J Shoulder Elbow Surg (2019) 28, 1378–1386

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Three-dimensional computed tomography modeling for kinematic analysis of double-strand lateral ulnar collateral ligament reconstruction

Erica Kholinne, MD[a,b], Tae-Hyun Ha, MS[b], Jun Tan, MD[c], In-Ho Jeon, MD, PhD[b,*]

[a]*Department of Orthopedic Surgery, St Carolus Hospital, Jakarta, Indonesia*
[b]*Department of Orthopedic Surgery, Asan Medical Center, College of Medicine, University of Ulsan, Seoul, Republic of Korea*
[c]*Department of Hand Surgery, Affiliated Hospital of Nantong University, Nantong, Nantong University, Jiangsu, China*

Background: When treating posterolateral rotatory instability, the lateral ulnar collateral ligament (LUCL) is more commonly reconstructed than the other dynamic stabilizer structures. Although numerous surgical techniques have been described for LUCL reconstruction, studies have been limited to static analyses of single-strand reconstructions. The aim of this study was to dynamically analyze the kinematics of double-strand LUCL reconstructions with 3 different configurations of graft placement: horizontal, vertical, and triangular.

Methods: Five healthy elbow joints with no signs of pre-existing pathology were scanned by computed tomography, and the images were converted into 3-dimensional models. The humeral origin and ulnar insertions of the 2 ligament strands were registered in 3-matic software for the 3 graft placement configurations. A dynamic elbow joint was simulated at 1° increments throughout the motion arc. The ligament strand lengths and the difference between them were measured.

Results: The ligament lengths for each strand for the 3 graft configurations were as follows: horizontal, 31.0 ± 4.6 mm and 34.3 ± 5.0 mm; vertical, 32.5 ± 3.6 mm and 35.4 ± 4.2 mm; and triangular, 32.0 ± 4.0 mm and 33.7 ± 3.1 mm. The minimum length differences for the graft strands through the motion arc for the horizontal, vertical, and triangular graft configurations were 1.1, 0.0, and 1.0 mm, respectively.

Conclusions: Dynamic analyses using a 3-dimensional elbow model showed that none of the configurations for double-strand LUCL reconstruction were isometric. However, the vertical double-strand configuration was nearly isometric and may therefore serve as a coequal option.

Level of evidence: Basic Science Study; Computer Modeling

Keywords: Lateral ulnar collateral ligament; 3-dimensional; double-strand reconstruction; kinematic analysis; isometric reconstruction; posterolateral rotatory instability

Institutional review board approval was provided by the Affiliated Hospital of Nantong University, Nantong, China (No. 2015-039).

*Reprint requests: In-Ho Jeon, MD, PhD, Department of Orthopedic Surgery, Asan Medical Center, College of Medicine, University of Ulsan, 88, Olympic-ro 43-gil, Songpa-Gu, Seoul 05505, Republic of Korea.
E-mail address: jeonchoi@gmail.com (I.-H. Jeon).

1058-2746/$ - see front matter
https://doi.org/10.1016/j.jse.2018.11.070

Posterolateral rotatory instability (PLRI) is a type of chronic elbow instability.[29,30-32,40] Many studies have described the lateral ulnar collateral ligament (LUCL) as the "principal lesion" that causes PLRI,[14,17,20,21,29,30,33] and LUCL reconstruction remains the most common surgical procedure for treating PLRI when conservative treatment fails.[20,28,33]

The principles of isometric and anatomic tunnel reconstruction to re-create a native ligament have been widely applied in the reconstruction of other ligaments,[3,4,12,16,42] but as yet, there are no universally established isometric points for LUCL tunnel placement. Studies have reported that the native LUCL is not isometric[5,23,27,35] and that reconstruction of the LUCL as isometrically as possible will ensure that equal force is transferred to the elbow joint.[15]

LUCL reconstruction techniques vary in the fixation technique used, the graft choice, the number of strands, and the bone tunnels created.[17,19,20,21,28,30,31,36-38] Identifying the anatomic landmark is paramount for successful LUCL reconstruction. The humeral tunnel position for LUCL reconstruction has been widely studied, and its isometric point is more consistent and reproducible than that of the ulnar tunnel.[2,28,41] The recommendation for humeral tunnel placement has been well described by Cohen and Hastings[9]: The placement should be at the base of the lateral epicondyle, where it flattens onto the lateral aspect of the capitellum. This would be consistent with some observations that have suggested that the elbow may have a rotational axis that passes through the center of the capitellum, although the existence of such a rotational axis remains debatable.[10,20,22,27,33] Anatomic guidelines for the isometric point for ulnar tunnel placement have not been well defined, although the ulnar tunnel contributes more to graft orientation. Previous studies have described the supinator tubercle as a reference point; however, this cannot be identified reliably in every individual.[1,2] A study has shown the supinator tubercle to be prominent in 50% of cadaveric specimens,[2] so a significant number of LUCL reconstructions may be nonanatomic at the ulnar insertion site, making it challenging for the surgeon to determine and reproduce the ulnar tunnel placement for anatomic reconstruction. This could lead to the inadvertent nonanatomic placement of tunnels.

Double-strand LUCL reconstructions have been described in several studies.[2,17,28,30,36] The benefit of a double-strand reconstruction is that varus and posterolateral rotational instability of the elbow can be achieved by using 2 separate strands of graft and a larger footprint to increase the stability of the radial head.[2,36] Isometric double-strand LUCL reconstructions have not been described widely,[2,36] with most studies concentrating on single-strand reconstructions analyzed statically.[17-19,28,30,31,36-38] Hence, there is a strong need to investigate the precise ulnar tunnel placement for double-strand LUCL reconstruction to achieve an isometric reconstruction. In this study, we compared 3 different graft configurations for double-strand LUCL reconstruction using 3-dimensional (3D) computed tomography (CT) modeling for each degree of the arc of elbow motion.

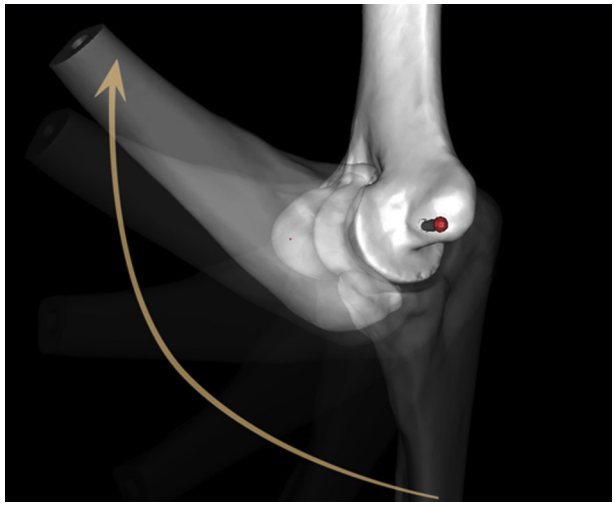

Figure 1 Simulated elbow movement *(arrow)* with the rotational axis selected as a reference point (●), from full extension (0°) to full flexion (135°) in 1° increments, with neutral forearm rotation.

Materials and methods

Image acquisition and 3D model reconstruction

We retrospectively reviewed 5 elbow joints from healthy volunteers with no history of trauma to the upper extremity. These elbow joints, from the distal humerus to the proximal radius and ulna, underwent CT scanning with 0.5-mm axial cuts, which were stored in Digital Imaging and Communications in Medicine (DICOM) format. MIMICS software (Mimics Research, version 17.0; Materialise, Leuven, Belgium) was used to convert the scans into patient-specific 3D computer models. Bone segmentation was performed using a single-threshold method, as previously described.[34] The growing region method was used to separate the humeral, ulnar, and radial bone segments.

Rotational axis selection

By use of several distal humerus cross sections, the geometric center points of the spherical capitellum and the circular trochlear groove were defined by the centroid of a circle-fitted surface tracing method, based on a method used in a previous study.[11] The best-fit line connecting these center points in all the cross sections was defined as the rotational axis (Fig. 1).[2,39] This axis was based on several studies that showed that the elbow's center of rotation is located in the medial aspect of the trochlea in the distal humerus.[7,8,13,18]

Footprint selection

The footprints were registered using the freeform patch function in 3-matic software (3-matic Research, version 9.0; Materialise).

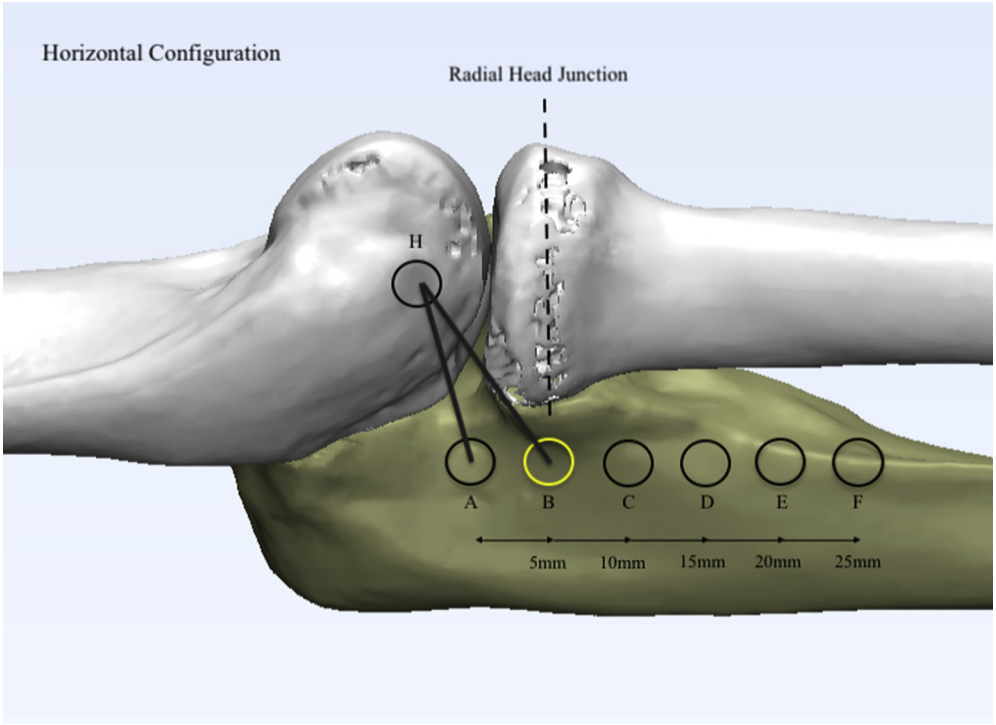

Figure 2 Horizontal subconfigurations. Humeral origin footprint (*H*) was registered at the center of the lateral aspect of the capitellum. The reference point (○) was located at the level of the radial head junction, which was also the second ulnar insertion (*B*). The first ulnar insertion was registered 5 mm proximal to the reference point (*A*). The subsequent ulnar insertions were located 10 mm (*C*), 15 mm (*D*), 20 mm (*E*), and 25 mm (*F*) distal to the reference point. There were 5 subconfigurations, registered as A-B, B-C, C-D, D-E, and E-F.

They were exported into a cloud of 3D vertices, which consisted of multiple points in each area. The LUCL reconstruction was double stranded. We applied 3 graft configurations with different ulnar insertions: horizontal, vertical, and triangular configurations. The selection of the humeral origin footprint was based on previous computer model studies, which located it at the center of the lateral aspect of the capitellum.[2,24,26] The landmark for the ulnar insertion footprint was also chosen based on previous computer model studies, which located it at the supinator crest, at the level of the radial head junction.[2,26] This acted as a reference point to register other ulnar insertion footprints (Fig. 2).[18] Each of the 3 configurations had 5 subconfigurations.

In the horizontal configuration, the first ulnar insertion was registered 5 mm proximally to the reference point. The subsequent ulnar insertions were registered at 5, 10, 15, 20, and 25 mm distally from the first ulnar insertion. Five pairs of horizontal subconfigurations were made according to the order (Fig. 2). The first 5 ulnar insertions of the horizontal configuration served as references for the vertical configuration, with the pairs for ulnar insertions made at intervals of 5 mm dorsally (Fig. 3). The selection of the triangular configuration was based on a previous study.[2] The first ulnar insertion of the triangle configuration was the same as that for the horizontal configuration. The pairs for each ulnar insertion were made 5 mm dorsally and 5 mm proximally (Fig. 4).

Ligament length kinematics and analysis

The 3D cloud points and rotational axis were imported into MATLAB software (MATLAB and Statistics Toolbox, release 2013b; The MathWorks, Natick, MA, USA). Movement of the elbow was simulated by rotating the ulna about the humerus along the rotational axis from full extension (0°) to full flexion (135°), at the initial and final flexion positions, and for each 1° increment between these. The execution program represented each tunnel length by interconnecting the vertices' points derived from the 3D model in 1° increments of elbow motion. The result files were exported from MATLAB software to a master data file. The lengths of the ligaments from the humeral origin to the first ulnar insertion (HU1) and second ulnar insertion (HU2) were measured at each point throughout the entire elbow motion arc, and the difference between them (HU1 – HU2) was calculated. This difference was used to represent the amount of graft motion at each point in the elbow motion arc. The smallest standard deviation of the length difference in the entire motion arc was used to identify the ligament length that produced the configuration that was closest to isometric. For this configuration, the minimum, maximum, and mean ligament length differences through the range of motion were recorded.

Statistical analysis

The data were expressed as mean and standard deviation. HU1 and HU2 across each subconfiguration were analyzed with analysis of variance. The differences in the lengths of the 2 ligaments for every configuration were also analyzed with analysis of variance. The level of statistical significance was set at $P < .05$.

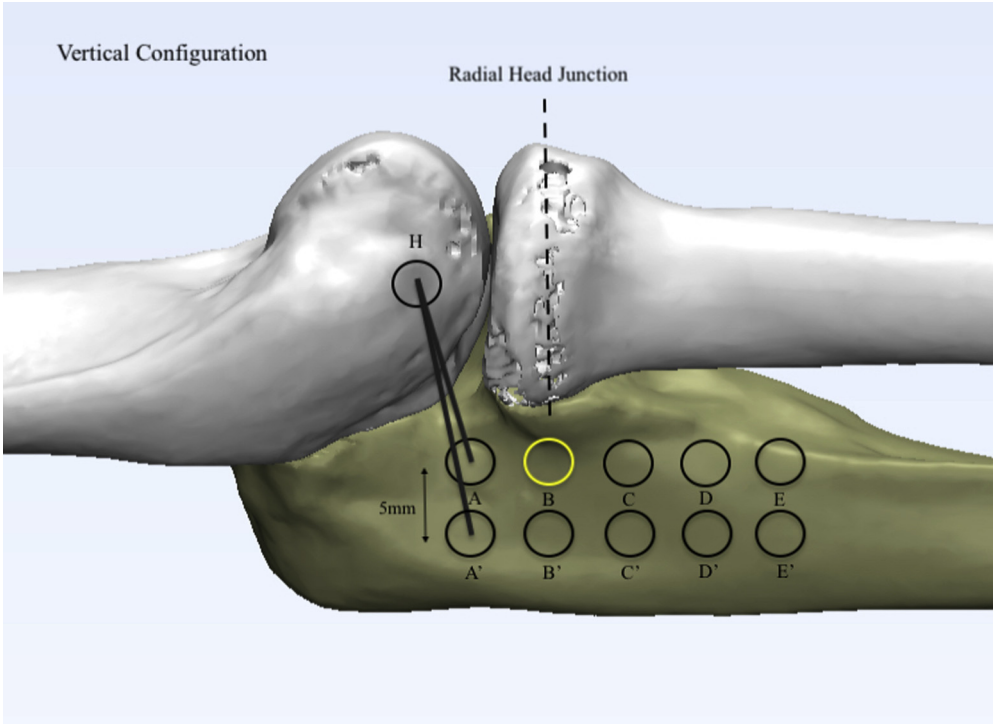

Figure 3 Vertical subconfigurations. Humeral origin footprint (*H*) was registered at the center of the lateral aspect of the capitellum. The level of radial head acted as reference point (○) for the following ulnar insertions registrations. The first 5 ulnar insertions of the horizontal configuration served as references for the vertical configuration, with the pairs for ulnar insertions made at intervals of 5 mm dorsally. There were 5 subconfigurations, registered as A-A', B-B', C-C', D-D', and E-E'.

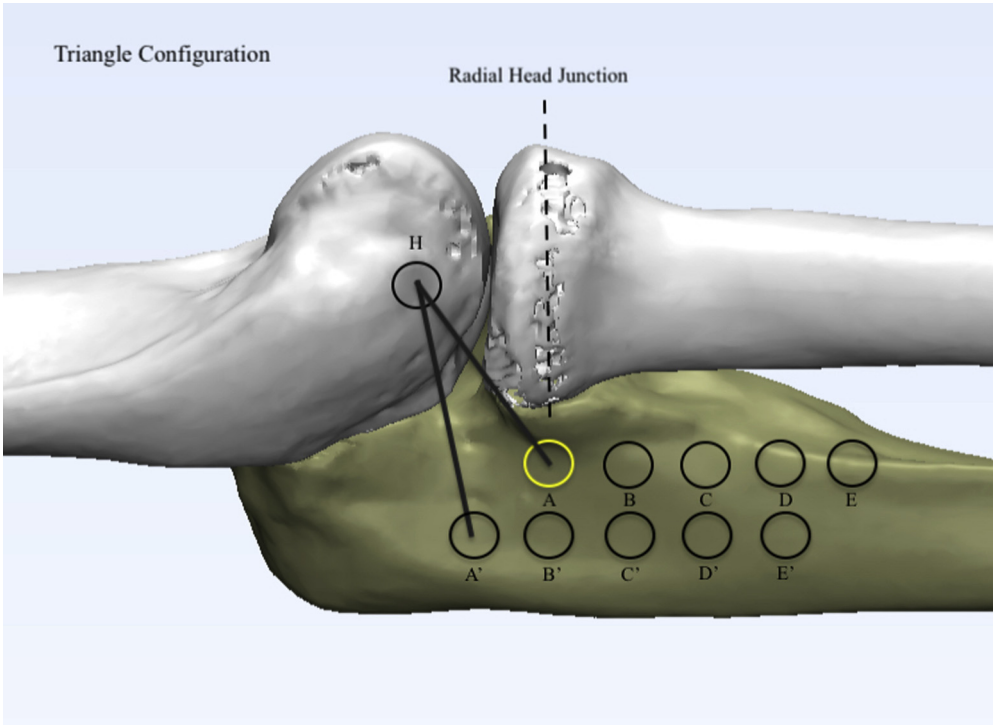

Figure 4 Triangular subconfigurations. Humeral origin footprint (*H*) was registered at the center of the lateral aspect of the capitellum. The level of radial head acted as reference point (○) for the following ulnar insertions registrations. The first ulnar insertion of the triangular configuration was similar to the horizontal subconfigurations. The pairs of ulnar insertions were made 5 mm dorsally and 5 mm proximally to each corresponding horizontal subconfiguration. There were 5 subconfigurations, registered as A-A', B-B', C-C', D-D', and E-E'.

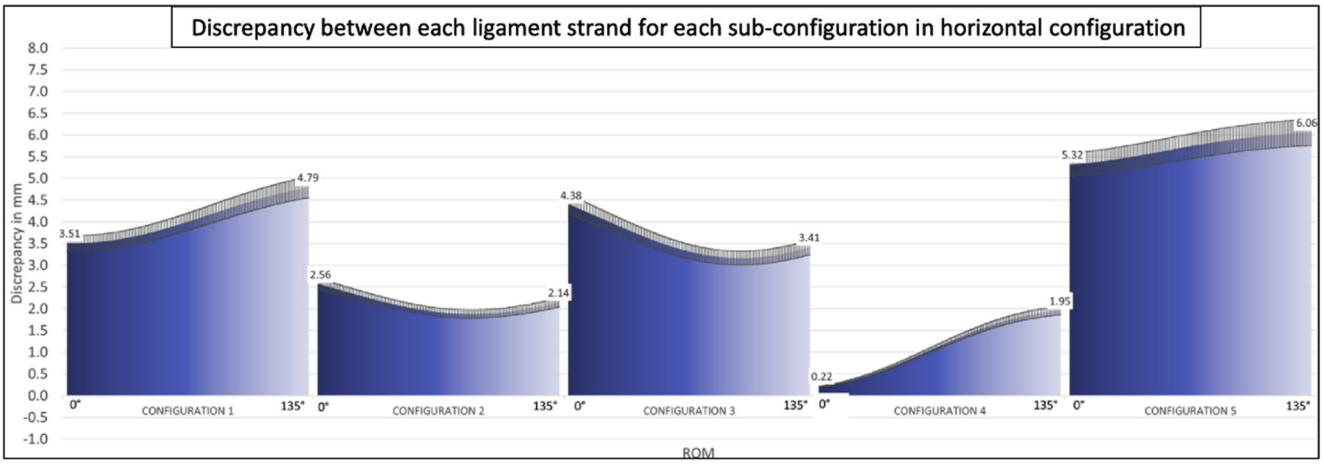

Figure 5 Of the subconfigurations of the horizontal graft placement configuration, subconfiguration 4 showed the smallest difference between the 2 ligament strands throughout the entire motion arc. *ROM*, range of motion.

Table I Maximum and minimum ligament lengths from humeral origin to first and second ulnar insertions

Configuration	Subconfiguration	Minimum HU1 length, mm	Maximum HU1 length, mm	Minimum HU2 length, mm	Maximum HU2 length, mm
Horizontal	1 (A-B)	25.9	28.2	29.8	33.0
	2 (B-C)	26.9	30.1	28.8	32.5
	3 (C-D)	27.2	30.4	30.6	33.8
	4 (D-E)	34.4	38.4	35.3	40.3
	5 (E-F)	34.8	39.5	40.4	45.5
Vertical	1 (A-A′)	26.3	29.0	30.9	33.6
	2 (B-B′)	29.8	32.5	30.4	33.6
	3 (C-C′)	32.4	37.2	32.5	37.0
	4 (D-D′)	34.1	37.9	37.6	41.1
	5 (E-E′)	34.2	39.4	36.8	41.4
Triangular	1 (A-A′)	27.0	29.9	29.6	32.1
	2 (B-B′)	28.0	31.5	30.4	32.9
	3 (C-C′)	29.5	32.7	33.2	36.4
	4 (D-D′)	34.0	38.1	33.1	36.4
	5 (E-E′)	35.7	40.5	37.3	41.0

HU1 length, ligament length from humeral origin to first ulnar insertion; *HU2 length*, ligament length from humeral origin to second ulnar insertion.

Results

All results were reported as mean and standard deviation with 0.1-mm measurements. We found no isometric point for any of the 5 subconfigurations of the 3 graft configurations. The ligament lengths for every configuration changed throughout the range of motion (Figs. 3–5), with the HU1 and HU2 lengths differing for each configuration (Tables I and II). For each degree of the motion arc, the ligament length changed in each configuration (Table III). The vertical configuration showed the smallest difference in ligament lengths, whereas the greatest difference was seen for the horizontal configuration. The minimum differences in ligament lengths were found in subconfiguration 4 for the horizontal configuration (Fig. 5), subconfiguration 3 for the vertical configuration (Fig. 6), and subconfiguration 4 for the triangular configuration (Fig. 7). The smallest overall difference was found with subconfiguration 3 of the vertical configuration, at 0.01 ± 0.09 mm of distance, which rounded to 0.0 ± 0.1 mm (Table III).

Discussion

The purpose of this study was to investigate the kinematics of a double-strand LUCL reconstruction with 3 different configurations of graft placement. We were unable to find a graft configuration for double-strand LUCL reconstruction that resulted in absolute isometricity. There were slight changes in both ligament strands throughout the arc of elbow motion, with loosening observed in the middle of the flexion arc and tightening in full flexion; these findings

Table II Ligament length from humeral origin to first and second ulnar insertions

Configuration	Subconfiguration	HU1 ligament length, mm	*P* value for HU1 ligament length	HU2 ligament length, mm	*P* value for HU2 ligament length
Horizontal	1 (A-B)	26.7 ± 0.7	.825	30.7 ± 0.9	.818
	2 (B-C)	28.0 ± 1.0		30.1 ± 1.1	
	3 (C-D)	28.2 ± 0.9		31.7 ± 1.0	
	4 (D-E)	35.7 ± 1.1		36.8 ± 1.4	
	5 (E-F)	36.2 ± 1.3		41.9 ± 1.5	
Vertical	1 (A-A′)	27.2 ± 0.8		32.5 ± 0.8	
	2 (B-B′)	30.7 ± 0.8		31.3 ± 0.9	
	3 (C-C′)	33.8 ± 1.3		33.7 ± 1.2	
	4 (D-D′)	35.3 ± 1.0		38.3 ± 1.0	
	5 (E-E′)	35.7 ± 1.5		41.1 ± 1.3	
Triangular	1 (A-A′)	27.9 ± 0.8		30.5 ± 0.8	
	2 (B-B′)	29.0 ± 1.0		31.3 ± 0.8	
	3 (C-C′)	30.7 ± 1.0		34.2 ± 0.9	
	4 (D-D′)	35.3 ± 1.2		34.2 ± 1.0	
	5 (E-E′)	37.1 ± 1.4		38.4 ± 1.0	

HU1 length, ligament length from humeral origin to first ulnar insertion; *HU2 length*, ligament length from humeral origin to second ulnar insertion.

Table III Length discrepancy of both ligament strands

Configuration	Subconfiguration	Minimum discrepancy, mm	Maximum discrepancy, mm	Mean discrepancy, mm	*P* value
Horizontal	1 (A-B)	3.5	4.8	4.1 ± 0.4	.482
	2 (B-C)	1.9	2.6	2.1 ± 0.2	
	3 (C-D)	3.2	4.4	3.5 ± 0.4	
	4 (D-E)	0.2	2.0	1.1 ± 0.6	
	5 (E-F)	5.3	6.1	5.7 ± 0.2	
Vertical	1 (A-A′)	4.0	5.2	4.6 ± 0.4	
	2 (B-B′)	0.0	1.2	0.7 ± 0.4	
	3 (C-C′)	0.0	0.2	0.0 ± 0.1	
	4 (D-D′)	3.2	3.7	3.4 ± 0.2	
	5 (E-E′)	2.0	3.4	2.5 ± 0.5	
Triangular	1 (A-A′)	2.1	3.1	2.6 ± 0.3	
	2 (B-B′)	1.3	3.6	2.3 ± 0.8	
	3 (C-C′)	2.7	3.9	3.6 ± 0.4	
	4 (D-D′)	0.4	2.0	1.0 ± 0.6	
	5 (E-E′)	0.5	2.2	1.3 ± 0.5	

were consistent with those from a previous study. This result suggests that a tendon graft would increase tension and strain by increasing the angles of elbow flexion, although tightening only started in the middle of the motion arc. We speculate that some graft creep would take place to allow full elbow flexion. The native LUCL is not isometric, so our findings were in accordance with the physiological condition. PLRI occurs in extension, so it is understandable why the tunnel length is longer at full extension, because this will tighten the graft to stabilize the elbow joint. There is a small amount of laxity in the middle of the flexion arc.

In this study, the lengths of the 2 ligament strands showed less fluctuation in the vertical configuration than in the other 2 configurations, indicating that the results of this technique were closest to isometric. The trends in changes in ligament length were minimal throughout the range of motion, indicating that there was minimal movement of the grafts through the range of motion of the elbow joint. The isometric placement of the graft during reconstruction has become a standard treatment, based on the premise of minimizing graft loads and elongation forces and providing early postoperative elbow range of motion.[25] Isometric grafting prevents the windshield-wiper effect, which can contribute to tunnel widening, graft wear, loss of fixation, residual instability, and decreased range of motion.[6]

Among the subconfigurations of the vertical graft placement configuration, the third showed the minimum length difference between the ligament strands. In this subconfiguration, the first tunnel was located at the supinator crest, 5 mm distal to the equator of the radial head. The next tunnel

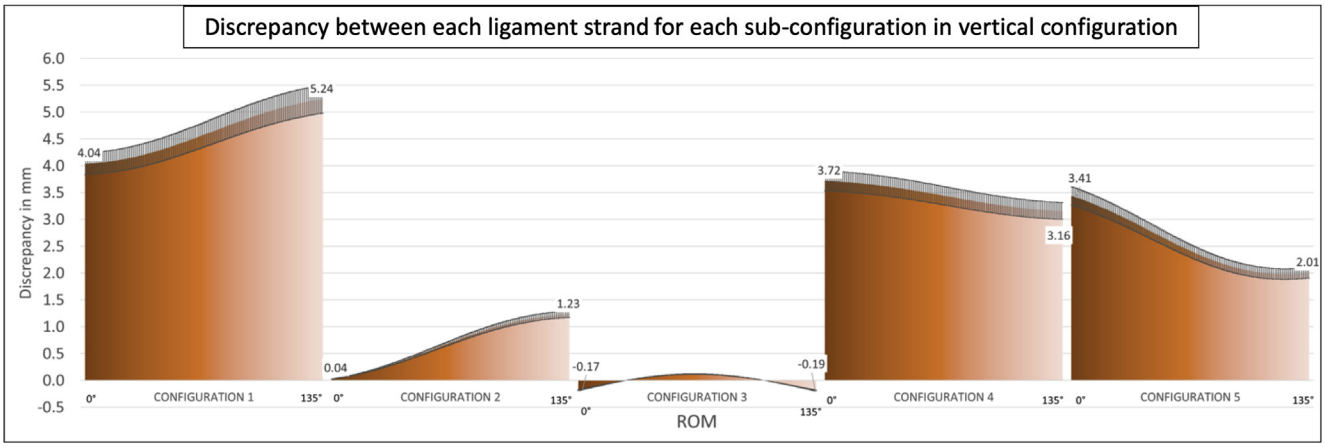

Figure 6 Of the subconfigurations of the vertical graft placement configuration, subconfiguration 3 showed the smallest difference between the 2 ligament strands throughout the entire motion arc. *ROM*, range of motion.

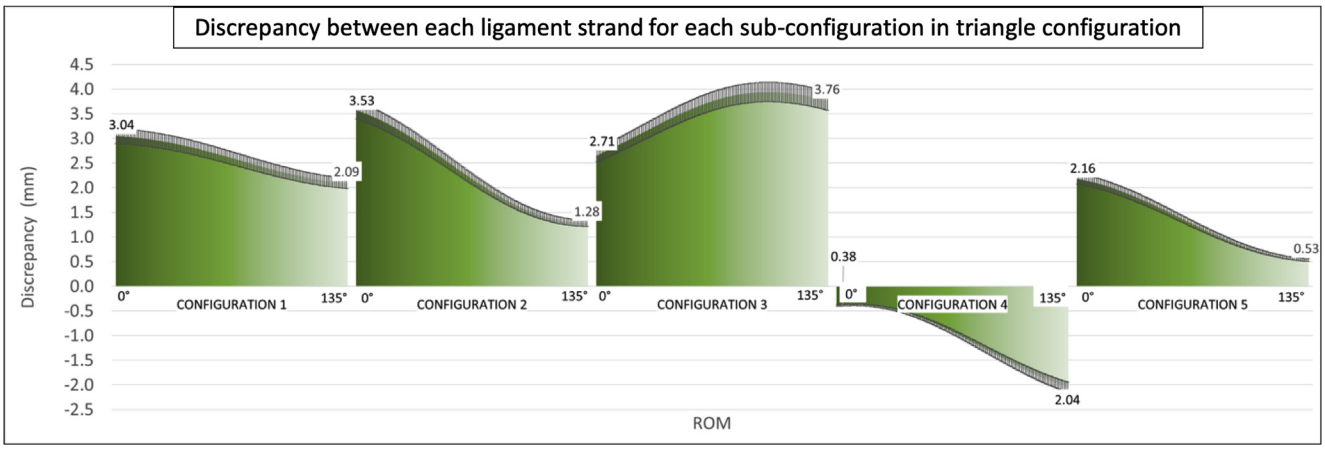

Figure 7 Of the subconfigurations of the triangular graft placement configuration, subconfiguration 4 showed the smallest difference between the 2 ligament strands throughout the entire motion arc. *ROM*, range of motion.

was located 5 mm dorsally. Our numerical result was rounded to the nearest tenth from 0.01 mm. We will use the hundredths value for the purpose of discussion. Although this configuration did not achieve a strictly isometric point, it could nevertheless be considered isometric, given that the mean difference in ligament lengths was only 0.01 mm throughout the whole range of motion. From a clinical point of view, a 0.01-mm change in movement would be almost impossible to distinguish. The results of our modeling found no isometric trends for any graft placement configuration. This is consistent with the findings of several studies that showed that the native LUCL is not isometric.[5,23,27,35] A biomechanical study of cadavers by Goren et al[15] was unable to find an isometric point for a single-strand LUCL reconstruction, with graft elongation of about 1 mm. Our study showed similar results but with graft elongation of only 0.01 mm. A 0.01-mm difference is not mathematically isometric but can be considered clinically isometric. We are of the opinion that the superior precision of our result was because of our use of computer modeling. The results of biomechanical studies of cadavers can be affected by ligament laxity, which is not present in computer model studies. Goren et al also found that not all specimens had the same optimal position and that the most nearly isometric point was likely to be patient specific. This means that there will always be individual morphologic characteristics for each specimen, which explains the variability of the data. However, we did not explore these properties in our study.

Our findings showed that the vertical configuration produced results that were closer to isometric than those of the other configurations. In our opinion, the vertical configuration is easier to reproduce than the isosceles triangle configuration described in the literature, given that it does not need any unusual angle measurements.[2,36] Using the vertical configuration would minimize the geometric error in the isosceles triangle configuration and would provide a broader graft to buttress the lateral radial head compared with the horizontal configuration. Our study found no LUCL reconstruction that was isometric, with at least a 0.01-mm difference in ligament lengths. This finding

suggests that no matter what configuration is used for LUCL reconstruction, it will not provide isometric graft properties. However, the point with the minimal length difference should be the fixation point for which to aim.

This study was not without limitations. First, the number of patient-specific elbow models used was limited. However, our study described the specific configuration for accurate and precise tunnel locations, resulting in a nearly isometric LUCL reconstruction. A strength of our study was lack of render bias owing to computer-aided design, which produced highly consistent and reproducible results. Second, the study used a fixed linear axis of rotation; however, it is universally agreed that the elbow joint has no fixed center of rotation. Nevertheless, because of minimal variation in the elbow flexion axis, the ulnohumeral joint can be assumed to be a uniaxial articulation with a fixed center of rotation. Our rationale for using this setting was that it created a uniform and consistent experiment setup. Third, the design of the study limited the involvement of muscle activity. The forearm extensors are known to play an important role in the active stabilization of the elbow joint and might, therefore, influence the results obtained. The origins and insertions of ligaments were determined based only on general anatomic information; individual variances in ligamentous and skeletal anatomy were not taken into account. In addition, this was a simulation study, so it cannot confirm whether the results would make a difference clinically.

Conclusion

The results of this study showed that dynamic analyses of the elbow joint provide a good understanding for LUCL reconstruction. Double-strand LUCL reconstruction using the vertical configuration can provide nearly isometric reconstruction. This will minimize graft motion and wear, as well as tunnel widening, and will prevent loss of motion and residual instability of the elbow joint.

Disclaimer

The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

This study was supported by the Global Frontier R&D Program on Human-centered Interaction for Coexistence and funded by the National Research Foundation of Korea via the Korean Government Ministry of Science, ICT (Information and Communications Technology) and Future Planning (MSIP) (grant No. 2017-0522). The funding source had no involvement in the study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

References

1. Ahmad CS, ElAttrache NS. Elbow valgus instability in the throwing athlete. J Am Acad Orthop Surg 2006;14:693-700.
2. Anakwenze OA, Khanna K, Levine WN, Ahmad CS. Lateral ulnar collateral ligament reconstruction: an analysis of ulnar tunnel locations. Am J Orthop (Belle Mead NJ) 2016;45:53-7.
3. Armstrong AD, Ferreira LM, Dunning CE, Johnson JA, King GJ. The medial collateral ligament of the elbow is not isometric: an in vitro biomechanical study. Am J Sports Med 2004;32:85-90. http://doi.org/10.1177/0363546503258886
4. Azar FM, Andrews JR, Wilk KE, Groh D. Operative treatment of ulnar collateral ligament injuries of the elbow in athletes. Am J Sports Med 2000;28:16-23.
5. Ball CM, Galatz LM, Yamaguchi K. Elbow instability: treatment strategies and emerging concepts. Instr Course Lect 2002;51:53-61.
6. Barrett GR, Treacy SH. The effect of intraoperative isometric measurement on the outcome of anterior cruciate ligament reconstruction: a clinical analysis. Arthroscopy 1996;12:645-51.
7. Bottlang M, Madey SM, Steyers CM, Marsh JL, Brown TD. Assessment of elbow joint kinematics in passive motion by electromagnetic motion tracking. J Orthop Res 2000;18:195-202.
8. Bryce CD, Armstrong AD. Anatomy and biomechanics of the elbow. Orthop Clin North Am 2008;39:141-154, v. http://doi.org/10.1016/j.ocl.2007.12.001
9. Cohen MS, Hastings H II. Rotatory instability of the elbow. The anatomy and role of the lateral stabilizers. J Bone Joint Surg Am 1997;79:225-33.
10. Deland JT, Garg A, Walker PS. Biomechanical basis for elbow hinge-distractor design. Clin Orthop Relat Res 1987:303-12.
11. Desai SJ, Deluce S, Johnson JA, Ferreira LM, Leclerc AE, Athwal GS, et al. An anthropometric study of the distal humerus. J Shoulder Elbow Surg 2014;23:463-9. http://doi.org/10.1016/j.jse.2013.11.026
12. Dodson CC, Thomas A, Dines JS, Nho SJ, Williams RJ III, Altchek DW. Medial ulnar collateral ligament reconstruction of the elbow in throwing athletes. Am J Sports Med 2006;34:1926-32. http://doi.org/10.1177/0363546506290988
13. Duck TR, Dunning CE, King GJ, Johnson JA. Variability and repeatability of the flexion axis at the ulnohumeral joint. J Orthop Res 2003;21:399-404. http://doi.org/10.1016/S0736-0266(02)00198-5
14. Eygendaal D. Ligamentous reconstruction around the elbow using triceps tendon. Acta Orthop Scand 2004;75:516-23. http://doi.org/10.1080/00016470410001367
15. Goren D, Budoff JE, Hipp JA. Isometric placement of lateral ulnar collateral ligament reconstructions: a biomechanical study. Am J Sports Med 2010;38:153-9. http://doi.org/10.1177/0363546509346049
16. 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;17:208-16.
17. Jones KJ, Dodson CC, Osbahr DC, Parisien RL, Weiland AJ, Altchek DW, et al. The docking technique for lateral ulnar collateral ligament reconstruction: surgical technique and clinical outcomes. J Shoulder Elbow Surg 2012;21:389-95. http://doi.org/10.1016/j.jse.2011.04.033
18. Kim HM, Andrews CR, Roush EP, Pace GI, Lewis GS. Effect of ulnar tunnel location on elbow stability in double-strand lateral collateral ligament reconstruction. J Shoulder Elbow Surg 2017;26:409-15. http://doi.org/10.1016/j.jse.2016.08.008
19. King GJ, Dunning CE, Zarzour ZD, Patterson SD, Johnson JA. Single-strand reconstruction of the lateral ulnar collateral ligament restores

varus and posterolateral rotatory stability of the elbow. J Shoulder Elbow Surg 2002;11:60-4. http://doi.org/10.1067/mse.2002.118483
20. Lee BP, Teo LH. Surgical reconstruction for posterolateral rotatory instability of the elbow. J Shoulder Elbow Surg 2003;12:476-9. https://doi.org/10.1016/S1058-2746(03)00091-0
21. Lin KY, Shen PH, Lee CH, Pan RY, Lin LC, Shen HC. Functional outcomes of surgical reconstruction for posterolateral rotatory instability of the elbow. Injury 2012;43:1657-61. http://doi.org/10.1016/j.injury.2012.04.023
22. London JT. Kinematics of the elbow. J Bone Joint Surg Am 1981;63:529-35.
23. Mehta JA, Bain GI. Posterolateral rotatory instability of the elbow. J Am Acad Orthop Surg 2004;12:405-15.
24. Miyake J, Moritomo H, Masatomi T, Kataoka T, Murase T, Yoshikawa H, et al. In vivo and 3-dimensional functional anatomy of the anterior bundle of the medial collateral ligament of the elbow. J Shoulder Elbow Surg 2012;21:1006-12. http://doi.org/10.1016/j.jse.2011.07.018
25. Morgan CD, Kalmam VR, Grawl DM. Isometry testing for anterior cruciate ligament reconstruction revisited. Arthroscopy 1995;11:647-59.
26. Moritomo H, Murase T, Arimitsu S, Oka K, Yoshikawa H, Sugamoto K. The in vivo isometric point of the lateral ligament of the elbow. J Bone Joint Surg Am 2007;89:2011-7. http://doi.org/10.2106/JBJS.F.00868
27. Morrey BF, An KN. Functional anatomy of the ligaments of the elbow. Clin Orthop Relat Res 1985:84-90.
28. Nestor BJ, O'Driscoll SW, Morrey BF. Ligamentous reconstruction for posterolateral rotatory instability of the elbow. J Bone Joint Surg Am 1992;74:1235-41.
29. O'Driscoll SW. Classification and evaluation of recurrent instability of the elbow. Clin Orthop Relat Res 2000:34-43.
30. O'Driscoll SW, Bell DF, Morrey BF. Posterolateral rotatory instability of the elbow. J Bone Joint Surg Am 1991;73:440-6.
31. O'Driscoll SW, Jupiter JB, King GJ, Hotchkiss RN, Morrey BF. The unstable elbow. Instr Course Lect 2001;50:89-102.
32. O'Driscoll SW, Morrey BF, Korinek S, An KN. Elbow subluxation and dislocation. A spectrum of instability. Clin Orthop Relat Res 1992:186-97.
33. Olsen BS, Sojbjerg JO. The treatment of recurrent posterolateral instability of the elbow. J Bone Joint Surg Br 2003;85:342-6.
34. Rathnayaka K, Sahama T, Schuetz MA, Schmutz B. Effects of CT image segmentation methods on the accuracy of long bone 3D reconstructions. Med Eng Phys 2011;33:226-33. http://doi.org/10.1016/j.medengphy.2010.10.002
35. Regan WD, Korinek SL, Morrey BF, An KN. Biomechanical study of ligaments around the elbow joint. Clin Orthop Relat Res 1991:170-9.
36. Sanchez-Sotelo J, Morrey BF, O'Driscoll SW. Ligamentous repair and reconstruction for posterolateral rotatory instability of the elbow. J Bone Joint Surg Br 2005;87:54-61.
37. Savoie FH III, Field LD, Gurley DJ. Arthroscopic and open radial ulnohumeral ligament reconstruction for posterolateral rotatory instability of the elbow. Hand Clin 2009;25:323-9. http://doi.org/10.1016/j.hcl.2009.05.010
38. Savoie FH III, O'Brien MJ, Field LD, Gurley DJ. Arthroscopic and open radial ulnohumeral ligament reconstruction for posterolateral rotatory instability of the elbow. Clin Sports Med 2010;29:611-8. http://doi.org/10.1016/j.csm.2010.06.008
39. Shiba R, Sorbie C, Siu DW, Bryant JT, Cooke TD, Wevers HW. Geometry of the humeroulnar joint. J Orthop Res 1988;6:897-906.
40. Takigawa N, Ryu J, Kish VL, Kinoshita M, Abe M. Functional anatomy of the lateral collateral ligament complex of the elbow: morphology and strain. J Hand Surg Br 2005;30:143-7. http://doi.org/10.1016/j.jhsb.2004.09.016
41. Yadao MA, Savoie FH III, Field LD. Posterolateral rotatory instability of the elbow. Instr Course Lect 2004;53:607-14.
42. 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;9:28-33.