Tensile Properties of the Deep Transverse Metatarsal Ligament in Hallux Valgus

A CONSORT-Compliant Article

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Abstract: The deep transverse metatarsal ligament (DTML) connects the neighboring 2 metatarsal heads and is one of the stabilizers connecting the lateral sesamoid and second metatarsal head. In this study, we aimed to determine the tensile properties of the DTML in normal specimens and to compare these results with hallux valgus specimens. We hypothesized that the tensile properties of the DTML would be different between the 2 groups of specimens.

The DTML in the first interspace was dissected from 12 fresh frozen human cadaveric specimens. Six cadavers had bilateral hallux valgus and the other 6 cadavers had normal feet. The initial length \( (L_0) \) and cross-sectional area \( (A_0) \) of the DTML were measured using a digital caliper, and tensile tests with load failure were performed using a material testing machine.

There were significant between-groups differences in the initial length \( (L_0) \) \( P = 0.009 \) and cross-sectional area \( (A_0) \) of the DTML \( P = 0.007 \). There were also significant between-groups differences for maximum force \( (N) \) \( P = 0.004 \), maximum distance \( (\text{mm}) \) \( P = 0.005 \), maximum stress \( (\text{N/mm}^2) \) \( P = 0.003 \), and maximum strain \( (%) \) \( P = 0.006 \).

The DTML is an anatomical structure for which the tensile properties differ in hallux valgus.

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INTRODUCTION

The deep transverse metatarsal ligament (DTML), which is a series of 4 short ligamentous bands that span between the distal ends of adjacent metatarsal bones and intersect with the plantar ligaments of the metatarsophalangeal (MTP) joint, is a narrow band that runs across and connects the heads of the metatarsal bones.\(^1\) The DTML connects the neighboring 2 metatarsal heads and adjoins with the plantar plate of the MTP joint anteriorly. The plantar side of the transverse metatarsal ligament is contiguous with the lumbricalis muscles and the neurovascular structure.\(^2\)

Intermetatarsal support is provided by the transverse metatarsal ligaments, the deep plantar aponeurosis, and the Lisfranc ligament.\(^3\) Stainsby\(^4\) found in his anatomic study that the plantar plates of the MTP joints and the intervening DTMLs form a continuous band of strong ligamentous structures across the forefoot. He hypothesized their role to be a “tie-bar” system that prevents undue splay of the forefoot. The DTML is one of the stabilizers connecting the lateral sesamoid and second metatarsal head.\(^5\)

The stress/strain mechanical characteristics of human ligaments change significantly with the ligament strain rate. Human ligaments exhibit viscoelastic behavior (i.e., small strain rates), which allows a relaxation rearrangement of the fibers during periods of tension, whereas quick changes in fiber length induce purely elastic behavior.\(^6\)

Hallux valgus is a common structural foot deformity in which the angular deviation of the hallux is >15° toward the lesser toes with respect to the first metatarsal bones, and it appears as a medial bony enlargement of the first metatarsal head.\(^7\) The first ray is an inherently unstable axial array that relies on a fine balance between its static (capsule, ligaments, and plantar fascia) and dynamic (peroneus longus muscle and small muscles of the foot) stabilizers to maintain its alignment.\(^8\)

The DTML is considered one of the contracted elements of the lateral MTP joint in hallux valgus. Some surgeons think that release of this ligament is necessary for complete correction,\(^9,10\) whereas others think that release of this ligament does not contribute to hallux valgus correction.\(^11,12\)

The association of the DTML with hallux valgus is thus debatable. In a study by Haines and McDougall\(^13\) the authors stated that the DTMLs are neither stretched nor displaced in hallux valgus, whereas Day\(^14\) concluded that the DTML became stretched due to deviation of the first metatarsal in hallux valgus. Kura et al\(^3\) concluded that the DTML did not contribute substantially to hallux valgus deformity.

The goal of the current cadaveric study was to determine the tensile properties of the DTML in the first interspace in normal big toes and to compare these properties in feet affected by hallux valgus to increase understanding of the pathology of the hallux valgus deformity. This understanding may provide valuable information for more effective treatment of hallux valgus. Our hypothesis was that there may be a difference between the tensile properties of the DTML in the first interspace in normal big toes and in those affected by hallux valgus.
MATERIALS AND METHODS

The study consisted of 12 female fresh frozen cadavers. Six cadavers had bilateral normal feet and the other 6 had bilateral hallux valgus feet. The mean age for the normal group was 55 ± 6.3 years, whereas the mean age for the hallux valgus group was 53 ± 4.2 years. The inclusion criteria for all cadavers were intact feet, ankles, and knees without any previous trauma to the lower limbs, no obvious ligament injuries or contractures, and no previous surgeries at the ankle or foot.

The hallux valgus feet had moderate to severe bilateral deformities (a hallux valgus angle >20°).15 Before the study, the cadavers were thawed to room temperature (24°C) for 24 hours before being examined. We only used specimens from individuals who consented before death to have their cadavers used for medical purposes. Ethics committee approval for the study was obtained from the institutional review board of the Department of Anatomy and Embryology of the Faculty of Medicine, Cairo University (approval number, 285; approval date, 20 March 2012).

Radiographic Assessment

Simulated dorsoplantar and lateral radiographs were obtained for all specimens before anatomical dissection. Each specimen was placed in a specially designed Plexiglas loading frame with a 35 kg vertical load applied to the proximal end of the tibia. The pneumatic load was applied through a coupling unit placed in the proximal tibial intermedialcular canal.

All radiographs were obtained using standardized techniques in both views.16 On the dorsoplantar radiographs, the hallux valgus first to second intermetatarsal angles were measured using mid-diaphyseal reference points.17

For the hallux valgus angle, normal is defined as ≤15°, mild as <20°, moderate as 20° to 40°, and severe as ≥40°. For the first to second intermetatarsal angle, normal is defined as ≤9°.18 The demographics and radiographic assessments for the specimens are shown in Table 1.

Anatomical Dissection of the DTML

All dissections of the DTML were performed by an anatomist experienced in anatomical foot dissection at the Anatomy and Embryology Department. The specimens were placed in the supine position, and the initial skin incision encircled the entire foot and was made 1.0 cm proximal to the tarsometatarsal articulation. The skin was removed distally, exposing all the subcutaneous structures. Blunt dissection of the subcutaneous tissues was performed. Attention was then directed toward the first MTP joint. Distal exposure revealed the extensor aponeurosis, which was incised to reveal the deeper musculotendinous, ligamentous, and capsular structures. The first dorsal interosseous muscle was detached from the first metatarsal shaft and retracted laterally to allow for better visualization of the conjoined tendon of the adductor hallucis muscle, first MTP joint capsule, and DTML. Plantar exposure allowed for visualization of the superficial slips of the plantar aponeurosis that were excised. The first lumbricalis muscle, long and short flexor tendons, and neurovascular structures were isolated and excised completely.

Intermuscular septa overlying the flexor hallucis brevis and adductor hallucis muscles were excised to allow for better visualization of the DTML.19 Attention was then directed to the second MTP joint exposure through the incision. The second MTP joint consists of a joint capsule that surrounds the second MTP joint and blends with the short and long extensor muscles dorsally, forming the extensor apparatus, which was retracted laterally. The plantar portion of the joint capsule and distal slip of the plantar aponeurosis were excised. Then, the intrinsic lumbricales and interosseous muscles were detached.20 The DTML was identified 0.1 to 0.3 cm from the first MTP joint and was harvested carefully from its attachments to avoid losing any part from it and ensure that the DTML needed for our study was not damaged. Dissections occurred in the same manner for the 24 DTMLs used in this study.

Tensile Properties Assessment for the DTML

To determine the tensile properties of the 24 DTML specimens, we measured the initial length (L0) and cross-sectional area (A0) of the DTML. All measurements were obtained using digital calipers (Mitutoyo, San Jose).

Uniaxial tensile failure tests were conducted at an extension rate of 0.5 mm/s. The fiber course of the DTML was in line with the direction of force, thereby stimulating rupture of the ligament. All specimens were tested by an Instron electromechanical testing system. This system is used to test a wide range of materials (Instron system ID number 3345 K 2068, assembled in the USA). We used a tight potting system to grip the ligament ends and prevent slippage. A cell load of 100 N was used, which was calibrated automatically before each testing session. Experiments were conducted in an environmental chamber (24°C) with 100% relative humidity to ensure that the material properties and water content did not alter during experimentation. All 24 DTMLs were tested without preconditioning cycles. Load failure (complete rupture of the DTML during the test at the midsurface) was measured in Newtons, and the ultimate extension distance (in millimeter was recorded for each DTML specimen. The sampling rate was set to 100 Hz. Stress–strain curves, ultimate tensile stress (in N/mm²), and ultimate strain (in %) were calculated from the L0 and A0.

Statistical Analysis

Statistical analysis was performed with use of SPSS version 15 for Windows (SPSS Inc., Chicago, IL). Data were statistically described in terms of mean and standard deviation (SD). Comparisons between the normal and hallux valgus groups were performed using the unpaired Student’s t test. Statistical significance was defined as P value <0.05. Normal distribution of data was confirmed with the Kolmogorov–Smirnov test of normality (not significant).

RESULTS

Radiographic Measurements

The mean hallux valgus angle was 13° ± 1.2, and the mean first to second intermetatarsal angle was 8° ± 0.9 in the normal
group (Table 1). The mean hallux valgus angle was $43^\circ \pm 3$ and the mean first to second intermetatarsal angle was $15^\circ \pm 2$ in the hallux valgus group.

**Initial Length and Cross-Sectional Area Measurements of the DTML in Both Groups**

There were significant between-groups differences for $L_0$ (normal group: $8 \pm 0.5$ mm and hallux valgus group: $6 \pm 0.3$ mm, $P = 0.009$) and $A_0$ (normal group: $3 \pm 0.8$ mm$^2$ and hallux valgus group: $1.6 \pm 0.7$ mm$^2$, $P = 0.007$) (Table 2).

**Tensile Properties of the DTML**

The mean maximum force for the normal group was $15.1 \pm 1.3$ N and for the hallux valgus group was $4.5 \pm 0.6$ N, $P = 0.004$. The mean maximum distance was $10.76 \pm 4.1$ mm in the normal group and $4.44 \pm 2.5$ mm in the hallux valgus group, $P = 0.005$. The maximum stress was $13.3 \pm 6$ N/mm$^2$ in the normal group and $2.6 \pm 3$ N/mm$^2$ in the hallux valgus group, $P = 0.003$. The maximum strain was $35 \pm 4\%$ in the normal group and $17 \pm 1\%$ in the hallux valgus group, $P = 0.006$ (Table 3).

The hallux valgus group differed significantly from the normal group with respect to maximum force, maximum distance, maximum stress, and maximum strain.

### DISCUSSION

A study by Haines and McDougall showed that the DTMLs were neither stretched nor displaced in hallux valgus, whereas Day reported that the DTMLs became stretched due to the deviation of the first metatarsal in hallux valgus. The purpose of our study was to determine the tensile properties of the DTML in the first interspace in normal big toes and to compare these with the properties of the DTML in feet affected by hallux valgus.

Our results demonstrated significant differences in both the $L_0$ and $A_0$ of the DTML between the normal and hallux valgus groups. With respect to the tensile properties of the DTML, the groups differed significantly from each other for maximum force, maximum distance, maximum stress, and maximum strain. These results demonstrate that the tensile properties of the DTMLs in the normal group were superior to those of the DTMLs in the hallux valgus group, supporting the results of Day’s study.

Several authors have shown the importance of DTMLs in function. Some surgeons think that integrity of this ligament is necessary for complete correction of hallux valgus, whereas others have suggested no role for the DTML in hallux valgus.

Stainsby showed in his anatomic study that the DTML could serve as a static structural restraint.

The present study showed significant differences between the tensile properties in the DTMLs from normal and hallux valgus feet. Our study was performed on 12 fresh frozen female cadavers due to the common association between hallux valgus and the female sex. All specimens were from women in order to exclude differences in physiology between men and women, as Nguyen et al suggested that the etiologic mechanism for hallux valgus may differ between men and women. Six specimens had bilateral hallux valgus and 6 specimens had normal big toes. We used fresh frozen cadavers according to the opinion of Cosson et al who stated that freezing does not damage prevertebral ligament strength. We examined the DTMLs without their bony attachments in order to study the characteristics of the ligament within a physiologic range, according to opinions expressed by Butler and Walsh.

Ligaments display viscoelastic behavior; that is, they display time-dependent and load-history-dependent mechanical behavior. These viscoelastic characteristics change with age, pathology, damage, and healing, so the viscoelastic characteristics of ligaments are useful for understanding normal and abnormal tissue behavior.

The DTML is part of the natural static restraint of dorsiflexion or dorsal subluxation of the lesser MTP joint. Operative transection, injury, or degeneration of this ligament may predispose the adjacent MTP joint to instability.

Dissection of the DTML would disrupt the connection between the sesamoid apparatus and the lesser metatarsal, leading to an unchanged or even increased first intermetatarsal angle, as medial capsular repair will pull the sesamoids under the displaced first MTP head rather than reposition the MTP head onto the sesamoids in their correct position, so under-correction of the first intermetatarsal angle must be avoided by maintaining the DTML.

Our results encourage alternative surgical treatment options in hallux valgus, such as repair of the ligament to allow presentation of normal joint stability and alignment. On the other hand, our results contradict the theory of soft-tissue release at the first MTP joint that surgeons should release the DTML. We encourage the use of a mechanism similar to a tightrope to augment DTML function specifically. This technique has been used to correct hallux varus deformity and achieve correction of the hallux in the transverse plane. A mini tightrope device has also been used to correct the intermetatarsal angle in hallux valgus deformity. Another method for correcting hallux valgus is to use an interosseous suture and button device positioned under tension between the first and second metatarsals, thereby reducing the first intermetatarsal angle.

In the present study, the DTML at the first interspace was investigated as an isolated structure. This study introduces information about the tensile properties of the DTML in normal big toes and compared those properties with the tensile properties of the DTML in hallux valgus. We believe that this information may be valuable in the correction of hallux valgus deformities.

### TABLE 2: Comparison Between Initial Length $L_0$ and Cross-Sectional Area $A_0$ Measurements of the DTML in Both Groups

| Parameters                  | Normal (Mean ± SD) | Hallux Valgus (Mean ± SD) | $P$ Value |
|-----------------------------|--------------------|---------------------------|-----------|
| Initial length $L_0$ (mm)   | $8 \pm 0.5$        | $6 \pm 0.3$               | 0.009*    |
| Cross-sectional area $A_0$ (mm$^2$) | $3 \pm 0.8$       | $1.6 \pm 0.7$            | 0.007*    |

DTML = deep transverse metatarsal ligament, SD = standard deviation.

*Statistically significant results.
This study has several limitations. First, it was a cadaveric study with a relatively small sample size. No previous data regarding the tensile properties of the DTML were found for comparison with our results. Further study is needed to confirm these results in normal big toes and to confirm the changes in the DTML’s tensile properties in hallux valgus deformities. Additionally, further studies are needed to compare tensile properties of the DTML in various degrees of hallux.

**CONCLUSION**

In this cadaveric study, we found significant differences in the tensile properties of the DTML in the first interspace in normal big toes and in feet affected by the hallux valgus deformity. We found that the DTMLs in the normal group had tensile properties superior to those for DTMLs in feet affected by hallux valgus. These results are important for pediatric surgeons attempting to restore alignment of the big toe and for improving understanding of the pathology of the hallux valgus deformity.

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