Positional and Dimensional Relation of Tendons Around the First Metatarsal Bone with Hallux Valgus

Zeliha Kurtoğlu Olgunus (zkurtoglu@yahoo.com)
Mersin University
Fatih Çiçek
Niğde Ömer Halisdemir University
Turan Koç
Mersin University

Research Article

Keywords: hallux valgus, tendon, extensor hallucis longus, abductor hallucis, flexor hallucis longus, biomechanics

Posted Date: July 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1826543/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Surgical and Radiologic Anatomy on December 29th, 2022. See the published version at https://doi.org/10.1007/s00276-022-03066-8.

Abstract

It was aimed to reveal whether the positions and dimensions of the extrinsic and intrinsic muscle tendons related to the hallux around the first metatarsal bone are affected by the severity of hallux valgus (HV) and whether tendon positional changes and tendon sizes affect each other.

In formalin-fixed 46 feet, three HV angle subgroups (normal, mild and moderate/severe) were defined. Width, thickness and cross sectional area (CSA) of tendons of the extensor hallucis longus (EHL) and brevis (EHB), abductor hallucis (AH) and flexor hallucis longus (FHL) were measured. On the clock model created in coronal plane, positional variations of each tendon were indicated. In the moderate-severe HV group, thickness and CSA of the EHB, width and CSA of the AH were smaller, compared to mild HV. Width and CSA of the FHL were smaller in moderate/severe HV than in the normal. Regardless of HV, the width and CSA of the FHL was greater in cases where the FHL located more lateral, and the width of both FHL and AT were greater in cases where AH located more plantar.

The smaller tendon size of two intrinsic (one plantar and one dorsal) and one extrinsic muscle in the moderate/severe HV group indicates that the changes reflected in the tendons are more pronounced in the case of high HV severity, and the changes are not limited to the tendons on just one side of the foot. The possible biomechanical effects of AH, FHL and EHB tendon dimensional weakness may be important when planning surgery for moderate/severe HV cases.

Introduction

Hallux valgus deformity (HV) is a progressive clinical problem characterized by lateral deviation of the hallux and medial deviation of the first metatarsal bone (MTB), affecting 2–4% of the population, and more common in individuals over 65 years of age and in women. [13, 23, 52, 54]. Usually, the deformity is diagnosed by radiography, and when the angle between the longitudinal axes passing through the MTB and the proximal phalanx is greater than 15 degrees [10, 27, 55]. It is well known that the development of HV is associated with genetic predisposition, gender, and shoe use. In addition, some specific anatomical and biomechanical factors such as variations in the relevant bones (such as long MTB, round articular surface, metatarsus primus varus) or weakness in the medial capsule and ligament of the first metatarsophalangeal joint (MTPJ) or impaired balance between the muscles around the joint were also held responsible for the initiation and progression of this deformity [9–11, 13, 47, 52–54, 57, 60].

When explaining the mechanism of HV, the inadequacy of the medial structures is considered essential for the development of deformity [11, 54]. The positions of the insertions of AH and adductor hallucis tendons, which are located in the plantar-medial and plantar-lateral aspects of the MTPJ, respectively, changes as the hallux valgus deformity increases [10]. When the phalanx deviates laterally and pronates, the adductor hallucis muscle that attaches to the plantar-lateral part of the base of the proximal phalanx and lateral sesamoid becomes a deforming force for the joint. As the insertion of AH, which is expected to strongly resist the valgus of the proximal phalanx and support the medial capsule of the joint in a normal individual, is displaced plantar, the resistance function of this muscle against valgus becomes less efficient [11, 54, 60]. The placement of the EHL, EHB and FHL tendons relative to the axes of MTPJ shifts laterally as a result of the lateral deviation of the hallux, and it is suggested that this new course of the tendons may increase the severity of the deformity [9, 12, 34, 46]. Although associating these anatomical changes with the degree of radiographic deformity may be important in surgical planning [9], the literature on morphometric definitions and analysis of positional changes in tendons is quite limited.

In pathologies that require the reorganization of muscle balances in the feet, weakening of some muscles and hypertrophy of others are considered as examples of adaptation [59, 61]. USG and electromyography studies in cases with HV showed that some intrinsic foot muscles differ from normal cases in terms of in size (CSA, thickness, width) [1, 41, 44, 46, 59], quality (fat infiltration, distribution of muscle fiber types, etc.) [28, 59] and function [3, 28]. These muscle changes of HV, which is more common in advanced ages, were also be associated with old age. Therefore, it is not clear whether this deformity is occur as a product of aging-related muscle weakness, or whether muscle weakness develops due to the deformity [47, 59]. On the other hand, it is also known that the reflection of the changes in the dimensions of the muscle belly to the morphometrical and biomechanical properties of its tendon includes variabilities and uncertainties according to concomitant factors such as age, duration of disuse or overuse, innervation pathologies etc. [7, 29, 36, 37, 49, 50, 62].

Extrinsic muscles, which have much greater mass than the intrinsic foot muscles are accepted as important determinants of foot function [14]. One of the extrinsic muscles, the flexor hallucis longus (FHL), is the multi-articular flexor of the hallux, and it has been shown that the isometric function of this muscle plays a role in the redistribution of force from the hind foot to the front, significantly affecting the ground contact strength of the hallux and the pressure under the forefoot [21, 35]. The effective pressure to the ground by the toes, which have a large ankle moment arm, is important for the management of ankle balance, and decreased muscle strength may cause instability in the involved joints, thereby, failure in posture and balance [42]. It has been reported that the risk of falling is higher in elderly individuals with HV, probably due to the deterioration of this function [24, 46].

It is stated that extensor hallucis longus (EHL) and brevis (EHB) form a lateral arc in all HV groups, and the FHL tendon is deviated to the plantar-laterally. Since the moment arm of the extensor and flexor muscles is turned laterally, these muscles are stated to increase the lateral angulation of the hallux (bowstring at the MTPJ) and become an adduction force on the hallux. These changes are also associated with the clinical severity of HV [9, 11, 12, 20, 31, 34, 46, 51, 54, 56].

Eustace et al. (1996) showed that the position of the AH tendon shifted smarkedly plantarward in the HV and they porposed that the level of displacement is related to the hallux valgus angle (HVA) and clinical severity of the HV deformity [20]. AH, which is the major force that attaches to the medial sesamoid and proximal phalanx and supports the joint capsule medially, plays an important role in providing 1MTPJ stability through isometric contraction [6, 24, 58, 63]. It is thought that the tendon of AH, which strongly resists the valgus of the proximal phalanx, displaces towards the plantar in the HV and becomes a flexor force instead of an abductor [9, 12, 34, 46, 51, 58, 60]. Arıncı Incel et al (2003), who showed that there is a decrease in both AH and adductor hallucis activity in HV, states that the adductor force may have become more dominant in the abductor-adductor balance due to the loss of antivalgus effect of this tendon displaced towards the plantar [3, 51]. While the directon of the cause-effect relationship between HV and structural and/or functional weakness of the AH muscle is still unclear [47, 59]. According to the first view, as changes in the joint cause the positional change in AH (and perhaps other muscles as well), it becomes dysfunctional in the new location, and then weakens in terms of structure and function. In the second view, the AH has atrophied or weakened due to disuse for any reason, so it cannot resist the pull from the adductor muscles enough, and the abduction-adduction imbalance is occur. Then, the proximal phalanx deviates laterally and HV develops. [3, 46, 59]. It is also possible that both mechanisms interact with each other during the HV process.

It is known that skeletal muscle exhibits plasticity in response to chronic loading or prolonged disuse, and this change can be reflected in the histological and mechanical properties of the muscle or tendon [29, 36, 49, 59, 62]. Hoffmeyer et al. 1988 found the surface electromyographic (EMG) activity and ultrastructural properties of intrinsic muscles in HV to be related to the results of gait analysis and interpreted these changes as a result of chronic ischemia caused by the increase in pressure in the foot [28]. While, it has been suggested that histological (increased fat deposition, collagen infiltration, changes in muscle fiber type distribution, etc.) and electromyographic findings in the AH may be secondary to HV deformity [54, 58].

HV is associated with lower performance on balance and functional tests [43]. It has been reported that hallux plantar flexion and abduction power are decreased in patients with moderate and severe HV [26]. It has been shown that some foot and toe strengthening exercises increase the cross sectional area (CSA) of the AH muscle and the flexor strength of the toe, and reduce the imbalance between AH and adductor hallucis muscles [32, 34, 45]. Strengthening the intrinsic toe muscles in the early period is asserted to reduce the incidence of foot deformities and that it can reduce the severity of the disease [24, 26, 41, 42, 44–46, 58, 59]. On the other hand, it has been stated that the highest activation of the AH muscle occurs with the isolated abduction of the hallux against adductor resistance, but the exercises aimed at strengthening this muscle will be adversely affected by the changing anatomical position of the tendon [32, 58].

The aim of HV surgical treatment is to eliminate the pathological factors causing this deformity and to preserve the biomechanical function of the forefoot. Depending on the severity of deformity, the size of the degenerative changes in the MTPJ, the shape and size of the MTB, and the degree of phalangeal deviation, open or percutaneous/ minimally invasive surgical procedures can be preferred [16, 18]. After foot percutaneous surgical techniques, tendon injuries reported as ranging from 0–5% [17]. For minimally invasive surgical procedures, new anatomical references may be needed that can assist in the three-dimensional orientation and localization of structures that cannot be seen directly [17, 64]. Dalmau-Pastor et al.(2020) defined a 'clock method' that only depict the localization of neurovascular structures in the MTB region by taking the EHL as a reference point [16]. In the present study, a version of this clock method with a similar perspective but a different application has been created in order to provide standardization in defining the positions of tendons.

After the corrective surgical treatment of HV, iatrogenic hallux varus deformity, which is a progressive medial deviation of the hallux, may develop with a frequency of 2–15.4%, as a result of the deterioration of the relationships between bones, tendons and capsuligamentous structures around the first MTP joint. In this deformity, AH and the medial head of flexor hallucis brevis muscle advancing the deformation by migrating medially, EHL stretches and pulls the toe into varus rotation, and FHL may produce significant flexion of the interphalangeal joint, leading to a hammertoe [4, 40]. In the repair of this iatrogenic deformity, partial or total transfer of tendons in the region (EHL, AH, EHB, AT) can be used [4, 8, 39, 40, 65]. The literature evaluating whether there is a structural change due to HV in tendons that are planned to be transferred for this repair is very limited [8].

In this study, tendons that may affect the biomechanical properties of the hallux, which may play a role in the etiology or course of HV, and that can be used in the repair of iatrogenic hallux varus due to HV surgery were examined. It was aimed to reveal whether the positions and sizes of the tendons around the MTB change according to the severity of HV and whether the tendon positional variations are reflected in the tendon sizes.

Material And Method

The study was approved by the Board of Ethics of Mersin

University (approval number: 2021-96), and supported by Mersin University Scientific Research Projects Unit (PN:2021-1-TP2-4313). 10% formalin fixed 46 lower extremities of adult cadavers and amputed lower extremities (aged between 43–84, Mean: 67.73 ± 11.54) (19 females and 27 males, and 20 left 26 right) from the inventory of Anatomy Department Laboratory of Mersin University were included. Feet with diffuse pathology around the big toe, except for HV, and feet that had previously undergone surgery were excluded. Digital caliper with 0.01 mm precision (MARCAL 16 ER, Mahr, Gottingen, Germany) and goniometer set (Lafayetta brand) were used for measurements. All measurements repeated by two different person (FÇ and TK) were analyzed by the interobserver reliability test.

After removal of skin at the dorsal and plantar aspect of the foot, the tendons revealed. The description of the parameters used in the study is given below:

Parameters about the size of feet:

FL: Foot Lenght

MM-CP: Distance from the tip of medial malleol to the coronal plane passing through the point where deep plantar artery returns to the plantar aspect of foot (DPAr)

Parameters about the c*oronal plane passing through the point of DPAr (CP) (*Fig. 1a, 2a*)*:

CP-MTP: Distance from the metatarsophalangeal joint to CP

CP-TMT: Distance from the tarsometatarsal joint to CP

CP-Length: Length of the wire around the determined coronal plane (circumference length of the CP)

Parameters about the size of tendons:

EHL-W, T, CSA: Width, thickness and cross sectional area of extensor hallucis longus tendon at CP level

AT-W, T, CSA: Width, thickness and cross sectional area of the accessory tendon of EHL at CP level

EHB-W, T, CSA: Width, thickness and cross sectional area of extensor hallucis brevis tendon at CP level

AH-W, T, CSA: Width, thickness and cross sectional area of abductor hallucis tendon at CP level

FHL-W, T, CSA: Width, thickness and cross sectional area of flexor hallucis longus tendon at CP level

The width measurements of each tendon were shown in the Fig. 2a-d. CSA was found with the ellipsoid area calculation formula using the width and thickness data of each tendon.

Parameters about the positions of the tendons:

At the CP level;

EHL-EHB: closest distance between the tendons of extensor hallucis longus and extensor hallucis brevis

EHL-AT: closest distance between the tendons of extensor hallucis longus and accessory tendon

EHL-AH: closest distance between the tendons of extensor hallucis longus and abductor hallucis

EHL-FHL: closest distance between the tendons of extensor hallucis longus and flexor hallucis longus

EHL-DPAr: closest distance between the tendon of extensor hallucis longus and DPAr

Determination of Hallux Valgus Angle:

The principle for the radiological HVA measurement [10] was adapted to cadavers; at first, the midpoints of the proximal and distal ends of the first metatarsal bone, and the proximal phalanx were marked with a pin. Then, two straight lines were created by passing a thread from the midpoint pins of each bone. The angle between the two stretched fibers was measured with a goniometer (Fig. 1a).

To describe the placement of tendons in a coronal plane, the clock and 360° circle models of Dalmau-Pastor et al. (2018) was modified. They described the clock pattern in the circle around the MTB on the cross-sectional surface of the foot by cutting 1 cm proximal to the MTPJ (approximately 1.5-2 cm more anteriorly than described in our study) in the coronal plane, and indicated the NCDMm and NFP position according to EHL on this model [15]. Unlike them, the coronal plane was designed by using a wire, without cutting the finger. The wire was inserted from dorsal to plantar at the level of DPAr, bent to wrap the toe medially and its two ends were joined on the medial side to form a ring in the coronal plane. Midpoint of EHL was marked as 12 on the clock model, and 0 on the 360 circle (Fig. 1a-c). The data in the ring of the right foot were transferred to the clock model as a “mirror image”, thus left and right feet could be analyzed together. To adapt the measurements of the closest distance of each structure to the EHL to the clock and circle models, the following simple proportion formulas were used:

Formula for clock model

Hour distance to point 12 = Measurement to EHL (mm) X 12/Length of the wire (mm)

Formula for 360° circle

Degree to “0” point in 360 circle = Measurement to EHL(mm) X 360/Length of the wire (mm)

The location of structures with respect to the mean values are indicated on the clock model and the 360 circle as Figs. 1a, 1b, respectively.

Statistical Analysis

Parameters with a significant difference between feet with and without HV were grouped. The data were found as normally distributed, and Independent-T test was used for comparison of two groups. Additionaly, ANOVA was used to evaluate whether there is a difference among the HVA subgroups (Normal, Mild HV and Moderate-Severe HV) for the parameters. Levene test used for variance homogenity found $p > 0.05$. Accordingly, Tukey test was used for post-hoc evaluation. The correlations of the parameters with each other were analyzed with the Pearson’s correlation test. Statistically significance level was accepted as 0.05 for comparisons and 0.01 for correlations.

The agreement between the measurements of two different observers (FÇ and TK) was evaluated with intraclass correlation coefficient for interobserver using 95% estimated confidence intervals, and high agreement was found between the observers.

Results

a) *General findings*:

Distribution of the cases in terms of HVA subgroups were as; 9 cases Normal (< 15) (6 male, 3 female), 14 cases with Mild HV (between 15 and 20) (9 male, 5 female), 23 cases with Moderate-Severe HV (> 20) (12 male, 11 female). There was no difference between the groups in terms of gender and side distribution by pearson chi-square test ($p = 0.664$, and $p = 0.288$ respectively).

Foot length, distance from medial malleol to CP, length of the wire around the determined coronal plane (CP), distance from the tarsometatarsal joint to CP and distance from the MTPJ to CP have no meaningful correlation with the HVA ($p > 0.05$). While the first three of these parameters, which are related to foot sizes, were significantly smaller in women than in men (p = 0.001), the gender-HVA interaction was not statistically significant (p > 0.05).

Considering the averages of the converted data according to the calculations using the previously mentioned formulas, the locations of the tendons and DPAr are shown on the clock model and on the 360 circle as in Fig. 1a and 1b. The mean distances of the tendons in metric, hour and degree to the EHL, as well as the definition of the ratios of positional variations the clock model are given in Table 1.

Table 1
At the DPAr level, mean distances to the EHL by direct measurement, the mean points at the clock model and the degree on the circle, and the rates of positional variations.

	(mm)*	(Hour)	(Degree in 360 circle)	Location on the clock n (%)	
EHL-EHB	0.89	0.11	3.17	At just 12 o'clock**	26 (57%)
				Between 12 – 1 o'clock	20 (43%)
EHL-DPAr	5.87	0.69	20.66	Between 12 – 1 o'clock	37 (80%)
				Between 1–2 o'clock	9 (20%)
EHL-AH	26.91	8.84	265.16	Between 7–8 o'clock	1 (2%)
				Between 8–9 o'clock	31 (68%)
				Between 9–10 o'clock	14 (30%)
EHL-FHL	46.89	6.50	194.91	Between 5–6 o'clock	4 (9%)
				Between 6–7 o'clock	42 (91%)

(*: Measurement from EHL toward the medial side, **: EHB merges with the EHL at or above the coronal plane).

b) Findings about tendon sizes and their changes according to the HVA groups are as follows:

EHL and FHL width were greater in males than in females (p = 0.017, p = 0.002). But, there was no difference for the other tendons between the gender, and also between the sides (p > 0.05).

According to pearson correlation test, both foot length and distance from medial malleol to CP have correlation with the CSA of the AH (r = 0.682, p = 0.0001 and r = 0.410, p = 0.005) and FHL (r = 0.462, p = 0.001 and r = 0.417, p = 0.004) respectively. Length of the wire around the CP has a correlation with only the CSA of the FHL (r = 0.425, p = 0.003, but not others. There was no meaningful correlation for the CSA of EHL, EHB and AT with those measurements for the foot sizes (p > 0.01).

When analyzed by ANOVA whether tendon size parameters differ according to HVA subgroups, EHB thickness and CSA were found significantly smaller in Moderate/Severe HV than the Mild HV (Ordered as: Mild HV > Normal > Moderate to Severe HV). AH width and CSA were significantly smaller in Moderate/Severe HV than the Mild HV (Ordered as: Mild HV > Normal > Moderate to Severe HV). FHL width and CSA were significantly smaller in Moderate/Severe HV than the Normal (Normal > Mild HV > Moderate to Severe HV) (Table 2).

Table 2
Descriptive statistics of the parameters with only statistically significant difference according to HVA subgroups by ANOVA.

Parameters	Level of HVA	n	Mean	SD	p
EHB-T(mm)	Normal	9	0.99	0.29	**0.035**
	Mild HV	14	1.22*	0.48	
	Moderate-Severe HV	23	0.92*	0.21	
	Total	46	1.02	0.35	
AH-W(mm)	Normal	9	7.28	2.62	**0.032**
	Mild HV	14	8.61	2.74	
	Moderate-Severe HV	23	6.55*	1.62	
	Total	46	7.32*	2.34	
FHL-W(mm)	Normal	9	4.93*	1.15	**0.020**
	Mild HV	14	4.51	1.12	
	Moderate-Severe HV	23	3.94*	0.58	
	Total	46	4.31	0.96	
EHB-CSA(mm^2)	Normal	9	3.02	1.31	**0.008**
	Mild HV	14	4.49*	2.55	
	Moderate-Severe HV	23	2.75*	0.73	
	Total	46	3.33	1.75	
AH- CSA(mm^2)	Normal	9	19.90	10.35	**0.025**
	Mild HV	14	26.08*	10.62	
	Moderate-Severe HV	23	17.36*	7.43	
	Total	46	20.51	9.66	
FHL- CSA(mm^2)	Normal	9	19.99*	8.42	**0.038**
	Mild HV	14	16.97	5.71	
	Moderate-Severe HV	23	14.18*	4.36	
	Total	46	16.17	6.04	
EHL- DPAr (mm)	Normal	9	5.73	2.28	0.015

T: Thicknesss, W: Width, CSA: Cross sectional area, *: The subgroups with meaningful difference.

Parameters	Level of HVA	n	Mean	SD	p
	Mild HV	14	7.45	2.44	
	Moderate-Severe HV	23	4.95	2.48	
	Total	46	5.86	2.62	
EHL- DPAr (Hour to the 12)	Normal	9	0.65	0.22	**0.022**
	Mild HV	14	0.86	0.26	
	Moderate-Severe HV	23	0.59	0.30	
	Total	46	0.68	0.30	
T: Thicknesss, W: Width, CSA: Cross sectional area, *: The subgroups with meaningful difference.					

The other tendon size parameters did not change according to the degree of HV (p > 0.05). Accessory tendon of EHL was found in 86.95% of feet. Presence or dimensions of the AT also did not differ according to degree of HVA (p > 0.05).

c) Findings regarding the position of tendons and whether they change according to the degree of HV are as follows:

EHL-AH and EHL-FHL distance were greater in males than in females (p = 0.002, p < 0.001). There was no difference for the other tendons between the gender and sides (p > 0.05). There was no significant difference between the genders in terms of any parameter related to the positional placement of the tendons in the clock model and 360 circle model (p > 0.05).

On the other hand, 41.9% (13 cases) of 31 cases where AH was located between 8–9 (close to the plantar) on clock model; FHL was between 5.5–6.5 (plantar lateral), while in 58.1% (18 cases) FHL was between 6.5–7.5 (plantar medial). In 92.9% (13 cases) of 14 cases in which AH was located between 9–10 (close to dorsal); FHL was between 5.5–6.5 (plantar lateral), while in only 1 case (5.3%) FHL was located between 6.5–7.5 (plantar medial). According to the analysis by Pearson Chi-Square test, the difference between the AH groups regarding FHL location was found statistically significant (p = 0.001).

No significant difference was found in terms of HVA degrees for the measured distances of the tendons to each other and their position on the clock model. (p > 0.05). While, both the direct measurement for the EHL-DPAr distance and the placement of it on the clock model are significantly smaller in Moderate-Severe HV than the Mild HV (Ordered as: Mild HV > Normal > Moderate to Severe HV) (p = 0.015, p = 0.022, respectively).

There were no normal cases in the group where FHL was located at the 5–6 o'clock position (more plantar lateral), and 1 of 4 cases with FHL at this location had mild HV and 3 had moderate-to-severe HV. The only case in which AH was located between 7 and 8 was moderate HV.

d) Findings regarding the effects of positional variations of tendons on tendon sizes are as follows:

According to the results of the Pearson correlation test, as EHL-FHL distance increased, EHL CSA ($r = 0.393$, $p = 0.007$), FHL CSA ($r = 0.461$, $p = 0.001$, EHL width ($r = 0.461$, $p = 0.001$), FHL width ($r = 0.479$, $p = 0.001$), FHL thickness ($r = 0.397$, $p = 0.007$) increased significantly. Besides circumference of the CP significantly correlated only EHL width ($r = 0.514$, $p = 0.0001$) and FHL CSA ($r = 0.425$, $p = 0.003$). As EHL-AH distance increased, only FHL width increased ($r = 0.450$, $p = 0.002$). The correlation of EHL-FHL distance, EHL-AH distance and circumference length of the CP with other tendon size parameters was not meaningful.

To reveal whether the sizes of the tendons differ according to the variations in the tendon positions in the coronal plane, the positions of the tendons on the clock model were categorized as in the Table 3, and the differences between the groups in terms of tendon sizes were analyzed by the Independent T test.

Table 3
Statistically significant results for comparison of tendon sizes between groups of positional variation in the independent t-test.

Variation in the position of the tendon on the clock model		Size parameter of affected tendon	n	Mean ± SD (mm)	p
FHL position	FHL, between 6.5–7.5 o'clock	FHL-W	26	3.98 ± 0.83	**0.005**
	FHL, between 5.5–6.5 o'clock		20	4.78 ± 0.97	
	FHL, between 6.5–7.5 o'clock FHL, between 5.5–6.5 o'clock	FHL-CSA	26 20	15.05 ± 4.29 18.56 ± 6.58	**0.036**
AH position	AH, between 8–9 o'clock AH, between 9–10 o'clock	FHL-W	30 14	4.52 ± 1.01 3.80 ± 0.64	**0.018**
	AH, between 8–9 o'clock AH, between 9–10 o'clock	AT-W	27 12	1.67 ± 0.49 1.30 ± 0.40	**0.025**
EHB position	EHB, between 12 – 1 o'clock	EHB-CSA	20	4.04 ± 1.84	**0.015**
	Fused EHB at the 12 o'clock		26	2.79 ± 1.50	
	EHB, between 12 – 1 o'clock	EHB-W	20	2.18 ± 0.44	**0.028**
	Fused EHB at the 12 o'clock		26	1.86 ± 0.48	
	EHB, between 12 – 1 o'clock	EHB-T	20	1.17 ± 0.41	**0.011**
	Fused EHB at the 12 o'clock		26	0.91 ± 0.26	

FHL width and CSA were found to be greater in the cases with FHL located more plantarly/laterally than those with located more medially (p = 0.005, p = 0.036 respectively) (Table 3).

The CSA, width and thickness EHB was found to be larger in those with converging more distally with the EHL than those with fused more proximally (p = 0.015, p = 0.028, p = 0.011 respectively).

FHL width and AT width were found to be greater in patients with AH located more plantarly than those with AH located more dorsally (p = 0.018).

Any tendon size did not change significantly according to the positional variation of EHL and AT (p > 0.05).

Discussion

The study was expected to provide evidence that HVrelated changes in the anatomical relationships of the first ray bones of the foot may coexist with changes in the relative position of the tendons around the MTB and/or tendon size. The placement of tendons was given on a clock model to provide a usefulness for surgeons, and on the 360 circle model to express data in more specific numbers. The clock model made it possible to categorize the variations in tendon positions in the coronal plane around the proximal part of the MTB and to evaluate these variations in terms of HVA, severity and interaction with tendon dimensions, by eliminating the effect of foot size factor. Our findings regarding the smaller size of the AH, FHL, and EHB tendons in the moderate-severe HV group, and the fact that the positional variations of the tendons are reflected in the dimensions of some tendons is presented as a contribution to the knowledge about the biomechanical details of HV and the use of tendons in surgery.

Studies investigating the relationship between HV development or progression and muscle weakness or atrophy have mostly focused on the dimensions of the belly of the intrinsic foot muscles, and studies on tendon dimensions are limited. We evaluated our data on tendon sizes together with these literatures, taking into account the knowledge that muscle size is directly related to muscle strength and that tendon CSA is well correlated with the physiological CSA of associated muscles [2]. In HV, by ultrasonography; Mickle et al (2014) reported that the CSA of the AH belly was significantly reduced in older women with moderate-to-severe HV. Aiyer (2015) found a significant decrease in AH belly's dorsoplantar thickness and CSA in people with HV over 65 years of age compared to younger age groups. Lobo et al (2016) and Taş et al (2019) found that the AH and FHB intrinsic plantar muscles had less CSA and thickness, and Mickle et al. (2017) defined that the CSA of AH and FHB decreased by 11% and 23%, respectively [1, 41, 44, 46, 59].

Stewart et al. (2013) found that the dorsoplantar thickness, mediolateral width and CSA of the AH muscle mass decreased in the 2nd and 3rd grade HV groups compared to the normal group. On the other hand, since there was no significant difference between mild, moderate, and severe HV groups, they suggested that these changes in AH may be a result of muscle disuse due to HV and may occur early in the development of the deformity [58]. However, in our study, the tendon width and CSA of AH were found to be significantly smaller in the moderate-severe HV group than in the mild HV group, while there was no difference between the normal group and mild or moderate-severe HV groups. Although not statistically significant, the mean value of the mild HV group was greater than that of the normal group, which also contradicted the muscle findings of Stewart et al. (2013) [58]. In addition, our findings regarding EHB thickness and CSA were similar in terms of being affected by HV groups. Our findings in favor of the idea that the HV-related adaptive response in the size of these tendons is markedly reduced in advanced HV severities, but not reduced (perhaps even enlarged) in low HV severity.

Stewart et al. (2013) also pointed out that the size characteristics of other muscles (ie, hallux flexors and extensors) that have lost their normal anatomical relations with the first MTPJ, which may play a role in the development of HV, should also be examined [58]. The FHL tendon, one of the extrinsic muscles, showed a change similar direction with the intrinsic muscle in the severity of advanced HV. But, unlike the intrinsic muscles, the CSA and width of the FHL tendon was smaller in the moderate-severe HV group than in the normal group, whereas the mild HV group was not different from these two groups.

All this can be interpreted in two ways in terms of cause-effect relationship: Changes in AH, EHB, and FHL sizes are an HV-related adaptive response that is not noticeably activated at small HVAs but only occurs significantly at advanced HVAs. Or, because all these tendons are smaller for some reason, it may be easier to progress to advanced stages of HV. For the latter suggestion, it may be necessary to find a common reason that can explain the shrinkage of the tendons of all two intrinsic muscles (one plantar and one dorsal) and one extrinsic muscle. Considering that there is no difference in various HV severities for EHL and AT, it becomes difficult to say that a weakness due to a general/common factor (genetic, metabolic, etc.) that may affect the formation of all tendon material may be responsible for advanced HV. On the other hand, muscle atrophy and decrease in muscle strength may be due to aging or long-term disuse, and advanced age is discussed in the literature as a factor that can both change the quality of AH and increase the risk of HV [1, 30, 50]. Fat infiltration in the AH muscle is associated with decreased muscle strength and function in older adults and is not considered a HV-specific change [58]. It seems also difficult to explain the HV-related change in both the plantar and dorsal intrinsic and extrinsic muscle tendons of the foot with chronic ischemia caused by the pressure increase in the foot, as proposed by Hoffmeyer et al. (1988) [28]. Based on all of these, we think that the first suggestion that the changes in tendons develop secondary to the biomechanical effects of bone and joint deformation in advanced HV seems stronger.

It has been suggested that the decrease in the stiffness and size of the AH and FHB muscles may cause a decrease in finger strength and stabilization, that the decrease in the stiffness of the intrinsic muscles of the foot is associated with a decrease in the resistance capacity against external loading and may result in HV [59]. In chronic overuse injuries, it has been reported that the internal structure of tendons, which exceed at least two joints, cross the apex of the convex or concave skeletal curve, and have insufficient vascular nutrition areas, are exposed to repetitive stress and may degenerate due to multiple microtrauma [38]. AH and EHB and FHL tendons, which are compatible with the anatomical part of this definition, may have suffered some form of chronic overuse injury and shrunk with a consequent degeneration as a result of the anatomical and biomechanical changes associated with HV.

Natsis et al. (2017) stated that the incidence of HV in feet with AT was higher than in feet without AT (almost 2/3), however, they did not find evidence of a relationship between the presence or morphological features of AT and the severity of HV [51]. Similarly, no evidence was found in our study showing the presence or dimensions of AT to be associated with HVA or severity.

Identifying the positional variations of the tendons around the first MTB may be important due to the risks in surgical approaches as well as its role in the clinical process of HV [5, 17, 19]. Mickle et al. (2018) reported that the tension of the EHL tendon, which should keep the hallux in extension, increases with lateral deviation in the HV. They suggested that in addition to the increased joint stiffness, the changing joint mechanics also reduced the active contraction capacity of the flexor muscles against the ground [46]. For the proximal portion of the first MTB, we found no evidence that the position of the tendons relative to each other was altered by HVA or severity. But it seems that the relative position of the tendons around the proximal part of the first MTB does not change as much as at the distal end. Besides, it is known that the distal end of the first MTB is deviated medially and the intermetatarsal angle increases in HV [9, 12, 34]. In our direct measurements and in the clock model, the closer EHL to the DPAr in Moderate-to-severe HV than the Mild HV seems to support the deviation of the EHL proximally also to the lateral. While it was expected that EHL displaced laterally in HV is closer to DPAr than normal in both HV deformity groups, the fact that this distance is not different from the normal group raises new questions for HV processes.

We could not find any study in which we could compare our data on the reflections of tendon positional variations, defined according to the clock pattern around the first MTB, on tendon sizes. According to our results; regardless of HV, FHL width and CSA of the more plantar/laterally located FHL around the proximal part of MTB are greater than in the cases with more medially located FHL. Considered in relation to HV, small tendon size was associated with the moderate-to-severe HV group, but we found no evidence for this level to suggest that the FHL shifted laterally in the HV or the positional variation is associated with tendon shrinkage.

The correlation findings showing that the CSA and width of the EHL increase as the distance of the FHL from the medial side to the EHL increases seems to be associated with foot size, considering that this distance also correlates with the coronal plane circumference. Indeed, we found no evidence that positional variations of FHL in the coronal plane affect EHL dimensions on the clock model that disables foot size.

According to the correlation analysis, the actual distance of AH to the EHL increased with FHL width and CP circumference, while in the clock model, regardless of HV, the width of the FHL was greater in cases where the AH was close to the plantar than those close to the dorsal, and the FHL was located more plantar-laterally. We could not find any evidence to directly associate the positional variation of AH with HV. Similarly, AT width, which was found to be smaller in cases with AH closer to dorsal, did not differ between HV groups. All these data suggest that for the proximal MTB level, if the AH is anatomically located close to the plantar, the FHL and AT are larger, and the FHL is located more plantar-laterally.

Where the level of attachment of EHB to EHL was more distal, all dimensional parameters of EHB were greater than those more proximal, and these variations were not associated with foot length and HV.

There was no evidence that positional variations of EHL varied with positional variations of AH and FHL, or with any tendon size. It can be assumed that all these determinations regarding the reflections of the positional variations of FHL, AH, EHB serve to maintain the delicate balances in the function of the arch of the foot and the hallux. Detailed morphometric studies including the distal end of the MTB and consisting of large series are needed to prove whether the deterioration in the positional variation and size relations of the tendons in the region lead to HV formation.

It is known that HV is more common in women than men [8, 9, 13]. In our series consisting of amputation and cadaver material, there was no difference in the distribution of gender to HV groups. The fact that there was no difference between the groups according to gender in terms of HVA is consistent with Lobo et al. (2016) [41]. The absence of correlation between the length of the proximal part of the foot, the circumference of the CP, the total length of the foot and the HVA is consistent with the foot length findings of Lobo et al. (2016) [41]. In our series, the difference between the genders in terms of CP circumference was consistent with the fact that the distance of AH and FHL to the EHL was longer in men than in women. While, this measurement was not reflected in the gender difference for other inter-tendon distances. In the clock model, in which the effect of the CP circumference was eleminated, the difference between the genders was disappear for tendons' positional interrelations. This indicates that the difference between the sexes observed in AH and FHL placement is not directly related to gender, but to CP circumference

In the literature, it is stated that it is not known whether foot size affects muscle size [46, 58]. Our findings, showing that total and proximal foot lengths correlate only with the CSA of AH and FHL, and CP circumference only with the CSA of FHL, and that none of the foot measurements are correlated with the dimensions of other tendons, can provide contribution to studies on foot and tendon biomechanics. EHL and FHL width and CSA were higher in males than females, as expected, due to greater muscle mass in males [30], while we could not find any study that could compare with our findings that there was no gender difference for EHB, AD, and AT.

Surgical repair of some pathologies involving the hallux may require transfer of tendons around the first MTB, AH, EHL and AT or FHL [10, 16, 33, 63–65]. Partial or complete transfer of tendons (EHL, AH, EHB) in the region may be needed for the repair of iatrogenic hallux varus that may develop after corrective surgical treatment of HV [4, 39, 40, 48, 65]. It has been reported that FHL is at risk during hallux surgeries such as Akin osteotomy, metatarsal osteotomy or soft tissue release [5, 19], while EHL is at risk when performing the dorsal part of PeICO [17]. Casal (2010) reporting that the AT and EHB are one-third and half the width of the EHL, respectively, suggests that the width, thickness, length, and consistency of the EHB would make it an excellent candidate as a source of tendon grafts for reconstructive surgical procedures [8]. We believe that in all these surgical approaches, it may be important to know the structural and localization variations in tendons and the changes associated with HV.

The limitations of the study

As all groups were exposed to the same fixative solution, the possible effects of fixation on measurements were ignored in comparisons. It is known that the geometry of the forefoot changes while carrying weight [22]. But, in this study, we had to measure HVA in feet without weight bearing conditions. It is unclear whether the morphometric adaptive response of the belly and tendon of the muscle to the biomechanical factors related to HV parallels at certain stages of the deformity or not, and, we did not evaluate the dimension of muscle bellies according to HV groups. Lastly, relationship between the positional features and dimensions of the tendons was evaluated only in the plane passing through the DPAr point (as a reference of pulse area on the dorsum of the foot, and first MTB proximal part). We suggest that when this relationship is evaluated at the distal end of MTB, where the positional changes of tendons are more prominent in HV, new significant morphometric data for HV can be obtained.

Conclusion

The smaller tendon sizes of two intrinsic (one plantar and one dorsal) and one extrinsic muscle in the moderate-to-severe HV group suggest that the source of these changes may not be due to a local effect such as chronic ischemia leading to pressure increase, and that they become evident when the severity of HV is high. It is recommended to consider the dimensional weakness of AH, FHL and EHB tendons when planning surgical treatment or evaluating the effectiveness of treatment in moderate and severe HV cases. The clock model allowed us to analyze by eliminating the effects of foot size on the positional relations of tendons. The literature pointing to dorsal-lateral displacement of EHL in HV is supported by our finding that only EHL was closer to DPAr in the moderate-to-severe HV group. The fact that the positions of the other tendons (FHL, AH) does not change relative to each other in the proximal part of first MTB in HV can be explained as a result of the bone-tendon relationship complicated by the medial deviation of the first MTB and the increased intermetatarsal angle. Our findings that the positional variations of FHL and AH affect some tendon sizes in the proximal part of the MTB (DPAr level), regardless of HV, will contribute to the evaluation of biomechanical features of the hallux tendons.

Declarations

Ethics approval and consent to participate:

The study has been approved by the Board of Ethics of Mersin University (Approval number: 2021-96).

Consent for publication

All authors (ZKO, FÇ, TK) read the manuscript and have approved the content of the article and agree to present the article in "Surgical and Radiologic Anatomy" for publication.

Availability of data and materials

The material used in the study was obtained from the inventory of Anatomy Department Laboratory of Mersin University.

Competing interests

The authors declare no conflict of interest.

Funding

The study is supported by Mersin University Scientific Research Projects Unit (PN:2021-1-TP2-4313).

Authors' Contribution

ZKO: Project development, Data analysis, Manuscript writing, Manuscript editing, FÇ: Project development, Data collection, Manuscript writing, TK: Data collection

Acknowledgements

The authors sincerely thank those who donated their bodies to science so that anatomical research could be performed. The results of such studies can contribute to the improvement of the health service that humanity receives. For this reason, we would like to express our gratitude to these donors and their families on behalf of researchers and humanity. Also, thanks to Mersin University Scientific Research Projects Unit for supporting this study.

Authors' information

Zeliha Kurtoğlu Olgunus[1], MD: Professor in the Department of Anatomy, Mersin University, Mersin, TURKEY

Fatih Çiçek[2]: PhD student of Anatomy and research assistant in the Niğde Ömer Halisdemir University, Faculty of Medicine, Niğde, TURKEY

Turan Koç[1]: PhD student in the Department of Anatomy, Mersin University, Mersin, TURKEY

References

1. Aiyer A, Stewart S, Rome K (2015) The effect of age on muscle characteristics of the abductor hallucis in people with hallux valgus: a cross-sectional observational study. J Foot Ankle Res 8:19.
2. An KN, Linscheid RL, Brand PW (1991) Correlation of physiological CSAs of muscle and tendon. J Hand Surg Br 16:66–7.
3. Arinci İncel N, Genç H, Erdem HR, Yorgancioglu ZR (2003) Muscle imbalance in hallux valgus: An electromyographic study. Am J Phys Med Rehabil 82:345–9.
4. Bevernage BD, Leemrijse T (2009) Hallux varus: classification and treatment. Foot Ankle Clin 14:51–65.

5. Brand Jr JC, Smith RW (1991) Rupture of the flexor hallucis longus after hallux valgus surgery: case report and comments on technique for adductor release. Foot Ankle 11:407–10.
6. Brenner E (1999) Insertion of the abductor hallucis muscle in feet with and without hallux valgus. Anat Rec 254:429–34.
7. Buchanan CI, Marsh RL (2002) Effects of exercise on the biomechanical, biochemical and structural properties of tendons. Comp Biochem Physiol A Mol Integr Physiol 133:1101–7.
8. Casal D, Pais D, Angélica-Almeida M, Bilhim T, Santos A, Goyri-O'Neill J (2010) Morphometric analysis of the extensor tendons of the hallux and potential implications for tendon grafting. Eur J Anat 14:11–8.
9. Cavalheiro CS, Arcuri MH, Guil VR, Gali JC (2020) Hallux valgus anatomical alterations and its correlation with the radiographic findings. Acta Ortop Bras 28:12–5.
10. Chhaya SA, Brawner M, Hobbs P, Chhaya N, Garcia G, Loredo R (2008) Understanding hallux valgus deformity: what the surgeon wants to know from the conventional radiograph. Curr Probl Diagn Radiol 37:127–37.
11. Coughlin MJ (1996) Hallux Valgus. J Bone Joint Surg Am 78:932–66.
12. Coughlin MJ, Shurnas PS (2003) Hallux valgus in menpart II: first ray mobility after bunionectomy and factors associated with hallux valgus deformity. Foot Ankle Int 24:73–8.
13. Coughlin MJ, Jones JP (2007) Hallux Valgus: Demographics, Etiology, and Radiographic Assessment. Foot Ankle Int 28:759–77.
14. Crofts G, Angin S, Mickle KJ, Hill S, Nester CJ (2014) Reliability of ultrasound for measurement of selected foot structures. Gait Posture 39:35–39.
15. Dalmau-Pastor M, Vega J, Malagelada F, Peña F, Manzanares-Céspedes MC (2018) An Anatomical Study of Nerves at Risk During Minimally Invasive Hallux Valgus Surgery. J Vis Exp 132:56232.
16. Dalmau-Pastor M, Malagelada F, Cordier G (2020) Anatomical Study of Minimally Invasive Lateral Release Techniques for Hallux Valgus Treatment. Foot Ankle Int 41:984–92.
17. Del Vecchio JJ, Ghioldi ME, Uzair AE, Chemes LN, Manzanares-Céspedes MC, Dealbera ED, Dalmau-Pastor M (2019) Percutaneous, Intra-articular, Chevron Osteotomy (PeICO) for the Treatment of Hallux Valgus: A Cadaveric Study. Foot Ankle Int 40:586–95.
18. Del Vecchio JJ, Ghioldi ME, Chemes LN, Dealbera ED, Brue J, DalmauPastor M (2021) Percutaneous, intraarticular, chevron osteotomy (PeICO) for the treatment of mildtomoderate hallux valgus: a case series. Int Orthop 45:2251–60.
19. Dhinsa B, Walker R, Jones I (2016) Technique to test flexor hallucis longus after Akin osteotomy. Ann R Coll Surg Engl 98:155–9.
20. Eustace S, Williamson D, Wilson M, O'Byrne J, Bussolari L, Thomas M, Weissman B (1996) Tendon shift in hallux valgus: observations at MR imaging. Skeletal Radiol 25:519–24.
21. Ferris L, Sharkey NA, Smith TS, Matthews DK (1995) Influence of extrinsic plantar flexors on forefoot loading during heel rise. Foot Ankle Int 16:464–73.

22. Fuhrmann RA, Layher F, Wetzel WD (2003) Radiographic changes in forefoot geometry with weight bearing. Foot Ankle Int 24:326–31.
23. Garrow AP, Papageorgiou A, Silman AJ, Thomas E, Jayson MI, Macfarlane GJ (2001)The grading of hallux valgus: the Manchester Scale. J Am Podiatr Med Assoc 91:74–8.
24. Glasoe WM (2016) Treatment of Progressive First Metatarsophalangeal Hallux Valgus Deformity: A Biomechanically Based Muscle-Strengthening Approach. J Orthop Sports Phys Ther 46:596–605.
25. Heo H, Koo Y, Yoo W (2011) Comparison of Selective Activation of the Abductor Hallucis during Various Exercises. J Phys Ther Sci 23:915–8.
26. Hurn SE, Vicenzino B, Smith MD (2015) Functional impairments characterizing mild, moderate, and severe hallux valgus. Arthritis Care Res (Hoboken) 67:80–8.
27. Hardy RH, Clapham JCR (1951) Observations on hallux valgus. J Bone Joint Surg 33:376–91.
28. Hoffmeyer P, Cox JN, Blanc Y, Meyer JM, Taillard W (1988) Muscle in hallux valgus. Clin Orthop Relat Res 112–8.
29. Holzer D, Epro G, McCrum C, Doerner J, Luetkens JA, Scheef L, Kukuk GM, Boecker H, Mierau A, Brüggemann GP, Maganaris CN, Karamanidis K (2018) The role of muscle strength on tendon adaptability in old age. Eur J Appl Physiol 118:2269–79.
30. Janssen I, Heymsfield SB, Wang Z, Ross R (2000) Skeletal muscle mass and distribution in 468 men and women aged 18–88 year. J Appl Physiol 89:81–8.
31. Joseph TN, Mroczek KJ (2007) Decision Making in the Treatment of Hallux Valgus. Bull NYU Hosp Jt Dis 65:19–23.
32. Jung D, Koh E, Kwon O (2011) Effect of foot orthoses and short-foot exercise on the CSA of the abductor hallucis muscle in subjects with pes planus: a randomized controlled trial. J Back Musculoskeletal Rehabil 24:225.
33. Kadel NJ, Donaldson-Fletcher EA, Hansen ST, Sangeorzan BJ (2005) Alternative to the modified jones procedure: outcomes of the flexor hallucis longus (FHL) tendon transfer procedure for correction of clawed hallux. Foot Ankle Int 26:1021–6.
34. Kim MH, Kwon OY, Kim SH, Jung DY (2013) Comparison of muscle activities of abductor hallucis and adductor hallucis between the short foot and toe-spread-out exercises in subjects with mild hallux valgus. J Back Musculoskelet Rehabil 26:163–8.
35. Kiranea YM, Michelson JD, Sharkeya NA (2008) Evidence of isometric function of the flexor hallucis longus muscle in normal gait. J Biomech 41:1919–28.
36. Kjær M (2004) Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. Physiol Rev 84:649–98
37. Kjær M, Langberg H, Heinemeier K, Bayer ML, Hansen M, Holm L, Doessing S, Kongsgaard M, Krogsgaard MR, Magnusson SP (2009) From mechanical loading to collagen synthesis, structural changes and function in human tendon. Scand J Med Sci Sports 19:500–10.

38. Kraushaar BS, Nirschl RP (1999) Tendinosis of the elbow (tennis elbow). Clinical features and findings of histological, immunohistochemical, and electron microscopy studies. J Bone Joint Surg Am 81:259–78.
39. Lau JTC, Myerson MS (2002) Modified split extensor hallucis longus tendon transfer for correction of hallux varus. Foot Ankle Int 23:1138–40.
40. Leemrijse T, Hoang B, Maldague P, Docquier PL, Bevernage BD (2008) A new surgical procedure for iatrogenic hallux varus: Reverse transfer of the abductor hallucis tendon A report of 7 cases. Acta Orthop Belg 74:227–34.
41. Lobo CC, Marin AG, Sanz DR, López LD, López PP, Morales CR, Corbalán IS (2016) Ultrasound evaluation of intrinsic plantar muscles and fascia in hallux valgus: a case-control study. Medicine (Baltimore). 95:e5243.
42. McKeon PO, Hertel J, Bramble D, Davis I (2015) The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med 49:290.
43. Menz HB, Munteanu SE (2005) Radiographic validation of the Manchester scale for the classification of hallux valgus deformity. Rheumatology (Oxford) 44:1061–6.
44. Mickle KJ, Nester CJ (2014) Size of the abductor hallucis muscle in older women with hallux valgus. J Foot Ankle Res 7:A57.
45. Mickle KJ, Caputi P, Potter JM, Steele JR (2016) Efficacy of a progressive resistance exercise program to increase toe flexor strength in older people. Clin Biomec (Bristol, Avon) 40:14–9.
46. Mickle KJ, Nester CJ (2018) Morphology of the toe flexor muscles in older people with toe deformities. Arthritis Care Res (Hoboken) 70:902–7.
47. MoralesOrcajo E, Bayod J, BecerrodeBengoaVallejo R, LosaIglesias M, Doblare M (2015) Influence of first proximal phalanx geometry on hallux valgus deformity: a finite element analysis. Med Biol Eng Comput 53:645–53.
48. Myerson MS, Kadakia AR (2019) Reconstructive Foot and Ankle Surgery: Management of Complications. 3rd Ed. Section 1. The Hallux and Sesamoids, Elsevier, Philadelpia p.56.
49. Nakagawa Y, Totsuka M, Sato T, Fukuda Y, Hirota K (1989) Effect of disuse on the ultrastructure of the Achilles tendon in rats. Eur J Appl Physiol 59:239–42.
50. Narici MV, Maganaris NC (2007) Plasticity of the muscle-tendon complex with disuse and aging. Exerc Sport Sci Rev 35:126–34.
51. Natsis K, Konstantinidis GA, Symeonidis PD, Totlis T, Anastasopoulos N, Stavrou P (2017) The accessory tendon of extensor hallucis longus muscle and its correlation to hallux valgus deformity: a cadaveric study. Surg Radiol Anat 39:1343–7.
52. Nix S, Smith M, Vicenzino B (2010) Prevalence of hallux valgus in the general population: a systematic review and meta-analysis. J Foot Ankle Res 3:21.
53. Nix SE, Vicenzino BT, Collins NJ, Smith MD (2012) Characteristics of foot structure and footwear associated with hallux valgus: a systematic review. Osteoarthritis and Cartilage 20:1059–74.

54. Perera A, Mason L, Stephens M (2011) The pathogenesis of hallux valgus. J Bone Joint Surg Am. 93:1650–61.
55. Piggot H (1960) The natural history of hallux valgus in adolescence, and early adult life. J Bone Joint Surg 42(4):749–60.
56. Saltzman CL, Aper RL, Brown TD (1997) Anatomic Determinants of First Metatarsophalangeal Flexion Moments in Hallux Valgus. Clin Orthop Relat Res 339:261–9.
57. Steadman J, Barg A, Saltzman CL (2021) First metatarsal rotation in hallux valgus deformity. Foot Ankle Int 42:510–22
58. Stewart S, Ellis R, Heath M, Rome K (2013) Ultrasonic evaluation of the abductor hallucis muscle in hallux valgus: a cross-sectional observational study. BMC Musculoskeletal Disorders 14:45.
59. Taş S, Çetin A (2019) Mechanical properties and morphologic features of intrinsic foot muscles and plantar fascia in individuals with hallux valgus. AOTT 53:282–6.
60. Thomas S, Barrington R (2003) Hallux valgus. Current Orthopaedics 17:299–307.
61. Wacker J, Calder JDF, Engstrom CM (2003) MR Morphometry of Posterior Tibialis Muscle in Adult Acquired Flat Foot. Foot Ankle Int 24:354–7
62. Wood LK, Arruda EM, Brooks SV (2011) Regional stiffening with aging in tibialis anterior tendons of mice occurs independent of changes in collagen fibril morphology. J Appl Physiol 111:999–1006.
63. Xiong Y, Shen B, Hao C, Xiao K, Wang J, Fang Z (2019) Transfer of abductor hallucis tendon combined with scarf osteotomy versus single scarf osteotomy in moderate to severe hallux valgus deformity: a comparative retrospective cohort study. BMC Musculoskeletal Disorders 20:455.
64. Zdilla MJ, Paulet JE, Lear JJ, Addie KM, Lambert HW (2018) A review of extensor hallucis longus variants featuring a novel extensor primi internodii hallucis muscle merging with extensor hallucis brevis. J Foot Ankle Surg 57:1218–20.
65. Zielinskaa N, Tubbs RS, Ruzike K, Olewnika Ł (2021). Classifications of the extensor hallucis longus tendon variations: Updated and comprehensive narrative review. Ann of Anat 238:151762.

Figures

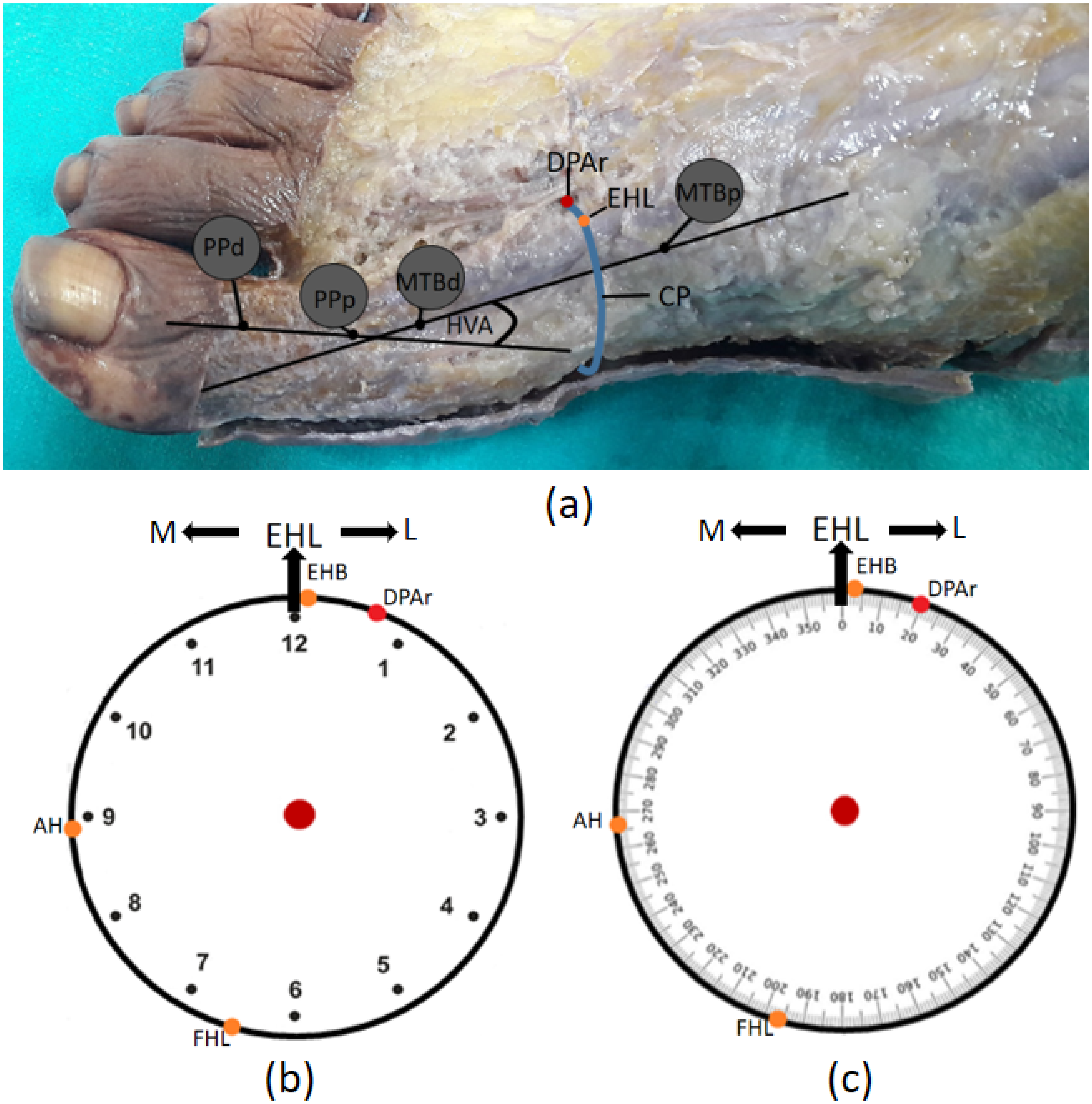

Figure 1

Measurement of hallux valgus angle (HVA) and demonstration of the coronal plane (CP) passing through the point where deep plantar artery returns to the plantar aspect of foot (DPAr) (a) (MTB: metatarsal bone, PP: proximal phalanx, p: proximal, d: distal). Mean location of the tendons on the clock model (b), and the 360° circle (c) (EHL: extensor hallucis longus, EHB: extensor hallucis brevis, AH: abductor hallucis, FHL: flexor hallucis longus, M: medial, L: lateral).

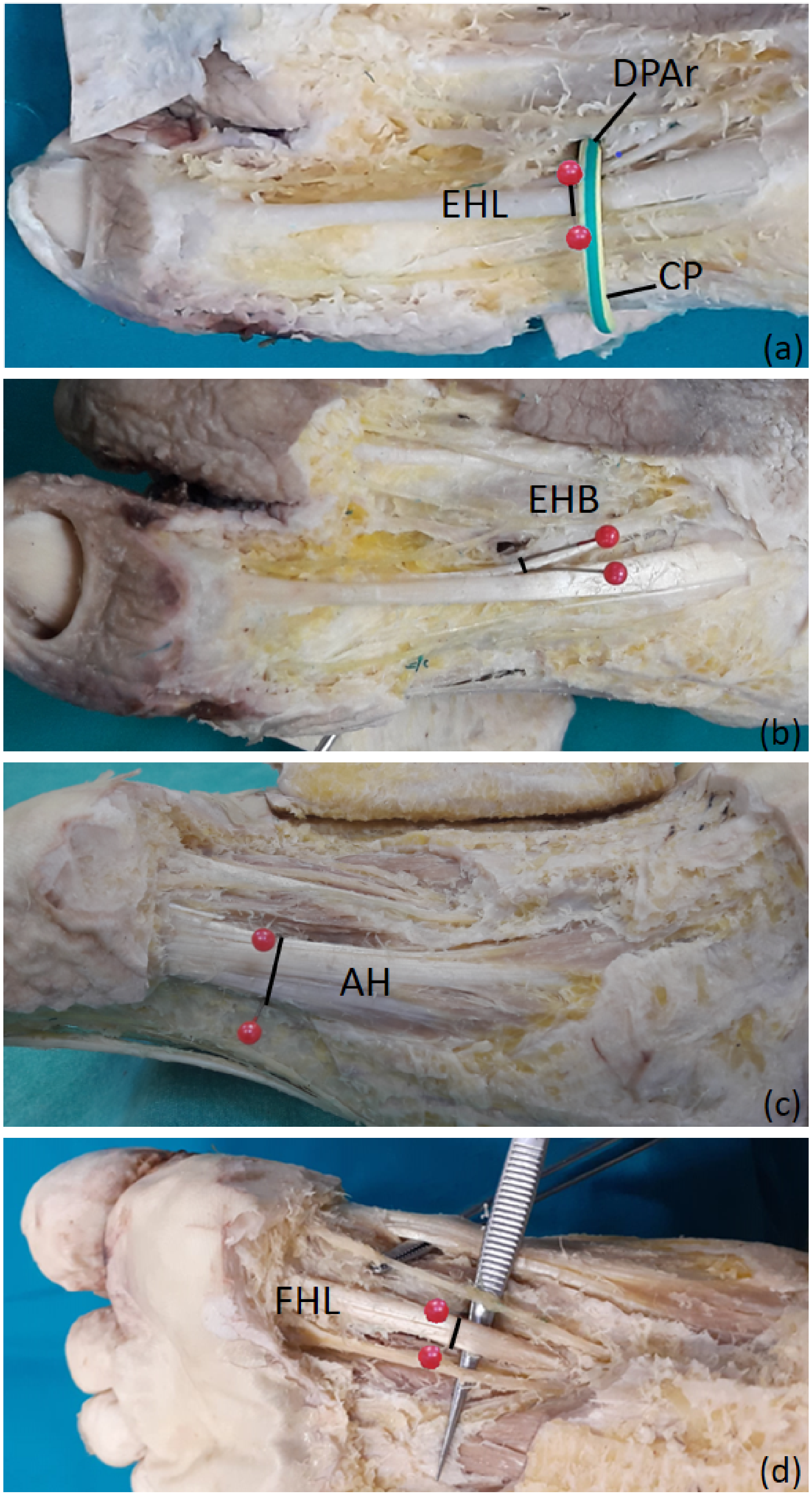

Figure 2

At the coronal plane (CP) passing through the point where deep plantar artery returns to the plantar aspect of foot (DPAr), width of the tendons of extensor hallucis longus (EHL) (a), extensor hallucis brevis (EHB) (b), abductor hallucis (AH) (c), flexor hallucis longus (FHL) (d).