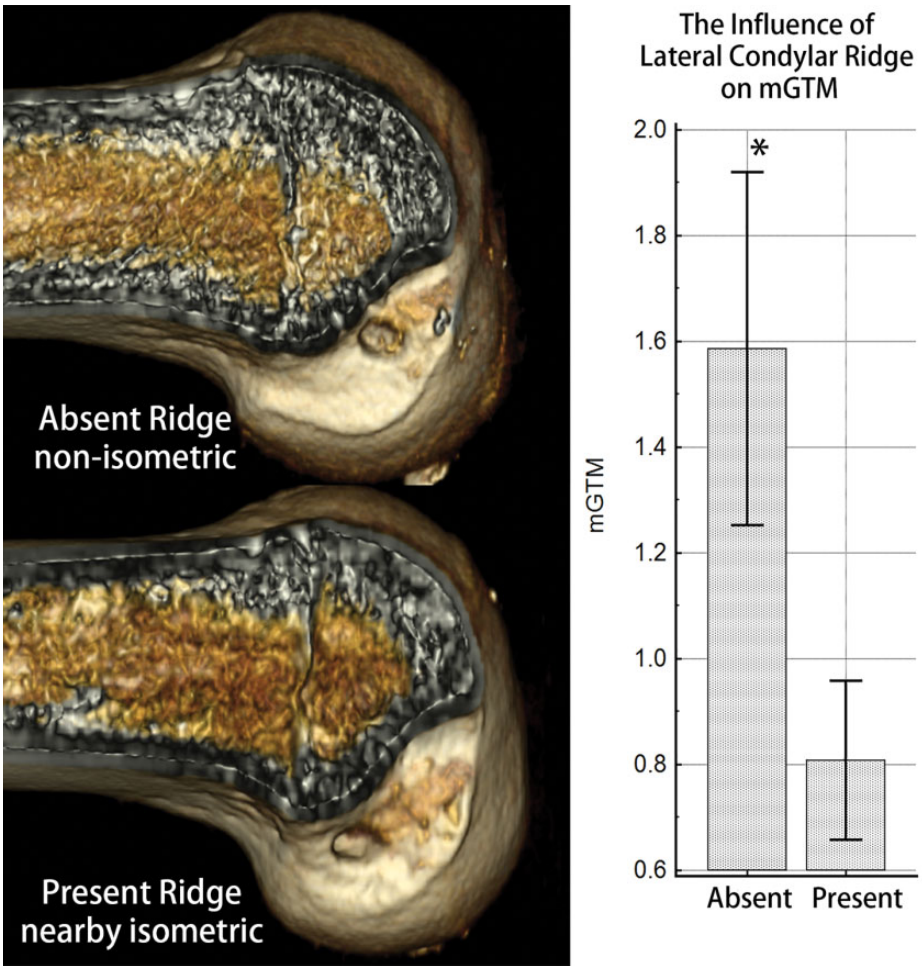

Figure 3. Maximal graft-tunnel motion (mGTM) was significantly lower in patients with a lateral intercondylar ridge. *$P < .0001$.

not be any impingement between the graft and intercondylar notch and posterior cruciate ligament.

Lee et al[12] conducted a more precise human anatomic study to evaluate the isometry of anatomic femoral tunnel and anterior tibial tunnel positions. They found that the anatomic femoral tunnel was nonisometric. When a femoral anatomic tunnel is chosen for ACL reconstruction, the anterior tibial tunnel offers greater isometric benefits than the conventional tibial tunnel, especially in near full extension.

Wang et al[23] found that only 4 of 10 specimens had an isometric point at a variable anterior point. The end-to-end distances of the anteromedial and posterolateral bundles were longer in extension and shorter in flexion. Those investigators pointed out that the nonisometric tendency of the ACL and the end-to-end distance to change during knee flexion-extension and internal-external rotation should be considered during ACL reconstruction to avoid overconstraint of the graft. Fu and Jordan[7] confirmed the importance of the lateral intercondylar ridge as a landmark to guide accurate femoral tunnel placement during ACL reconstruction. In our study, the femoral tunnels tended to be more posterior and inferior when the lateral intercondylar ridge was present compared with when it was absent. A clearly visualized lateral intercondylar ridge is crucial for nearly isometric tunnel positioning.

Theoretically, GTM may differ with different types of graft and fixation devices. Hoher et al[10] found that hamstring graft motion existed in the femoral bone tunnel when using titanium button and polyester tape fixation. Tsuda et al[22] reported that EndoButton fixation of a soft tissue graft via an elastic material resulted in significantly greater GTM and, consequently, greater anterior knee laxity compared with more rigid fixation using an interference screw closer to the intra-articular entrance of the bone tunnel. However, the methods of measuring GTM used in those cadaveric studies were different from the method used in our study. However, we did not find significant differences in mGTM among the 3 graft type groups intraoperatively.

Hart et al[8] evaluated femoral tunnel positioning by using 3D MRI. Although 3D MRI provides slightly more information than 3D-CT, 3D MRI is far more time-consuming (45 minutes vs 5 seconds, respectively) and expensive (700 RMB vs 300 RMB in China, respectively) than 3D-CT.

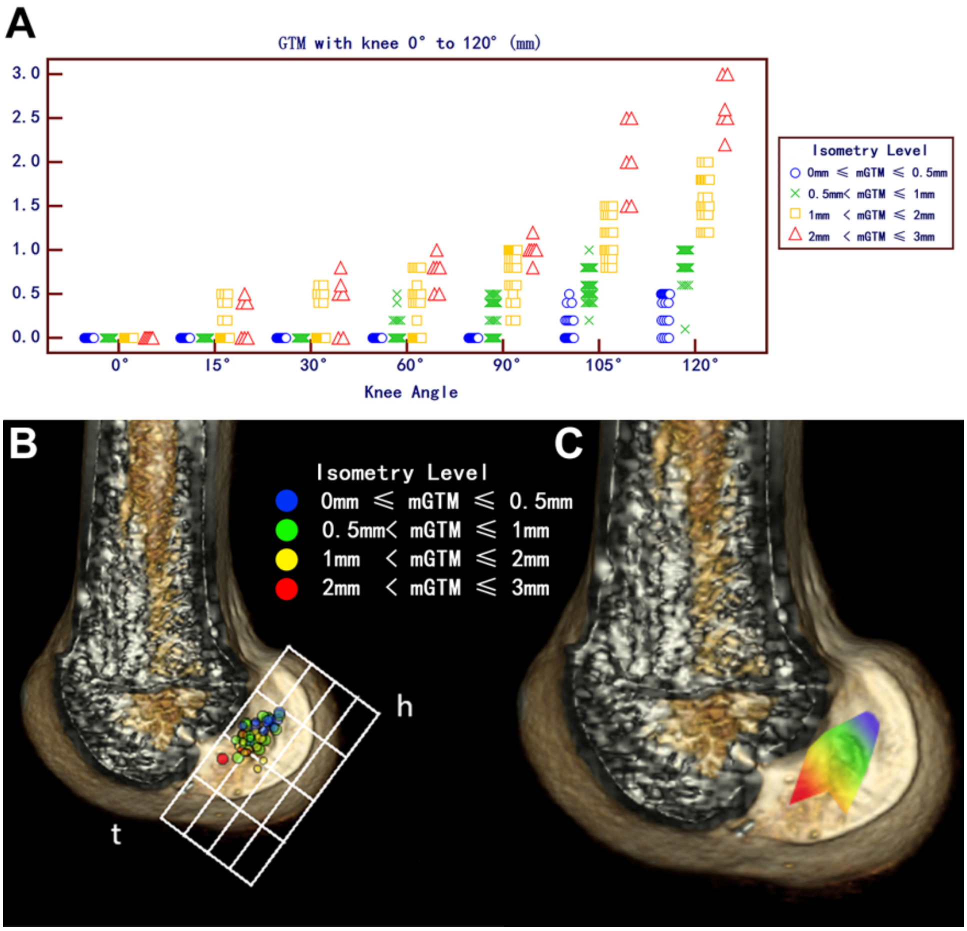

Figure 4. (A) Patients were divided into 4 groups according to their maximal graft-tunnel motion (mGTM): (1) blue, 0 mm $\le$ mGTM $\le$ 0.5 mm (n = 22); (2) green, 0.5 mm < mGTM $\le$ 1 mm (n = 39); (3) yellow, 1 mm < mGTM $\le$ 2 mm (n = 28); (4) red, 2 mm < mGTM $\le$ 3 mm (n = 6). The overall GTM increased significantly after the knee was bent at 105° (P = .010). (B) All of the femoral aperture coordinates were projected onto the same medial aspect of the lateral condyle according to their group color. (C) A gradient pattern was made to show the nearly isometric zone. The blue zone was found to overlap with IDEAL position described by Pearle et al[17] (black circle).

Despite the minor radiation exposure, 3D-CT is cost-efficient and can be performed routinely.

Coincidentally, in our study, the nearly isometric blue zone overlapped with the "IDEAL position" as described by Pearle et al[17] (black circle on Figure 4C). Thus, our nearly isometric zone was consistent with the IDEAL position.

Finally, we discovered that the overall GTM was slight and increased slowly before 90° but increased significantly after the knee was bent more than 90°. This finding might be instructive for the postoperative rehabilitation protocol. Although the literature emphasizes the importance of early recovery of range of motion (0°-120°),[3] we suggest taking GTM or healing possibility into account at the early stage of postoperative rehabilitation. If the ACL reconstruction is nearly isometric, the patient may be allowed 120° of flexion at an early stage of recovery. Otherwise, we believe the patient should be allowed only 90° of flexion.

In summary, the femoral isometric tunnel point varies among individuals. Currently, we can find the absolute isometric tunnel point only during laboratory studies on specimens. However, the passive motion of specimens is unable to mimic the motion of a living knee, so the knowledge we gain from the laboratory offers limited assistance in terms of clinical procedures. Even by using intraoperative fluoroscopy,[14] we still cannot achieve absolute isometry. This led to our concept of nearly isometric ACL reconstruction.

Overall, current knowledge about GTM, including its mechanisms and consequences, is limited. We believe that GTM contributes to loosening, retearing, and failure of ACL reconstruction. To increase the benefit of ACL reconstruction and decrease the failure rate, more sophisticated studies should be performed. We believe the topic of isometry and graft-tunnel motion should be brought to the forefront.

Limitations

This study confirmed the possibility of achieving a nearly isometric zone through use of our nearly isometric reconstruction technique. The limitations of the study are (1) the lack of a control group, (2) lack of long-term follow-up, and (3) potential confounding variables stemming from different grafts with different fixation devices. Also, we did not consider the direction of GTM or whether the graft moved toward the femur or tibia.

CONCLUSION

This was a pioneering study investigating the correlation of isometric tunnel position and GTM by using intraoperative measurement and a postoperative 3D-CT coordinate system. A nearly isometric zone can be achieved by exact tunnel placement in both the femoral tunnel aperture and the tibial plateau, which will minimize GTM. A feasible, simple, and radiation-free technique of nearly isometric reconstruction has been developed that includes direct measurement of GTM intraoperatively. A clearly visualized lateral intercondylar ridge is crucial for nearly isometric tunnel positioning. GTM can be minimized in all types of graft in order to gain better clinical outcomes. Mass spectrometry CT and 3D reconstruction may be used to evaluate the tunnel position and potential outcomes.

A Video Supplement for this article is available at http://journals.sagepub.com/doi/suppl/10.1177/2325967119890382.

REFERENCES

1. Amis AA, Zavras TD. Isometricity and graft placement during anterior cruciate ligament reconstruction. *Knee*. 1995;2(1):5-17.
2. Borbas P, Wieser K, Rahm S, Fucentese SF, Koch PP, Meyer DC. Radiodense ligament markers for radiographic evaluation of anterior cruciate ligament reconstruction. *Knee*. 2014;21(6):1018-1022.
3. Cavanaugh JT, Powers M. ACL rehabilitation progression: where are we now? *Curr Rev Musculoskelet Med*. 2017;10(3):289-296.
4. Chen T, Zhang P, Chen J, Hua Y, Chen S. Long-term outcomes of anterior cruciate ligament reconstruction using either synthetics with remnant preservation or hamstring autografts: a 10-year longitudinal study. *Am J Sports Med*. 2017;45(12):2739-2750.
5. Dabirrahmani D, Hogg CM, Walker P, Biggs D, Gillies RM. Comparison of isometric and anatomical graft placement in synthetic ACL reconstructions: a pilot study. *Comput Biol Med*. 2013;43(12):2287-2296.
6. Dabirrahmani D, Hogg M, Biggs D, Walker P, Laboureau JP, Gillies RM. Isometric placement of a synthetic ACL graft. Poster No. 2288 presented at: ORS 2012 Annual Meeting; February 4-7, 2012; San Francisco, CA.
7. Fu FH, Jordan SS. The lateral intercondylar ridge—a key to anatomic anterior cruciate ligament reconstruction. *J Bone Joint Surg*. 2007;89(10):2103-2104.
8. Hart A, Sivakumaran T, Burman M, Powell T, Martineau PA. A prospective evaluation of femoral tunnel placement for anatomic anterior cruciate ligament reconstruction using 3-dimensional magnetic resonance imaging. *Am J Sports Med*. 2017;46(1):192-199.
9. Hefzy MS, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments, part II: the anterior cruciate ligament. *Am J Sports Med*. 1989;17(2):208-216.
10. Hoher J, Livesay GA, Ma CB, Withrow JD, Fu FH, Woo SL. Hamstring graft motion in the femoral bone tunnel when using titanium button/polyester tape fixation. *Knee Surg Sports Traumatol Arthrosc*. 1999;7(4):215-219.
11. Hoher J, Moller HD, Fu FH. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? *Knee Surg Sports Traumatol Arthrosc*. 1998;6(4):231-240.
12. Lee JS, Kim TH, Kang SY, et al. How isometric are the anatomic femoral tunnel and the anterior tibial tunnel for anterior cruciate ligament reconstruction? *Arthroscopy*. 2012;28(10):1504-1512.
13. Ma R, Ju X, Deng XH, Rodeo SA. A novel small animal model of differential anterior cruciate ligament reconstruction graft strain. *J Knee Surg*. 2015;28(6):489-495.
14. Mehta VM, Paxton EW, Fithian DC. Does the use of fluoroscopy and isometry during anterior cruciate ligament reconstruction affect surgical decision making? *Clin J Sport Med*. 2009;19(1):46-48.
15. Mohan R, Webster KE, Johnson NR, Stuart MJ, Hewett TE, Krych AJ. Clinical outcomes in revision anterior cruciate ligament reconstruction: a meta-analysis. *Arthroscopy*. 2018;34(1):289-300.
16. Nakase J, Kitaoka K, Toratani T, Kosaka M, Ohashi Y, Tsuchiya H. Grafted tendon healing in femoral and tibial tunnels after anterior cruciate ligament reconstruction. *J Orthop Surg (Hong Kong)*. 2014;22(1):65-69.
17. Pearle AD, McAllister D, Howell SM. Rationale for strategic graft placement in anterior cruciate ligament reconstruction: I.D.E.A.L. femoral tunnel position. *Am J Orthop (Belle Mead NJ)*. 2015;44(6):253-258.
18. Rodeo SA, Kawamura S, Kim HJ, Dynybil C, Ying L. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? *Am J Sports Med*. 2006;34(11):1790-1800.
19. Sidles JA, Larson RV, Garbini JL, Downey DJ, Matsen FA III. Ligament length relationships in the moving knee. *J Orthop Res*. 1988;6(4):593-610.
20. Smith JO, Yasen S, Risebury MJ, Wilson AJ. Femoral and tibial tunnel positioning on graft isometry in anterior cruciate ligament reconstruction: a cadaveric study. *J Orthop Surg (Hong Kong)*. 2014;22(3):318-324.
21. Take Y, Mae T, Nakata K, Nakagawa S, Tachibana Y, Shino K. Excursion of bone–patella tendon–bone grafts during the flexion-extension movement in anterior cruciate ligament reconstruction: comparison between isometric and anatomic reconstruction techniques. *Asia Pac J Sports Med Arthrosc Rehabil Technol*. 2015;2(3):85-89.
22. Tsuda E, Fukuda Y, Loh JC, Debski RE, Fu FH, Woo SL. The effect of soft-tissue graft fixation in anterior cruciate ligament reconstruction on graft-tunnel motion under anterior tibial loading. *Arthroscopy*. 2002;18(9):960-967.
23. Wang JH, Kato Y, Ingham SJ, et al. Measurement of the end-to-end distances between the femoral and tibial insertion sites of the anterior cruciate ligament during knee flexion and with rotational torque. *Arthroscopy*. 2012;28(10):1524-1532.
24. Williams A, Devic N. Tunnels, graft positioning, and isometry in ACL reconstruction. In: Amendola MA, MacDonald SJ, Menetrey J, Bellemans J, eds. *The Knee Joint: Surgical Techniques and Strategies*. Paris: Springer Paris; 2012:183-194.
25. Zavras TD, Race A, Bull AM, Amis AA. A comparative study of "isometric" points for anterior cruciate ligament graft attachment. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(1):28-33.

APPENDIX

Figure A1. On the tip of our custom-designed graft-tunnel motion measurement device, each black block is 0.2 mm in width, as validated by a digital Vernier caliper (Masterproof).