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Original Article

Lateral column lengthening: A cadaveric biomechanical study

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Abstract

Objective: This cadaveric biomechanical study aimed to investigate the potential cause of the subtalar joint impingement after lateral column lengthening (LCL).

Methods: Eight fresh-frozen cadaveric feet underwent sequential LCL osteotomy with grafts of 6 mm, 8 mm, 10 mm, and 12 mm. Uniplanar motion analysis tracked anterior and posterior fragment movements. Mixed linear regression was used to assess correlations between graft size and fragment displacement.

Results: During LCL, the anterior fragment shifted anteriorly while the posterior fragment shifted posteriorly, with the anterior shift being greater than the posterior shift. From 6 mm to 12 mm of lengthening, the amount of posterior shift per millimeter peaked at 8 mm of lengthening and then decreased. A linear regression relationship was detected between the amount of lengthening and the anterior shift, with 1 mm lengthening inducing 1.07 mm anterior shift ($p < 0.001$).

Conclusion: In non-deformed cadaveric feet, LCL not only produced an anterior shift as expected but also induced a posterior shift of the tuberosity. Linear correlation was detected between the size of the lengthening and the anterior shift of the anterior fragment. The posterior shift eventually decreased after the insertion of a large graft (10 mm and 12 mm). The clinical application of these findings to flatfoot deformities remains uncertain and should be validated in future studies.

Level of Evidence III.

Keywords: Bone lengthening; Osteotomy; Flatfoot; Subtalar joint.

Introduction

Lateral column lengthening (LCL) osteotomy was introduced to treat symptomatic flatfoot deformities associated with abduction of the midfoot or uncovering of the talonavicular joint[1,2]. It was originally introduced in 1975 by Evans[3], who described the abduction deformity of the midfoot with lateral rotation of the navicular and decreased talonavicular coverage, could be corrected through a lengthening osteotomy in the lateral process of the calcaneus[3]. Over the years, variations of the initial procedure have been developed with the same concept of lengthening the lateral column to correct the midfoot abduction and improve coverage of the talonavicular joint[4-7].

The indication for LCL in adult patients is a flexible, painful flatfoot, with midfoot and forefoot abduction, hindfoot valgus, and unresponsive to conservative treatment. Although LCL has been proven to be a robust procedure with satisfactory radiographic and functional outcomes[2,8], it has complications ranging from sural nerve injury, peroneal tendon injury, subtalar impingement, calcaneocuboid joint arthritis, over-correction leading to overload in the lateral foot, and associated fifth metatarsal stress fractures[8].

Study performed at the Department of Orthopedics, University of Colorado School of Medicine, Denver, CO, USA

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This cadaveric biomechanical study aimed to investigate the potential cause of the subtalar joint impingement after LCL. It was hypothesized that in LCL, in addition to the distal fragment moving anteriorly as planned, the calcaneal tuberosity would simultaneously shift posteriorly, which can potentially cause subtalar joint impingement, particularly when a large graft is used (Figure 1)[9].

Methods

Study design

Eight fresh frozen blow-knee-amputated cadaveric feet without deformities and a history of prior trauma in the foot were used. An osteotomy was made perpendicular to the long axis of the anterior calcaneal process, 1.5 cm posterior to the calcaneocuboid joint, perforating the medial cortex. To capture shifts of the anterior and posterior calcaneal fragments in the sagittal plane during the lengthening, a MaxTRAQ motion capture system (Innovision Systems, Inc.) using one OMRON Sentech model STC-MBCM401U3V camera (OMRON Sentech Co., Ltd) and 12.5 mm optical markers was utilized. Each marker was attached to a 1.6 mm K-wire. Five markers were used, with one being placed in the anterior fragment and one in the posterior fragment of the osteotomy, one in the lateral process of the talus, one in the base of the third metatarsal, and one in the table within the testing zone for reference purposes (Figure 2). System calibration was performed using a cubic shape calibration wand.

Two smooth-tipped lamina spreaders were used to perform the lengthening and were placed on the plantar and dorsal sides of the osteotomy, simulating a bone graft. The thickness of the lamina spreader tips in a completely closed status was 4 mm. Therefore, following the osteotomy and insertion of the two closed lamina spreaders, the starting point of the lengthening was 4mm. Then, sequential lengthening by 2 mm each time was performed to achieve graft sizes of 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm. The exact opening of the osteotomy achieved during each attempted lengthening procedure was measured with a micro-caliper.

Measurements and statistical analyses

Shifts of the anterior and posterior fragments in the sagittal plane were recorded by the camera and calculated in the motion capture system. To study the correlation between the actual lengthening and fragment shifts, mixed linear regression analysis was performed using R[10], with 95% confidence intervals (95% CI) and both the marginal R^2 and conditional R^2 provided to support the strength and precision of the analysis. All measurements were recorded in mm and rounded to two decimals. A p-value of < 0.05 was set to indicate statistical significance.

Results

During LCL, it was observed that the anterior fragment shifted anteriorly, while the posterior fragment shifted posteriorly. The anterior shift was larger than the posterior shift (Table 1). The 14 mm of attempted lengthening failed due to high tension in the surrounding bony and soft-tissue structures. On average, at 6 mm, 8 mm, 10 mm, and 12 mm of lengthening, the anterior fragment shifted anteriorly by 1.70 mm, 3.81 mm, 5.62 mm, and 8.22 mm, respectively. In the meantime, the posterior fragment shifted posteriorly by - 0.02 mm, 0.54 mm, 1.13 mm, and 1.37 mm. The amount of posterior shift increased with each additional 2 mm of lengthening, peaking at 10 mm of lengthening (the posterior shift was 0.56 mm at the lengthening from 6 mm to 8 mm, 0.59 mm from 8 mm to 10 mm, and 0.24 mm from 10 mm to

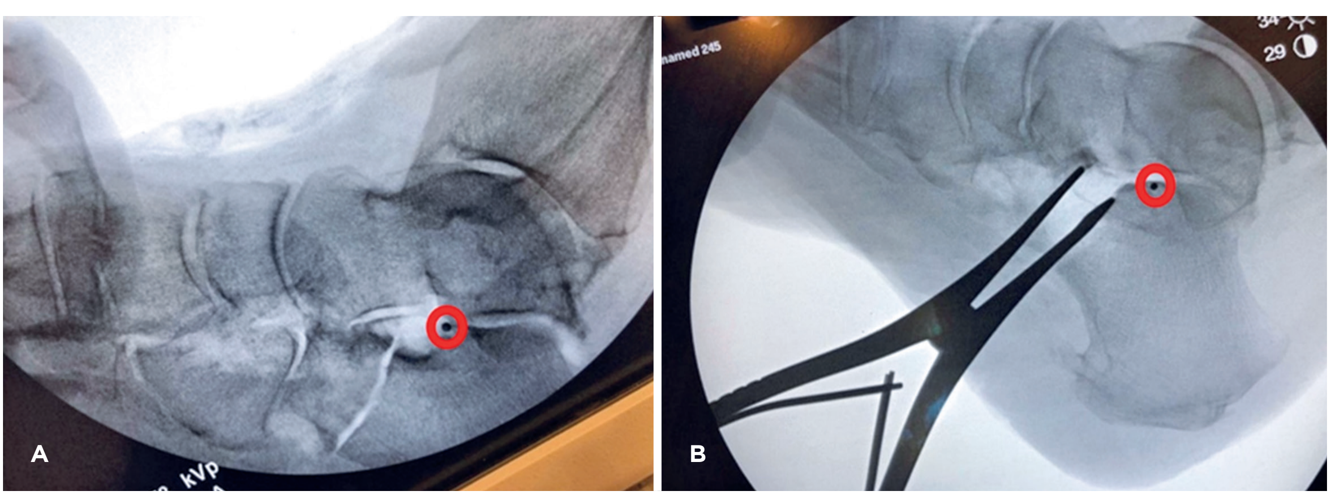


Figure 1. A demonstration of the posterior shift of the posterior fragment during the lateral lengthening procedure in a cadaveric foot. A radiograph marker was inserted into the anterior corner of the posterior facet in the calcaneus. Note the posterior shift of the marker into the posterior facet after the osteotomy was opened with a lamina spreader.

12 mm). The posterior fragment impinging against the lateral process of the talus, i.e., subtalar impingement, was observed under direct visualization. However, this impingement could not be determined kinematically using the current uniplanar motion tracking system.

For the anterior fragment, a linear correlation was noted ($p < 0.05$) between the fragment shift and the actual lengthening achieved (Figure 3). Starting from 6 mm of lengthening, every 1 mm of attempted lengthening/increasing of the graft size could induce 1.07 mm (95% CI (0.87, 1.26)) of anterior shift (anterior shift = -4.80 + 1.07 × attempted LCL, $p < 0.001$, Marginal $R^2 = 0.58$, Conditional $R^2 = 0.87$).

Figure 2. The lateral column lengthening procedure and marker system settings.

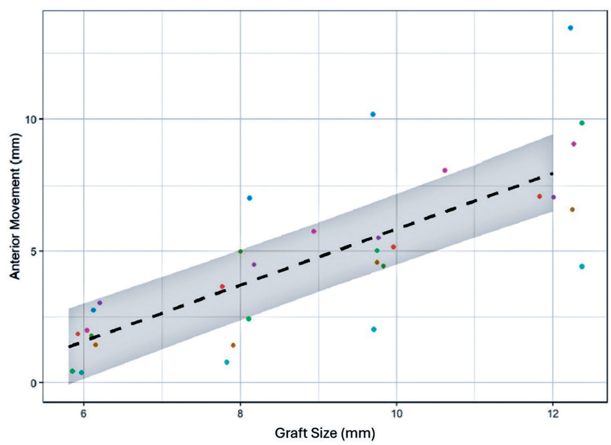
Discussion

As initially described, the Evans osteotomy, i.e., LCL, was designed to correct midfoot abduction in flatfoot deformities through lengthening the anterior process of the calcaneus and subsequently improving the talonavicular joint coverage[3,11,12]. Ruffilli et al.[13,14] published data with a ten-year follow-up of clinical outcomes stating that patients who underwent LCL in combination with medial soft tissue reconstruction procedures and a medializing calcaneal osteotomy had a satisfaction rate reaching up to 86% with a significant increase in the talonavicular coverage radiographically. Tellisi et al.[15] reported statistically significant improvements in both clinical and radiographic outcomes after LCL. They showed an increase in the American Orthopaedic Foot and Ankle Society Hindfoot Score (AOFAS) from 53.1 ± 14.5 preoperatively to 83.2 ± 12.2 postoperatively. Biomechanically, Chan et al.[16] proved that every millimeter of LCL corresponded with a 6.8 degree of change in the lateral incongruency angle. They also stated that the LCL procedure mainly corrects the mid-forefoot abduction. Recently, a retrospective cohort study by Tsai et al.[17] provided results indicating significant improvements in the anteroposterior talus-first metatarsal angle, calcaneal pitch, talocalcaneal angle, and the talonavicular uncoverage angle, supporting the clinical improvement results recognized after LCL procedures.

Despite LCL being well established for correcting the abduction deformity, postoperative pain in the lateral foot is a common complication. This has been attributed to a range of causes, including sural nerve injury, peroneal tendon injury, nonunion, sinus tarsi impingement, subtalar impingement, hindfoot stiffness, lateral column overload, calcaneocuboid joint arthritis, and fifth metatarsal stress fracture[2,11,18]. Some studies have questioned whether LCL may not reliably correct forefoot supination deformity and may even produce greater

Table 1. Raw lengthening data recorded by the marker system. For the anterior fragment, positive values mean the fragment shifted anteriorly. For the posterior fragment, positive values mean the fragment shifted posteriorly, and negative values mean the fragment shifted anteriorly. “NA” indicates that further lengthening was not possible due to high tension.

	Actual opening of the osteotomy by the lamina spreader to mimic different graft sizes					Anterior fragment shift				Posterior fragment shift			
	4 mm	6 mm	8 mm	10 mm	12 mm	6 mm	8 mm	10 mm	12 mm	6 mm	8 mm	10 mm	12 mm
1	4.08	5.92	7.77	9.96	11.83	1.85	3.66	5.17	7.09	-0.07	1.07	2.45	2.93
2	3.94	6.15	7.91	9.75	12.25	1.43	1.42	4.57	6.58	0.95	2.88	1.92	3.34
3	4.88	6.10	8.00	9.83	NA	1.78	4.98	4.44	NA	-0.21	-0.77	2.10	NA
4	5.09	5.85	8.11	9.75	12.37	0.42	2.42	5.03	9.85	0.06	0.87	0.94	0.79
5	4.67	5.97	7.83	9.71	12.37	0.37	0.77	2.03	4.42	0.26	1.76	2.53	2.82
6	4.68	6.12	8.12	9.70	12.23	2.76	7.02	10.17	13.47	-0.51	-1.34	-2.03	-2.34
7	4.02	6.20	8.18	9.77	12.01	3.02	4.49	5.51	7.05	0.02	1.59	2.61	3.13
8	4.61	6.04	8.94	10.62	12.27	1.98	5.75	8.07	9.05	-0.67	-1.78	-1.45	-1.11
Mean	4.50	6.04	8.11	9.89	12.19	**1.70**	**3.81**	**5.62**	**8.22**	**-0.02**	**0.54**	**1.13**	**1.37**
SD	0.43	0.12	0.37	0.31	0.20	0.96	2.16	2.47	2.91	0.50	1.65	1.86	2.30



Linear Mixed Model

Characteristic	Beta	SE	Statistic	95% CI	p-value
Marker Distance (mm)	1.065	0.093	11.4	0.871, 1.258	<0.001

Abbreviations: CI = Confidence Interval, SE = Standard Error

$$R^2_{\text{Marginal}} = 0.5752$$

$$R^2_{\text{Conditional}} = 0.8703$$

Figure 3. Linear model of the anterior shift of the anterior fragment. Starting at 6 mm of graft size, every 1 mm attempted lengthening/increase in the graft size will induce the anterior fragment to shift 1.07 mm anteriorly. This result is statistically significant (p < 0.001).

forefoot supination, leading to postoperative overload in the lateral foot[14,19]. A study by Chan et al.[16] investigated lateral column overload by comparing a population undergoing LCL in combination with tendon transfer and medializing calcaneal osteotomy with medializing calcaneal osteotomy and tendon transfer without an LCL. 45% of patients undergoing the LCL procedure reported lateral-sided foot pain compared with 17% of patients who did not have the lateral column procedure.

Ellis et al.[20] suggested using precisely sized metallic wedge trials prior to inserting the final graft. Their results indicated that, when correctly titrated, these trial wedges significantly decreased postoperative lateral foot pain from 14.7% to 6.3% (p = 0.084) with a mean graft size of 6.8 mm (range, 4-10 mm). The concept of titrating the graft size under fluoroscopy was further recommended by the progressive collapsing foot deformity (PCFD) consensus group[21]. Regarding the graft shape, Mosca[15] suggested that a trapezoidal wedge instead of a triangular wedge should be considered. Mosca's trapezoidal wedge had a lateral border of 10-12 mm and a medial border of 4-6 mm, aiming at a stronger power of adducting the midfoot, and a possibility of that through decreasing the length of the graft, reducing the effect of overloading the lateral column[15,22].

This study investigated the graft size and the corresponding shifts of the anterior and posterior fragments in the sagittal plane. The amount of posterior shift reduced when a large-sized graft (10 mm or 12 mm) was inserted. Insertion of a large graft (10 mm and 12 mm) caused the edge of Gissane's angle of the calcaneus to impinge on the talar lateral process, which was directly visualized, although its kinematic contribution was not assessed in this study. The 14 mm attempted lengthening failed due to high tension in the surrounding bony and soft-tissue structures, and 14 mm lengthening was then discontinued for this study.

It is necessary to note that the subtalar posterior facet impingement described in this study is different from the sinus tarsi impingement associated with PCFD Class D[23]. The latter type was caused by peri-talar subluxation[24,25]. It is the bony contact between the inferior aspect of the talus and the dorsal aspect of the calcaneus, as Johnson and Strom[26], Malicky et al.[27], and Jeng et al.[28] found in flat foot deformities[27,28]. The subtalar joint impingement described in this study is also different from the impingement of a prominent graft against the anterior process of the talus in LCL. The latter impingement is unrelated to a large graft and is due to either the dorsal side of the graft not fully inserted and packed into the osteotomy or to the graft height exceeding the vertical depth of the osteotomy. And that issue can be solved by shaving the prominent dorsal section of the graft with a saw or rongeur[18]. So far, there are no precise parameters for diagnosing sinus tarsi impingement and subtalar impingement associated with LCL intraoperatively, nor postoperatively, clinically, radiographically, or on weight-bearing computed tomography[24,25,29]. The authors of this study proposed that subtalar impingement should be evaluated intraoperatively by evaluating the shift of the posterior fragment and the corresponding change in posterior facet motion under direct visualization.

This study has a few limitations. Firstly, this study was designed to investigate only the shift of the anterior and posterior fragments in the sagittal plane. Therefore, only one camera and marker per segment were used to track uniplanar motion; the system was not capable of tracking 3D motion. This study did not aim to observe relevant changes in the coverage of the talonavicular joint in the transverse plane, nor the power of the LCL in correcting hindfoot valgus and abduction deformity of the midfoot (or uncovering of the talonavicular joint). How well the anterior shift of the anterior fragment corresponds with the improvement in talonavicular coverage, and whether the anterior and posterior shifts can reduce hindfoot valgus, will need to be explored in future studies. Secondly, subtalar impingement caused by a large graft was visualized in this study but was not recorded due to the limited ability of the current uniplanar motion-tracking system. Therefore, this subtalar impingement concept should be considered a plausible hypothesis rather than a demonstrated outcome and requires further investigation. Thirdly, this study used normal feet without flatfoot or midfoot abduction deformities. Possible soft tissue contracture in the lateral column in flatfeet may limit the excursion of the anterior and posterior shifts in the LCL. Therefore, the results of this study may not be extrapolated to flatfeet with a midfoot abduction deformity. Although the posterior shift of the tuberosity during LCL has been noted clinically by the senior author and verified in the current study, one cannot assume that the clinical complication of sinus tarsi pain is caused solely by overlengthening. This may require determining motion in the subtalar and calcaneocuboid joints, combined with weight-bearing computed tomography pre- and post-wedge insertion, in cadaveric studies. Finally, the sample size was small, although the measurements were consistent across all specimens; further cadaveric study may be required to validate these findings.

Conclusion

This study observed that in non-deformed cadaveric feet, during the LCL, in addition to the anterior shift of the anterior calcaneal segment, the posterior fragment shifted posteriorly simultaneously. There is a linear correlation between the size of the graft and the amount of the anterior shift, while the amount of the posterior shift reduced with the size of the graft being increased. The clinical application of these findings to flatfoot deformities remains uncertain and should be validated in future studies.

Authors' contributions: Each author contributed individually and significantly to the development of this article: MZ *(https://orcid.org/0000-0002-9685-4048) Conceived and planned the activities that led to the study, data collection, statistical analysis, interpreted the results of the study, formatting of the article, participated in the review process; MA *Conceived and planned the activities that led to the study, data collection, formatting of the article; THB *Conceived and planned the activities that led to the study, data collection, interpreted the results of the study; CK *Statistical analysis, interpreted the results of the study; MSM *(https://orcid.org/0000-0001-5124-2403) Conceived and planned the activities that led to the study, formatting of the article, participated in the review process; SL *(https://orcid.org/0000-0003-1238-8455) Conceived and planned the activities that led to the study, survey of the medical records, clinical examination, formatting of the article, participated in the review process. All authors read and approved the final manuscript. *ORCID (Open Researcher and Contributor ID) iD.

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