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Zigzag tenotomy of the extensor hallucis longus through minimally invasive surgery in cadaveric specimens: description of a new technique

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Abstract

Background Lengthening of the extensor hallucis longus (EHL) is performed to address various forefoot pathologies. The retraction of this tendon is strongly associated with the Hallux Abductus Valgus (HAV) deformity. Minimally Invasive Surgery (MIS) lengthening of the EHL is carried out in combination with other surgical techniques for HAV bone realignment. It is performed without ischemia, using local anesthesia and sedation if required by the patient. One of the advantages of this technique is immediate ambulation with a postoperative shoe without the need for a cast. The objective of the research was to demonstrate the efficacy and safety of the minimally invasive technique for lengthening the tendon in patients with HAV.

Materials and methods The procedures were performed on 11 fresh cryopreserved cadaveric feet. HAV surgery was performed through dorsomedial and dorsolateral portals for Reverdin-Isham, Akin and adductor tenotomy. In addition, EHL tendon elongation was performed using the Beaver 67 MIS scalpel through an incomplete zigzag tenotomy. The specimens used did not present any type of disease nor had they undergone previous surgeries that could affect the technique. First, the plantar flexion of the metatarsophalangeal joint was measured with a goniometer to establish the degrees of this joint before proceeding with the technique, the tenotomy was performed and remeasured and finally the osteotomy was performed. In addition, an anatomical dissection of cadaveric specimens was performed and various anatomical and surgical relationships were analyzed and measured.

Results The data indicate that, after performing zigzag tenotomy, there is an average improvement of 13.91 degrees in plantar flexion.

Conclusions The study confirms the effectiveness and safety of elongating the extensor hallucis longus tendon of the hallux using minimally invasive surgery. The zigzag technique for tendon elongation may be considered a viable minimally invasive treatment option for addressing tendon hyperextension in patients with HAV.

Keywords Minimally invasive surgical procedures, Reverdin-Isham, Osteotomy, Hallux valgus, Extensor hallucis longus

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Background

Hallux valgus (HAV) is a common foot deformity, characterized by a painful prominence at the first metatarsal head (bunion), bursa inflammation, and lateral deviation of the big toe [1], often causing metatarsalgia, functional limitations, and difficulty wearing narrow shoes [2]. In advanced stages, it can alter forefoot biomechanics and deform adjacent toes [3]. It affects 20–30% of adults [4, 5], is more common in women [6], and increases with age [7].

The etiology is multifactorial [8], involving hereditary factors, anatomical changes, biomechanical issues [2], improper footwear, and degenerative changes [9–11]. The extensor hallucis longus (EHL) also contributes to HAV, with metatarsal varus, increased pronation, and sesamoid displacement leading to muscle imbalance and hallux deviation [12, 13].

The balance of tendons, particularly (EHL), plays a critical role in the pathogenesis HAV. Imbalance and maltracking of the EHL tendon can cause or exacerbate the deformity [14, 15]. The EHL exerts excessive lateral traction on the hallux, leading to its valgus deviation, especially in cases where there is increased pronation or varus positioning of the first metatarsal. This imbalance results in a mechanical disadvantage, contributing to deformity progression. Tightness in the EHL can also aggravate valgus forces, and in some cases, tendon lengthening and realignment are necessary to restore balance [13].

This tendon shifts laterally, creating a cord-like structure within between the phalanx and the metatarsals, reducing its normal extension function and turning it into an adductor muscle [2].

Initial treatment is usually conservative and involves the use of wide shoes, orthopedic insoles, anti-inflammatory medications, infiltrations, or physiotherapy sessions [16–18]. In situations where conservative treatment proves ineffective, surgery is considered as a second option. Over the past decades, surgical techniques for this condition have undergone significant evolution [4, 19, 20] transitioning from open procedures with extensive incisions to minimally invasive approaches. Advantages of minimally invasive surgery include less trauma to soft tissues, reduced risk of wound infection, less postoperative pain, and faster recovery [21, 22]. However, in some cases, there are recurrences of the pathology due to the retraction of the long extensor, as the force vectors toward the medial side are not completely modified, causing a slight extension of the hallux again.

Specifically, the authors hypothesize that the chronic hyperextension of the EHL tendon is closely related to HAV, and that by performing multiple partial zigzag cuts along the tendon, it will be possible to lengthen and balance it, restoring its normal function and contributing to correcting the foot deformity.

The study compares whether there is an increase in range of motion of the big toe joint following EHL Zig Zag tenotomy and corresponding osteotomies for HAV correction with hyperextension of the toe.

Materials and methods

Study design and specimens

This study conducted on cadaveric feet followed the principles of the 1964 Helsinki Declaration. The sample was provided by the Department of Anatomy at the Catholic University of Valencia (Valencia, Valencian Community, Spain). The total sample consisted of 11 cryopreserved cadaveric feet (5 right and 6 left), extending up to the mid-third of the tibia and fibula, with no signs of pathology. The extensor hallucis longus (EHL) was identified at the ankle level and grasped with Kocher forceps, where maximum tension was applied to simulate toe hyperextension for the first measurement. Following this, osteotomies were performed, and the second measurement was taken. The procedure concluded with a zigzag tenotomy. Despite the potential anatomical variability of the EHL, it is a tendon that, when placed under tension, becomes clearly defined and visible beneath the skin.

The study was approved by the Research Ethics Committee of the Catholic University of Valencia (Valencia, Valencian Community, Spain) UCV/2022–2023/035 in accordance with the ethical guidelines of the Helsinki Declaration [23, 24].

The surgical procedure was performed by two podiatrists specialized in minimally invasive surgery at the Faculty of Medicine and Health Sciences of the Catholic University of Valencia San Vicente Mártir (Valencia, Valencian Community, Spain).The InSight II fluoroscope was used as the radiological equipment to verify the correct location of the osteotomies. Additionally, a surgical micromotor, Surgic Pro2 from the NSK brand, was used to perform bone cuts. All the necessary instruments for minimally invasive surgery were also employed.

Measurement of hallux hyperextension

The measurement of hallux hyperextension is performed using a goniometer to assess the range of motion in the metatarsophalangeal (MTP) joint. The goal of this procedure is to quantify the hyperextension angle, which is crucial for preoperative planning and evaluating postoperative outcomes. One arm of the goniometer is placed along the shaft of the first metatarsal, while the movable arm is positioned parallel to the shaft of the proximal phalanx. Passive plantar flexion is then induced at the MTP joint, and the flexion angle is recorded based on the direct reading from the goniometer. This angular value constitutes the baseline range of joint hyperextension, limited by hyperextension.

To ensure the validity and reproducibility of the data obtained, measurements were independently conducted by two experienced researchers, each performing three measurements on each specimen. Interobserver reliability was quantified using the intraclass correlation coefficient (ICC) [25], which allowed for the establishment of consistency in the preoperative and postoperative measurements following osteotomy and tenotomy. The results indicate a high interobserver reliability, with an ICC of 0.99 for preoperative measurements, 0.95 for those following tenotomy, and 0.98 after osteotomy. These values reflect excellent agreement between evaluators, reinforcing the precision of the measurements conducted (Fig. 1).

Surgical procedure

The surgery of the hallux was performed in the usual manner [26, 27], (Fig. 2) including osteotomy at the head of the first metatarsal using the Reverdin-Isham technique, tenotomy of the adductor and osteotomy at the base of the proximal phalanx of the big toe (Akin technique) [28].

Secondly, partial zigzag tenotomy was performed using the Beaver 67 MIS scalpel. The foot was positioned in a supine position on the dissection table. Passive plantar flexion of the metatarsophalangeal and interphalangeal joints of the big toe was carried out to tension the EHL.

Cuts were made following a zigzag pattern, meaning the cutting side alternated at each entry point, maintaining a constant distance of 5 mm between each cut. The cuts were performed gradually, starting from the distal area before the interphalangeal joint towards the proximal end of the tendon (see Fig. 3A). During the cuts, an assistant held the big toe in a plantar flexion position to facilitate palpation of the tendon and maintain tension. In all examined feet, a total of 5 partial cuts were made in the EHL.

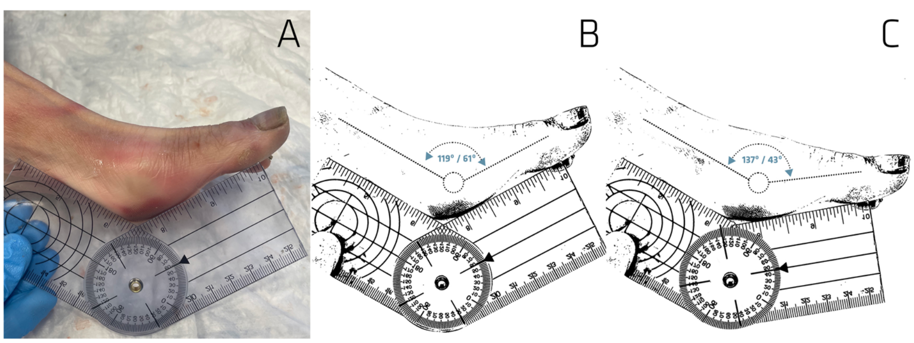

Fig. 1 Measurement of the degrees of hyperextension in the big toe. **A** Actual photograph of the actual measurement. **B** Diagram of the preoperative measurement. **C** Diagram of the postoperative measurement. The image illustrates the process of measuring the plantar flexion angle before and after two procedures: osteotomy and tenotomy. The angle is first evaluated after osteotomy and again after tenotomy to assess changes in plantar flexion angle

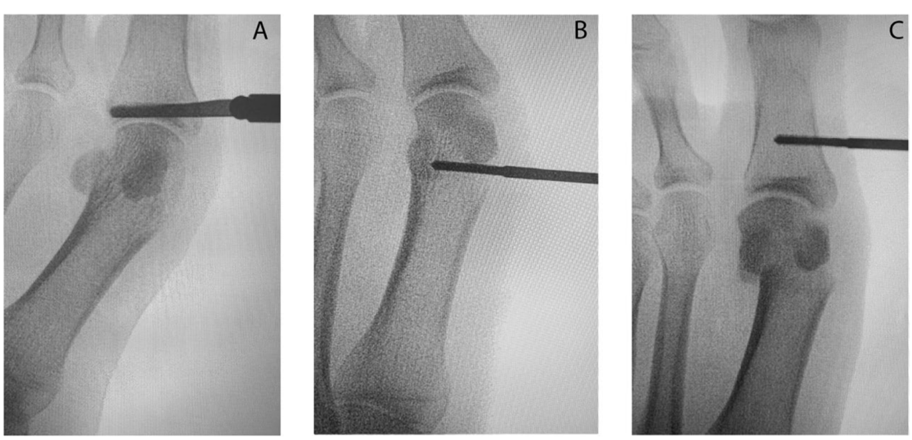

Fig. 2 These images provided a visual description of the procedures carried out. **A** Tenotomy of the Adductor. **B** Reverdin-Isham Osteotomy. **C** Akin Osteotomy

Fig. 3 Dorsal view of superficial dissection. **A** A longitudinal dissection is performed on the dorsal surface of the big toe. **B** The involvement oof the medial dorsal distal nerve is assessed

Anatomic dissection

Anatomic dissection of the specimens was performed. Surgical dorsal dissection of the big toe was carried out. The integrity of the extensor tendon, as well as the potential involvement of adjacent structures (medial dorsal nerve, dorsal vessels, and joint capsule), was independently assessed by two investigators (Fig. 3). Subsequently, any differences in observations made by each examiner were discussed and consensus was reached.

Data analysis

An observer who was unaware of the experimental setup performed all analyses. The mean and standard deviation (SD) were used to express the data. The Shapiro–Wilk test was used to evaluate the assumption of normality. Levene's test was also used to calculate the homogeneity of variance assumption. At p 0.05, the significance level was established. For the statistical analysis and graphical display of the data, SPSS 24 (SPSS 24 Inc, Chicago, Illinois, USA) and Jeffreys's Amazing Statistical Package (JASP, https://jasp-stats.org/) were used respectively. The variation in the plantar flexion angle was measured preoperatively and compared with the measurements obtained after the osteotomy and following the completion of the tenotomy. These were analyzed using the paired samples T-test, whereas the comparison between the osteotomy and tenotomy measurements was analyzed using the Wilcoxon test due to the lack of normality in the data.

The Effect size (ES) was calculated by determining Cohen's d coefficient, which was then expressed as the difference in the standardized mean change. The ES was classified as trivial (<0.20), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99) or very large (>2.00) [29].

Results

After the surgical procedure, a dissection was performed, followed by an analysis of the partial tenotomy incisions to assess the extent of anatomical damage. The dissection confirmed the lengthening of the extensor hallucis longus (EHL) in all 11 cadaveric feet. Macroscopic evaluation revealed complete preservation of dorsal nerve integrity in all specimens ($n=11$, 100%), while the joint capsule remained intact in 8 specimens ($n=8$, 72.72%), and the tendinous expansions were preserved in 10 cases ($n=10$, 90.90%). Additionally, in all samples ($n=11$, 100%), no alterations were observed in the vascular system. These findings suggest that EHL zigzag tenotomy is a safe procedure for the preservation of adjacent structures (Table 1).

The percentage of the cut section in relation to the total width of the tendon was analyzed at five points along its length. The mean percentage of the first four measurements was consistent with respect to hemitenotomy, ranging from 52.07% (±15.21) to 53.72% (±12.51). However, at the fifth measurement, the mean percentage decreased to 43.34% (±20.55), suggesting a reduction in tendon integrity in this specific region following zigzag tenotomy.

When evaluating plantar flexion of the big toe, a progressive decrease in the mean joint range of motion was observed after surgical interventions. In the pre-surgical measurement, the mean plantar flexion was 45.82° (±9.22°).

When assessing the plantar flexion of the big toe, a progressive decrease in the average joint range was observed following surgical interventions. In the preoperative measurement, the average plantar flexion was 45.82° (±9.22°). Subsequently, after performing osteotomies on the first metatarsal and the proximal phalanx, this average was reduced to 33.64° (±8.88°) with a *P*-value < 0.001 (Table 2). Finally, after completing the procedure with a zigzag tenotomy of the extensor hallucis longus tendon, an additional decrease in plantar flexion was observed, reaching an average of 31.91° (±6.73°) with $p = 0.57$ (Table 2).

Compared to the initial measurement, this resulted in a total average reduction of 13.91°(±6,56°) in the range of plantar flexion of the big toe, combining the effects of the osteotomies and the zigzag tenotomy ($P < 0.001$, Table 2).

The effect size, measured with Cohen's d, is large in the case of Pre-surgical vs. Osteotomies only (1.60) and increases to very large (2.12) when measuring after the extensor tenotomy (Table 2, Fig. 4A and B). However,

Table 1 Macroscopic feature assessed after surgical dissection

Case	Laterality	Integrity of the medial dorsal nerve	Integrity of the joint capsule	Dorsal vessels	Integrity of the expansions
1	Right	Correct	Correct	Correct	Correct
2	Left	Correct	Correct	Correct	Correct
3	Left	Correct	Correct	Correct	Correct
4	Right	Correct	Correct	Correct	Correct
5	Left	Correct	Medially sectioned	Correct	Correct
6	Left	Correct	Correct	Correct	Correct
7	Right	Correct	Laterally sectioned	Correct	Correct
8	Right	Correct	Correct	Correct	Correct
9	Left	Correct	Medially sectioned	Correct	Correct
10	Right	Correct	Correct	Correct	Correct
11	Left	Correct	Correct	Correct	Medially sectioned

Table 2 T-test for paired samples t-test comparing measurements after osteotomy and cadaveric tenotomy

Paired Samples T-Test

								95% CI for Cohen's d	
Measure 1		**Measure 2**	**t**	**df**	***p***	**Cohen's d**	**SE Cohen's d**	**Lower**	**Upper**
Pre-surgical	-	Osteotomy	5.30	10	< .001	1.60	0.38	0.67	2.49
Pre-surgical	-	Tenotomy	7.03	10	< .001	2.12	0.42	1.02	3.19
Osteotomy	-	Tenotomy[a]	22.50	10	0.57	0.25	0.38	-0.48	0.78

For the Student t-test, effect size is given by Cohen's d

[a] For the Wilcoxon test, effect size is given by the matched rank biserial correlation

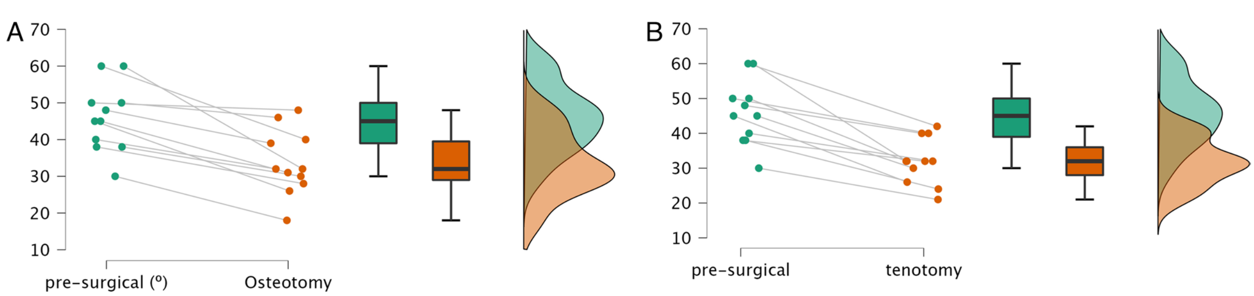

Fig. 4 Comparison of scores between the measures. **A** Pre-surgical and Osteotomy. **B** Pre-surgical and tenotomy

there are no significant differences between measurement 2 (osteotomy) and measurement 3 (tenotomy).

When measuring plantar flexion, an average reduction of 12.18 degrees in hyperextension of the big toe was achieved after performing the osteotomies. This reduction increased by an additional 1.73 degrees following the zigzag tenotomy as a complementary technique.

Discussion

The zigzag tenotomy technique of the EHL tendon through minimally invasive surgery, presented in this study, represents a significant advancement in the surgical treatment of forefoot deformities, such as HAV. This technique has been designed with the aim of addressing the hyperextension of the EHL tendon, a condition that is closely related to the onset and progression of HAV. This technique will complement the increasingly popular percutaneous surgery techniques for HAV [27–30].

This technique involves performing the intervention through a minimal incision of 1–3 mm, foregoing direct visualization of underlying structures. Instead, the podiatrist is guided through intraoperative fluoroscopy and relies on their sense of touch, using a scalpel for delicate soft tissue dissection and a rotating burr on bony parts [30].

The authors suggest that by performing multiple partial zigzag cuts along the tendon, it is possible to increase its length to correct the deformity and improve foot functionality, an approach that has already been proposed by other researchers in relation to rebalancing the forces between the extensor and flexor muscles [13]. In this way, the EHL, which assumes an adductive function in cases of moderate or severe HAV, would return to its natural function as an extensor.

The use of cadaver specimens in the study provides a controlled environment to evaluate the efficacy and safety of this technique. The authors highlight that, after performing the zigzag tenotomy, the surrounding anatomical structures, such as the dorsal nerves, blood vessels, and joint capsule, were adequately preserved in most cases. This suggests that the technique is safe and does not compromise the important structures of the foot, which is essential to avoid postoperative complications [31–33]. The high preservation rate of these structures (100% for the dorsal nerves and vessels, 72.72% for the joint capsule) indicates that this technique minimizes the risks of collateral damage during the procedure, reinforcing its viability as a surgical option.

Despite these encouraging results, it is important to recognize the inherent limitations of the research. The use of cadaveric feet, while useful for evaluating the technique in a controlled environment, does not fully reflect the clinical reality in living patients. The tissue response and healing processes that occur in a real patient cannot be replicated in cadaveric specimens, limiting the extrapolation of the results to clinical practice. Additionally, the sample size (11 cadaveric feet) is relatively small, reducing the statistical power of the study. Therefore, future studies with a larger number of participants, ideally in a clinical setting with living patients, would be beneficial to confirm these preliminary findings and explore the long-term impact of the tenotomy, including functional gait evaluations, radiological assessments, pain levels, and quality of life [18, 34].

This technique improves plantar motion while preserving anatomical structures, making it an effective adjunct to surgical treatment of AVH. Clinical indications for performing this procedure in conjunction with osteotomies include patients with chronic hyperextension of the EHL tendon, which contributes to deformity in moderate to severe cases of HAV. It is especially useful when muscle imbalance and EHL tendon retraction lead to hallux valgus deviation, which worsens the condition and impairs foot function. In addition, it is indicated for patients whose previous surgical procedures have failed to correct the deformity. Zigzag tenotomy is performed to lengthen the tendon without compromising vital anatomic structures, making it a viable option in minimally invasive surgeries for moderate to severe HAV. This innovative approach could significantly improve surgical outcomes and increase patients' quality of life.

Conclusion

Our research demonstrates the effectiveness and safety of elongating the extensor hallucis longus of the hallux through minimally invasive surgery.

Tendon elongation through the zigzag technique could be considered a minimally invasive treatment option for addressing tendon hyperextension in patients with Hallux Abductus Valgus.

Abbreviations

EHL Extensor hallucis longus
HAV Hallux Abductus Valgus
MIS Minimally Invasive Surgery
SD Standard deviation
ES Effect size

Authors' contributions

Conceptualization, SSV and JFT; Data curation, JFT, S-SV; Formal analysis, LGR and JF-T; Investigation, SSV, NGE, LGR, CVG and JFT; Methodology, JFT and SSV; Supervision, JFT AND LGR; Validation, SSV, ENG and JFT; Writing – original draft, SSV; Writing – review & editing, SSV, ENG, LGR, CVG, NGE and JF-T.

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Availability of data and materials
The data sets used and/or analyzed during the present study are available upon request from the corresponding author, although they are all included in this article.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of the Catholic University of Valencia (Valencia, Valencian Community, Spain), approval number UCV/2022–2023/035. It's affirmed that we have successfully secured all requisite permits for conducting experiments involving human subjects, inclusive of the utilization of tissue samples. This research also complies with the guidelines and general principles included in the code of ethics of the General Council of the Spanish Association of Podiatrists, amended in 2018 (Código Deontológico | Consejo General de Colegios Oficiales de Podólogos (CGCOP). It also complies with Spanish Data Protection Legislation (L.O3/2018 of 5 December).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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