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Research Article

Reliability of Ultrasound-Based Measurement of Flexor Hallucis Longus Tendon Excursion in Asymptomatic and Symptomatic Adults: A Comparison Study

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Abstract

Purpose: To develop a reliable ultrasound method for measuring flexor hallucis longus (FHL) tendon excursion in adults.

Materials and Methods: This cross-sectional study evaluated the reliability of the ultrasound-based measurement of FHL tendon excursion in 37 adults. A total of 444 ultrasound measurements were performed on 17 females and 20 males with 11 asymptomatic and 26 symptomatic individuals. Each participant had their FHL tendon excursion measured three times by two experienced musculoskeletal sonographers. Inter- and intra-observer reliability was assessed using the intraclass correlation coefficient (ICC).

Results: The ICC shows excellent reliability of ultrasound-based measurement of FHL tendon excursion in asymptomatic and symptomatic adults with the intra-rater ICC of the two sonographers equalling 0.990 and 0.992 respectively and the inter-rate reliability showing an ICC of 0.942 in the measurement of the FHL tendon in both symptomatic and asymptomatic Adults.

Conclusion: Ultrasound-based measurement of FHL tendon excursion is an excellent and reliable method for assessing FHL tendon excursion in both asymptomatic and symptomatic adults. The FHL tendon excursion is significantly greater (6.60 mm) in asymptomatic adults compared to those with symptoms (4.82 mm). This can help in enhancing the diagnosis and treatment of foot and ankle conditions.

Keywords: Flexor Hallucis Longus Excursion; Sonographic Tendon Excursion; Muscle Kinematics in Ultrasound; Sonographic Flexor Hallucis Longus Displacement; Sonographic Measurement of Flexor Hallucis Longus Normal Movement

Introduction

Although a functional hallux limitus (FnHL) is a well-described entity in the literature, little is known about its cause [1-4]. The entrapment of the flexor hallucis longus (FHL) proximally at the fibro-osseous tunnel causes a painful and restricted movement of the first MTP joint, due to increased intraarticular compression generated at the joint. This results in a functional hallux limitus; the first MTP joint is limited to less than 40° during the second half of the single-support phase of gait, although there is a passive range of motion of 50° or more [1,2,5-9]. The myotendinous junction of the FHL resides just above the fibro-osseous tunnel at the posteromedial side of the ankle.

Symptoms of FHL dysfunction are diverse. A reduced movement of the FHL tendon derails a normal gait pattern [1,10], it can lead to a painful first MTP joint, pain around the tendon, and inability to push off but also complaints of heel pain, caused by the lack of push-off and increased heel landing. It can also constitute a sagittal plane blockade during gait leading to disrupted mechanical support and stability mechanisms of the foot [1].

Diagnosis of FnHL is a combination of complaints and physical examination. Until now, no straightforward diagnostic tool to measure the FnHL has been available.

The current literature does not clarify the normal extent of FHL tendon excursion required for maximal dorsal flexion of the first metatarsophalangeal (MTP) joint. Therefore, knowledge of the normal excursion of the FHL tendon is critical to better understanding FHL pathology.

We hypothesized that the excursion of the flexor hallucis longus (FHL) tendon could be accurately and reproducibly measured using ultrasound. To test this hypothesis, we conducted this cross-sectional study to compare the FHL tendon excursion in both asymptomatic and symptomatic adults. We anticipated that the FHL tendon excursion would be significantly greater in asymptomatic adults than in symptomatic adults, suggesting that a decrease in FHL tendon excursion may be a potential marker of FHL pathology. This study aimed to refine the accuracy and reliability of FHL tendon excursion ultrasound measurements, thereby enhancing the diagnosis and treatment of foot and ankle conditions.

There are several challenges to accurately and reliably measure the excursion of the fibrillar FHL tendon sonographically

- The fibrils of the FHL tendon are twisted, and a measuring point of reference will disappear out of view from the image as soon as the tendon is tensed.
- Measuring in the muscle belly is not reliable because the muscle cells are contractile, which can create the illusion of an excursion that may or may not be present.
- The movement in millimetres at the top of the FHL tendon may be more or less than the movement at the bottom of the same tendon.
- The excursion of the tendon may vary along its length.

We hypothesize that the challenges of measuring the excursion of a fibrillar tendon can be overcome by using manual speckle-tracking imaging in the myotendinous junction.

Materials and Methods

Ultrasound images of the flexor hallucis longus tendon (FHL) were acquired using an ultrasound system type: Arietta Prologue (Hitachi Aloka Medical 6-22-1, Mure, Mitaka-shi, Tokyo, 181-8622, Japan), set to a depth of 20 mm with a 12-18 MHz linear array transducer with compound imaging.

Participants

All participants voluntarily participated in the study and signed an informed consent form. The study population included 37 individuals (17 females and 20 males), with an average age of 44.59 years (SD = 12.90 (Figure 1). The study excluded participants with foot or ankle conditions that could affect the FHL tendon excursion.

Participants were divided into two groups

- **Asymptomatic group:** 11 participants with no history of foot or ankle pain or limitation of great toe range of motion.
- **Symptomatic group:** 26 participants with a history of foot or ankle pain or limitation of great toe range of motion.

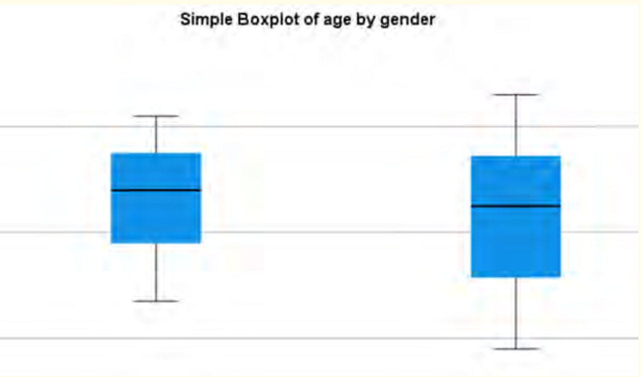

Figure 1: Graphic of the total group participants divided into female and male participants, The line in the middle is the median. The upper part is the upper quartile (Q3) and the lower part is the second quartile(q1). The whisker shows the minimum and maximum.

Exclusion criteria

To ensure that participants had no underlying conditions that could influence the measurement of normal FHL tendon excursion, we administered a brief questionnaire to screen for potential confounding factors. Participants who responded "Yes" to any of the following questions would not be included in the group of "asymptomatic participants".

- Do you have pinch calluses at the IP joint? [4,11-15].
- Do you have swelling in the first MTPJ? [4,16,17].
- Have you had any foot or ankle pain in the past year? [4].
- Have you ever had heel spur (longer than four weeks)? [18].
- Have you ever had medial tibial pain (longer than four weeks)? [19,20].
- Do you have any pain in your big toe? [17].
- Do you have any cramping (in one or both legs)? [2,6].

Procedure

Participants were given a brief description of the purpose of the research and the testing procedures during the initial contact; informed consent was obtained from all who participated in the study.

After giving informed consent, the ultrasound measurements were performed by two MSK sonographers-podiatrists trained in appropriate measures of speckle tracking imaging of the FHL tendon.

Specific steps

- Both participants' feet were examined by the same sonographer three times using *in vivo* manual ultrasound speckle-tracking imaging (SPI) to measure the longitudinal excursion of the FHL tendon (Figure 2).
- To perform the measurements in weight-bearing we used a custom-made standing platform where the participant stood with their knees fully extended and their hallux on an integrated separate hallux platform (Figure 3).
- The participant was asked to passively extend their hallux to a 70-degree upward position by tilting the hallux platform upwards using a wire.
- The operator manually tracked the movement of a speckle point on the FHL myotendinous junction using the SPI software.
- The distance from the initial position to the final position of the speckle point was measured, corresponding to the maximum dorsiflexion of the big toe. This measurement was repeated three times and the average value was calculated.
- The dorsiflexion of the hallux was measured using a goniometer in the hallux platform, with the foot positioned so that the hallux was dorsiflexed to the full range of motion of the hallux platform, which is at a 70-degree angle to the ground (Figure 3).
- Both researchers performed the measurements on the left and right foot of each participant three times on the same day.

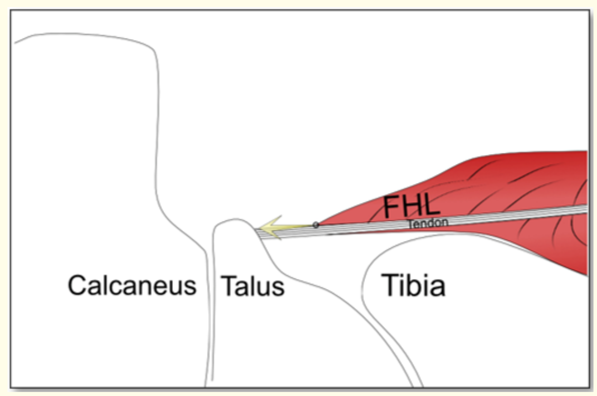

Figure 2: Excursion of the FHL measure point in the musculoskeletal junction at the level of the talocrural joint.

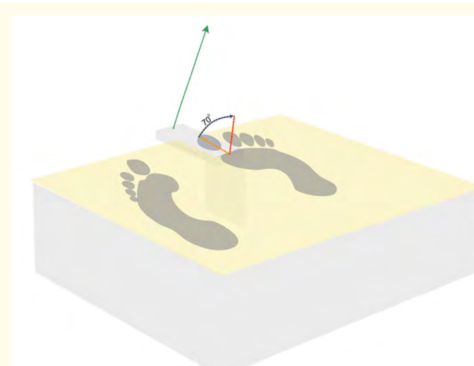

Figure 3: Footplate with hallux platform using mechanical dorsiflexion until the maximum ankle dorsiflexion of 70 degrees of the big toe.

Statistics

The primary outcome of this cross-sectional study is the intra-class correlation coefficient (ICC) for the FHL tendon excursion measurement. The ICC is a measure of the agreement between two or more raters. The ICC rule of thumb is that based on the 95% confidence interval of the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively [21]. The secondary outcome of this study is to know if the mean of asymptomatic adults is significantly greater than symptomatic adults.

Statistical analysis methodology

The data were analysed using the ICC 2-way mixed model and absolute agreement for the intra- and inter-rater reliability test. An independent sample t-test was used to measure if the FHL tendon excursion of the asymptomatic adults was significantly greater than symptomatic adults and a correlation coefficient was used to examine the relationships between the measured FHL tendon excursion and age and the measured FHL tendon excursion and symptomatic adults.

Three (ICC) analyses were conducted. Two of these assessed the intra-rater reliability of the two sonographers, while the third evaluated the inter-rater reliability by averaging the measurements taken by both sonographers when measuring the FHL tendon excursion in asymptomatic and symptomatic adults.

An independent sample t-test was used to determine whether the FHL tendon excursion of asymptomatic adults is significantly greater than that of symptomatic adults, with a significance level of 5%. This statistical test compared the mean values of two independent groups.

To draw further insight, an additional analysis was conducted to explore the potential association between FHL tendon excursion, age, and symptom status (asymptomatic/symptomatic).

The results of the data analysis were employed to assess the reliability and reproducibility of ultrasound measurements of the FHL tendon excursion, potentially leading to improved diagnostic accuracy and treatment efficacy for various foot and ankle conditions.

Descriptive statistics

The two sonographers measured the FHL tendon at different times, the first sonographer is represented with PS and the second sonographer was represented with RW. The Measurements of the first sonographer are PS Measurement 1(M = 5.57, $SD = 2.19$), PS Measurement 2(M = 5.57, $SD = 2.28$), and PS Measurement 3(M = 5.65, $SD = 2.19$) which show the average of measuring the same patient for three different times.

The Measurement of the second sonographer is RW Measurement 1(M = 5.57, $SD = 2.19$), RW Measurement 2(M = 5.57, $SD = 2.28$), and RW Measurement 3(M = 5.65, $SD = 2.19$) which show the average of measuring the same patient for three different times.

The average of the three measurements taken by the first sonographer was M = 5.597mm (SD = 2.20 mm) while the average of the three measurements taken by the second sonographer was M = 5.102 mm (SD = 2.64). The table of these measurements is shown in table 1.

Descriptive Statistics							
	N	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
PS Measurement result 1	74	.0	10.9	5.570	.2550	2.1932	4.810
PS Measurement result 2	74	.0	11.7	5.570	.2651	2.2807	5.202
PS Measurement result 3	74	.0	10.6	5.650	.2550	2.1938	4.813
PS average	74	.0	11.1	5.597	.2559	2.2018	4.848
RW Measurement result 1	74	-.4	11.1	5.104	.3025	2.6020	6.771

RW Measurement result 2	74	-1.0	12.2	5.065	.3083	2.6521	7.034
RW Measurement result 3	74	-1.4	11.3	5.137	.3188	2.7426	7.522
RW average	74	-.9	11.5	5.102	.3074	2.6441	6.991
Valid N (listwise)	74						

Table 1: Descriptive analysis of the Measurements of each Sonographer.

Intra-rater result

The Intra-rater reliability ICC was conducted for the two sonographers who measured the excursion of the flexor hallucis longus (FHL) tendon at the posteromedial ankle during passive tendon gliding exercises. The ICC report is given below for both sonographers, PS (1) and RW (2). The results show an excellent interrater reliability of ultrasound-based measurement of FHL tendon excursion in both the asymptomatic and symptomatic adults for the two sonographers.

Statistical report

An Excellent degree of reliability was found in the three measurements of the FHL tendon performed by the PS researcher with an average ICC of 0.990, demonstrating excellent agreement. The confidence interval for ICC was 0.986 to 0.994, ($F(73,146)= 103.376$, $p<.001$), indicating a high degree of consistency in the measurements. This result was calculated using IBM SPSS statistical package version 27 based on three measurements with absolute agreement and a 2-way mixed-effects model. The detailed results are shown in table 2.

PS Intra-rater Correlation Coefficient							
	Intraclass	95% Confidence Interval		F Test with True Value 0			
	Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.971[a]	.958	.981	103.379	73	146	<.001
Average Measures	.990[c]	.986	.994	103.376	73	146	<.001

Table 2: PS Intra-rater correlation coefficient of the first sonographer.`

Two-way mixed effects model where people effects are random and measures effects are fixed.

[a] The estimator is the same, whether the interaction effect is present or not.

[b] Type A intraclass correlation coefficients using an absolute agreement definition.

[c] This estimate is computed assuming the interaction effect is absent because it is not estimable otherwise.

An excellent degree of reliability was found in the three measurements of the FHL tendon performed by the RW researcher with an average ICC of 0.992, demonstrating excellent agreement.

The confidence interval for ICC was 0.988 to 0.994 ($F(73,146)= 119.256$, $p < .001$), indicating a high degree of consistency in the measurements. This result was calculated using IBM SPSS statistical package version 27 based on three measurements with absolute agreement and a 2-way mixed-effects model. The detailed results are shown in table 3.

RW Intra-rater Correlation Coefficient							
	Intraclass	95% Confidence Interval		F Test with True Value 0			
	Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.975[a]	.964	.984	119.256	73	146	<.001
average Measures	.992[c]	.988	.994	119.256	73	146	<.001

Table 3: RW Intra-rater correlation coefficient of the second sonographer.

Two-way mixed effects model where people effects are random and measures effects are fixed.

[a] The estimator is the same, whether the interaction effect is present or not.

[b] Type A intraclass correlation coefficients using an absolute agreement definition.

[c] This estimate is computed assuming the interaction effect is absent because it is not estimable otherwise.

Inter-rater result

An excellent level of inter-rater reliability for ultrasound-based measurement of FHL tendon excursion was demonstrated in both asymptomatic and symptomatic adults. The intraclass correlation coefficients (ICCs) for both sonographers, PS (1) and RW (2) were found to be high, indicating consistency in their measurements of FHL tendon excursion. The detailed ICC results are presented below.

Statistical result

An excellent level of reliability was established in the three measurements of the FHL tendon performed by the RW researcher whose average ICC was 0.942, indicating strong agreement between the measurements. The 95% confidence interval for ICC ranged from 0.883 to 0.968 ($F(73,73)= 20.453$, $p < .001$), further demonstrating the consistency of the measurements. This result was obtained using IBM SPSS statistical package version 27 based on the average of each sonographer's measurement ($k = 3$) with absolute agreement and a 2-way mixed-effects model. The detailed results are provided in table 4.

Inter-rater Correlation Coefficient							
	Intraclass	95% Confidence Interval		F Test with True Value 0			
	Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.889[a]	.790	.938	20.453	73	73	<.001
average Measures	.942[c]	.883	.938	20.453	73	73	<.001

Table 4: Inter-rater correlation coefficient of the two sonographers.

Two-way mixed effects model where people effects are random and measures effects are fixed.

[a] The estimator is the same, whether the interaction effect is present or not.

[b] Type A intraclass correlation coefficients using an absolute agreement definition.

[c] This estimate is computed assuming the interaction effect is absent because it is not estimable otherwise.

Larger FHL Tendon Excursion in Asymptomatic Individuals Compared to Symptomatic Individuals

Our statistical analysis revealed that the FHL tendon Excursion in Asymptomatic adults is greater than in symptomatic adults. These findings pave the way for further research, clinical implications, and potential therapeutic interventions targeting FHL function to elucidate the underlying mechanisms of this disparity.

Statistics report

- **H_0:** There is no significant difference in FHL tendon excursion between asymptomatic and symptomatic adults.
- **H_a:** FHL tendon excursion is significantly greater in asymptomatic adults compared to symptomatic adults

A one-tailed t-test revealed a statistically significant difference in FHL tendon excursion between asymptomatic and symptomatic adults. The mean excursion was 6.60 mm in asymptomatic adults (SD = 2.62 mm, N = 44) and 4.82 mm in symptomatic adults (SD = 2.16 mm, N = 104). This difference was statistically significant at a 5% significance level ($t(146) = 4.291$, $p = 0.00$), as depicted in table 5 and table 6.

Group Statistics					
	FnHL Y/N	N	Mean	Std. Deviation	Std. Error Mean
Average	ASYMPTOMATIC	44	6.599	2.6234	.3955
	SYMPTOMATIC	104	4.821	2.1577	.2116

Table 5: Descriptive statistics of the Asymptomatic and Symptomatic groups.

Independent Samples Test										
F		Levene's Test for Equality of Variances					t-test for Equality of Means		95% Confidence Interval of the Difference	
		Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper	
average	Equal variances assumed	.058	.811	4.291	146	<.001	1.7786	.4145	.9595	2.5978
	Equal variances not assumed			3.965	68.781	<.001	1.7786	.4485	.8838	2.6735

Table 6: Independent statistical result.

Additional Analysis

To further explore the relationship between FHL tendon excursion, age, and symptomatology, a correlation analysis was conducted. A weak positive correlation was found between FHL tendon excursion and age ($r(148) = 0.331$, $p = 0.00$), suggesting that FHL tendon excursion tends to increase with age.

Additionally, a weak negative correlation was identified between FHL tendon excursion and symptomatology ($r(148) = -0.335$, $p = 0.00$), implying that FHL tendon excursion tends to be lower in symptomatic individuals. This can be seen in table 7.

Correlations					
		Avarage	FnHL	Age	Shoe size
Avarage	Pearson Correlation	--			
	N	148			
FnHL	Pearson Correlation	-.335**	--		
	Sig. (2-tailed)	<. 001			
	N	148	148		
Age	Pearson Correlation	.332**	-.453**		
	Sig. (2-tailed)	<.001	<.001		
	N	148	148	148	
Shoe size	Pearson Correlation	.085	-.079	-.190*	
	Sig. (2-tailed)	.303	.341	.021	
	N	148	148	148	148

Table 7: Correlation coefficient.

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Results

In this cross-sectional study we investigated the reliability of ultrasound-measured FHL tendon excursion and its potential link to hallux dorsiflexion limitations using a total of 444 measurements on 74 feet of 37 participants.

Key findings

- **Significant difference in tendon excursion:** Asymptomatic individuals exhibited a larger mean tendon excursion of 6.60 mm (SD 2.62 mm) compared to 4.82 mm (SD 2.16 mm) in those with symptoms, suggesting a potential role of FHL in hallux dorsiflexion. This difference reached statistical significance ($t = 4.29$, $p < 0.001$).
- **Overlap between groups:** Despite the statistical difference, considerable overlap existed in excursion values between symptomatic and asymptomatic groups (Figure 4), indicating FHL excursion alone cannot definitively predict hallux dorsiflexion limitations.
- **Reliable measurement technique:** The study confirmed good inter-rater reliability of the ultrasound manual speckle tracking measurement technique, supporting its accuracy as a diagnostic tool for understanding FHL pathology.
- **FHL contribution and threshold:** While the FHL tendon excursion may contribute to restricted hallux dorsiflexion, our findings suggest a threshold of at least 4 mm in asymptomatic individuals and potentially below 4 mm in symptomatic individuals with functional limitations. This indicates a potential role of FHL pathology in causing complaints when excursion falls below this threshold.
- **Further considerations:** The movement of the subtalar joint and flexibility of the Lisfranc joint also play crucial roles in hallux dorsiflexion. In healthy individuals, hallux dorsiflexion typically involves subtalar joint inversion and medial arch elevation. When these mechanisms are compromised, even FHL excursions above 4 mm might lead to complaints. Future research should investigate these contributing factors for a more comprehensive understanding of functional hallux limitations.

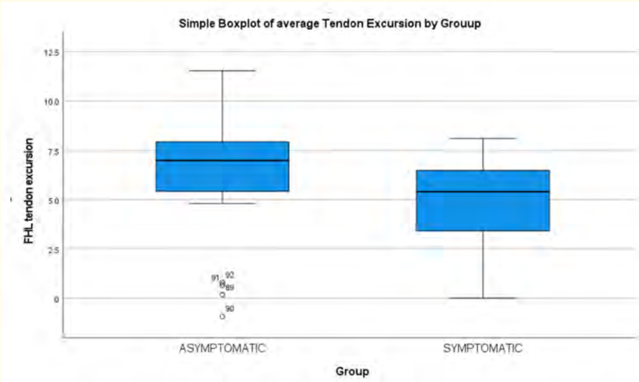

Figure 4: Boxplot with measurements of the FHL excursion in symptomatic and asymptomatic groups makes the overlap visible.

Discussion

FHL Tendon Excursion Measurement Limitations

The results of this study demonstrate that manual speckle tracking can be used to reliably and accurately measure the excursion of the flexor hallucis longus (FHL) tendon at the talocrural joint. However, there are some limitations to this technique that should be considered, including

- The mobility of the subtalar joint and the degree of supination or pronation of the foot during measurement;
- Maintaining the correct position of the ankle during an ultrasound adds to this challenge;
- Hypertrophy of the FHL musculotendinous tissue and additional tendinous or doubled tendon structures, and posttraumatic scarification [22].
- The flexibility of the collagen matrix and/or micro-damage to the fibres are responsible for changes in tendon excursion [23,24].
- The excursion of the tendon may vary along its length.

Relevance of sonographic FHL tendon excursion measurement

Despite the limitations noted above, sonographic measurement of FHL tendon excursion can be a crucial tool for clinicians evaluating patients with symptoms such as hip, knee, and lower back pain[1]. Detecting a limitation of movement challenges the sonographer to further characterize the possible causes, which include

- Tendon excursion inhibition due to adhesions of fibroblasts from the paratenon [25,26].
- A tendinous cause for a posterior impingement in the ankle [27].
- Calcifications due to damaged or necrotic tissue [28].
- Diffuse calcification (generally metastatic) like phosphate (increased calcium-phosphate product) and other ions [28].
- Tendon sheath cyst located on the course of the FHL tendon sheath [26].
- Anatomical variants of the FHL like an accessory FHL [26].
- Anomalous osseous structure disturbing the course of the FHL (like a firm prominence of an os trigonum/ Stieda process) [26].
- Localized swelling of a cystic mass (soft and movable) suggesting the presence of a pseudocyst [29].
- Partial tear of the central fibres of the FHL [29-31].
- Tenosynovitis of the FHL [29,32].
- Nodular thickening of the tendon may lock or restrict extension or flexion of the hallux proximal or distal to the fibro-osseous tarsal tunnel [29,33,34].

In conclusion, while FHL tendon excursion measurement using ultrasound has limitations, it remains a valuable tool for musculoskeletal sonographers to assess tendon function, identify potential pathologies, and guide treatment decisions. Further research is warranted to refine the technique and improve its discriminatory ability for diagnosing FHL dysfunction.

Additional thoughts

Exploring the practicality of employing speckle tracking for measuring the FHL tendon's excursion in alternative positions warrants interest. This includes scenarios where the patient is lying supine or when the subtalar joint is oriented differently.

Some experts [35] have suggested that it must be possible to calculate the movement trajectory 'A1' in Figure 5 of the flexor hallucis longus in millimetres, assuming all joints remain stationary during the movement, except for the MTP-I joint [36].

However, this assumption is complicated because the MTP-I joint has multiple instantaneous centres of rotation in the sagittal plane. These centres of rotation (1,2,3,4,5 and 6) move throughout the movement, except at the limit of dorsal extension, where compression occurs. As a result, dorsal extension in the MTP-I joint is a combined movement [37]. This is a complicating factor for calculating the movement trajectory of the flexor hallucis longus, as it means that the joint does not move as a single unit. Instead, it moves in a series of smaller, more complex movements.

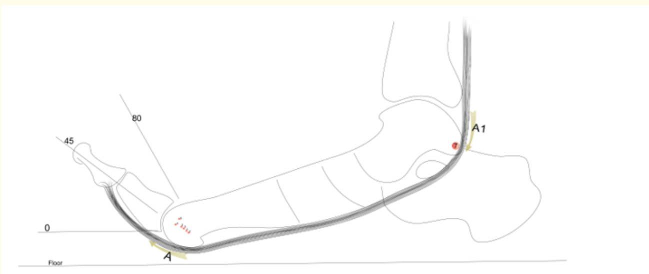

Figure 5: Movement trajectory of the flexor hallucis longus tendon in A and A1.

In summary, the trajectory of movement can be estimated using a formula based on several assumptions:

- Movement is confined to the MTP1 joint.
- The distal head of the first metatarsal is round.
- The tendon is inelastic.

The calculation for the tendon's excursion when the toe is at an 80-degree angle uses the formula (2πR/360) * degrees of toe movement, with R being the radius of the first MTP head. Given a 60-degree movement over the MTP-I joint and a metatarsal head radius of 11 mm, the tendon's excursion is calculated to be 11.52 mm. While these assumptions are acceptable for research, it's important to recognize that the formula provides only an estimated movement trajectory and actual motion may vary with individual anatomical and joint movement differences.

In a previous study, Michelson., *et al.* [38]. presented a semi-quantitative technique to assess the FHL excursion using a footplate and a series of mechanical wedges. They found that ankle dorsiflexion decreased with progressive hallux dorsiflexion increase, but they did not report a reference value for 'normal' FHL excursion in millimetres. This is a limitation of their study, making comparing results between different studies difficult.

Conclusion

This cross-sectional study investigated the potential of ultrasound-measured FHL tendon excursion for understanding hallux dorsiflexion limitations.

Key Findings

- **Ultrasound reliability:** The study confirmed the reliability of ultrasound manual speckle tracking for measuring FHL excursion, supporting its use as a diagnostic tool.
- **FHL excursion and symptoms:** Asymptomatic individuals exhibited significantly larger FHL excursions (6.60 mm) compared to those with symptoms (4.82 mm), suggesting a potential role of FHL pathology in limited dorsiflexion.
- **Threshold for concern:** However, considerable overlap existed between groups, indicating FHL excursion alone cannot definitively predict limitations. Our findings suggest a potential threshold of at least 4 mm for asymptomatic individuals, with lower values in symptomatic individuals potentially indicating FHL involvement in complaints.
- **Multifactorial limitations:** The study emphasizes the importance of considering other contributing factors like subtalar joint mobility and Lisfranc joint flexibility. Future research should investigate these factors for a more comprehensive understanding of functional hallux limitations.

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