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The Role of Plantar Fascia Tightness in Hallux Limitus: A Biomechanical Analysis

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ABSTRACT

Restriction of greater toe dorsiflexion without degeneration of the first metatarsophalangeal joint is defined as hallux limitus. We assume that in hallux limitus the limitation of greater toe dorsiflexion takes place in the terminal stance phase because of massive tightening of the calf and plantar structures. The current study investigated the role of a tight plantar fascial structure in impairing dorsiflexion of the greater toe. For the purpose of the study, 7 lower limbs from Thiel-fixated human cadavers were evaluated. To simulate double-limb standing stance, the tibia and fibula were mounted on a materials testing machine and constantly loaded with 350 N. Additionally, the tendons of the specimens were loaded using a custom-made system. The plantar fascia was fixed to a clamp and tensioned using a threaded bar. Four different tensile forces were then applied to the plantar fascia (approximately 100, 200, 300, and 350 N) and the extension of the first toe was measured.

The results show a significant positive correlation between the decrease in extension of the hallux and the tension applied to the plantar fascia reaching a maximum mean decrease of 4.2° (117% compared with the untightened situation) for an applied tension of 364 N.

Sufficient dorsiflexion of the hallux is a prerequisite for normal propulsion during gait (1). The amplitude of dorsiflexion at the first metatarsophalangeal joint (MTPJ) usually averages 58° in healthy individuals (2–4).

A painful functional limitation of the first MTPJ during the terminal stance phase without degenerative signs of the first MTPJ is defined as a pathologic entity, which has been termed hallux limitus (HL). The functional restriction is supposed to lead to abnormal loading of the first MTPJ and might predispose to osteoarthritis (5). Despite its clinical importance, little is known about the etiology and treatment of HL (6–8).

The dorsiflexion at the first MTPJ in patients with HL is not much affected in the non-weightbearing condition and with the ankle held in plantarflexion; therefore, a possible explanation for the HL could be found in the windlass mechanism (8–10). The windlass mechanism, first described by Hicks (9), shows an increase in height of the medial arch because of a tightened plantar aponeurosis when the first MTPJ becomes dorsiflexed (11). On the contrary, lowering the medial arch increases the dorsiflexion of the first toe (9); thus, tightening of the plantar aponeurosis is likely to decrease the extension of the first toe and might lead to HL (8). To our knowledge, however, no study quantitatively addressed the question how tightening of the plantar fascia affects the extension in the first MTPJ during the stance phase.

We hypothesized that the dorsiflexion at the first MTPJ would decrease significantly while increasing the tension of the plantar fascia during terminal stance phase.

Materials and Methods

All experiments were performed on 7 cadaveric lower limb specimens. All specimens were amputated through the middle of the leg. Two right and 5 left feet were obtained from the Institute of Anatomy of the University of Zurich. Approval for the study was provided by the local ethics committee. Before testing, each specimen was carefully inspected clinically and under fluoroscopy to verify that no preexisting foot pathologies, specifically osteoarthritic changes , were present (A.F.V., R.S.C.). The specimens were fixed in a Thiel (12) solution and all dissections were carried out by an experienced anatomist (M.V.). The skin and subcutaneous tissues were removed, keeping the retinacular structures intact. All tendons found proximally to the retinaculum were dissected close to the musculotendinous junction. The Achilles, peroneus longus, peroneus brevis, flexor

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digitorum longus, flexor hallucis longus , posterior tibial and anterior tibial, extensor hallucis longus. and extensor digitorum longus tendons were grasped by means of baseball stitch using a number 2 ultrastrong braided polyethylene thread (FiberWire®, USP No. 2, Arthrex Inc., Naples, FL) (A.F.V., R.S.C.). The tibial and fibular bones were fixed to a 20 kN loading cell (Gassmann Theiss™, Bickenbach, Germany) of a universal material testing machine (Zwick™ 1456, Zwick™ GmbH, Ulm, Germany). To simulate double-limb standing stance phase at the early stage of muscle activation just before heel rise from the 2-limb standing position both, the tibia and fibula were continuously loaded with 350 N. Specific loads were applied to each tendon. All tendons have been loaded using a custom-made apparatus to simulate stance phase (Fig. 1). The extensor hallucis longus tendon was loaded with a submaximal force to enforce dorsal extension of the first toe (13).

Tensile forces applied to each tendon during the intact state were:

Anterior tibial: 200 N

Posterior tibial:40 N

Flexor digitorum longus: 22 N

Flexor hallucis longus: 22 N

Peroneus brevis and peroneus longus: 35 N

Anterior tibial: 40 N

Extensor hallucis longus and extensor digitorum longus: 40 N (13,14).

The interphalangeal joint was fixed by introducing a K-wire through the distal to the proximal phalanx allowing improved visualization of greater toe dorsiflexion at the first MTPJ. The plantar fascia was fixed to a metal bar that could be tensioned by a custom-made device. The following consideration was used to estimate the additional force applied to the plantar fascia. A contracture of the Achilles tendon can increase the forefoot pressure of up to 27% (15). It is also known that the load of the plantar fascia is changed similarly to the ground reaction force for the terminal stance phase (16). Thus, a tightened Achilles tendon might increase the plantar fascia tension by 27% or approximately 180 N for a 70-kg person. For the present study, we assumed that a similar effect on the plantar fascia load as tightening of the Achilles tendon would result in an additional tensional load of about 180 N; therefore, an additional maximal force of 360 N has been calculated. Because of technical reasons, a maximal force of 350 N was applied stepwise (100, 200, 300, and 350 N) to the plantar fascia. The force was measured with a Piezo-electric force transducer (Type 9217A and Type 9313AA1, Kistler™ Instrumented AG, Winterthur, Switzerland). For each applied tension, the shortening of the plantar fascia was measured at the tensioning device using a vernier caliper and the extension of the first toe was recorded with a digital camera (D800, Canon®, Tokyo, Japan) oriented perpendicular to the foot and centered over the first metatarsal head. The extension angle of the first metatarsophalangeal joint was then measured for each set up in Photoshop (CS5, Adobe Systems®, San José, CA) as the angle formed between the baseplate and the K-wire (A.F.V., R.S.C.).

A statistical analysis (A.F.V.) was performed using Prism (GraphPad Software®, Inc., CA). The difference between the extension angles was studied using the Wilcoxon test. The correlation between the extension angles of the first toe and the applied forces to the plantar fascia and the shortening of the plantar fascia. Statistical significance was defined at the 5% ($p \leq .05$) level.

Results

The results showed an increasing restriction of the dorsal extension of the first toe for a force applied to tension the plantar fascia for all specimens (Fig. 2).

This restriction was significant for all tension levels compared with the intentioned plantar fascia ($p < .001$). The decrease in dorsal extension was also significant for all other tension levels ($p = .043$ for level 1 to 4; other level steps $p = .018$) but further tensioning the plantar fascia

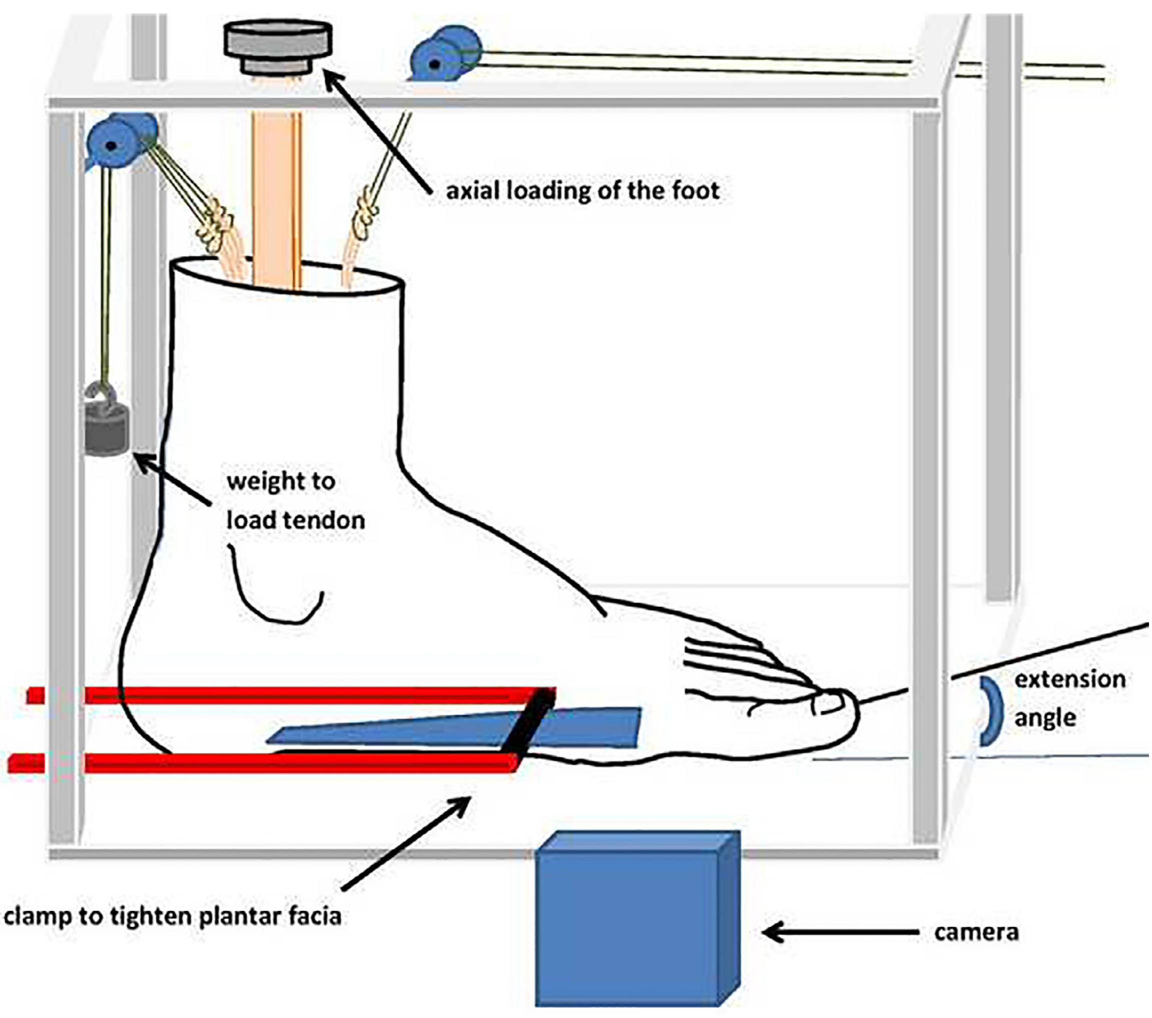

Fig. 1. Drawing of experimental setup.

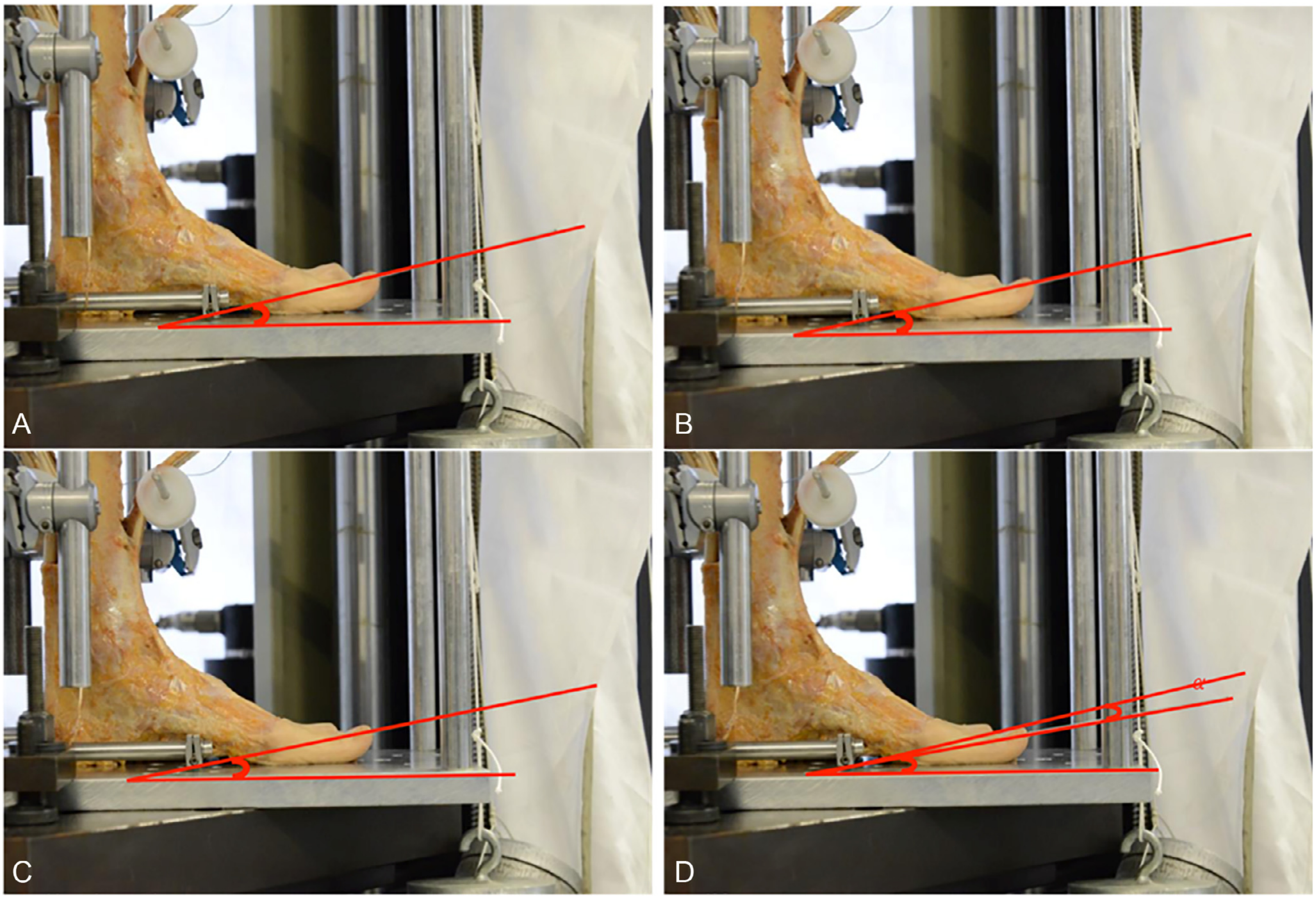

Fig. 2. Dorsal extension in (*A*) 1 specimen without tensioning of the plantar fascia compared with the same specimen with loading of approximately (*B*) 100 N, (*C*) 200 N, (*D*) and 350 N of the plantar fascia. Red lines indicate the angle between the ground and the dorsal extension. In the second row (right), the 2 red lines indicate the difference between extension of the great toe in tension level 1 (100 N, taken from the picture in first row, left) and extension with an applied load of 350 N. The difference in dorsal extension is significant (p = .048)

from the second or third tension level (200 and 300 N) to the maximum (p = .345 and p = .686, respectively).

The data for the tension comprise a non-Gaussian distribution according to the D`Agostino and Pearson omnibus normality test. A positive correlation with the decrease in extension of the great toe was found with a Spearman ρ = 0.87 (Fig. 3).

Significance was stated by the performed *t* test ($p < .001$). The maximum tension applied to the plantar fascia was 364 ± 13.87 N with a

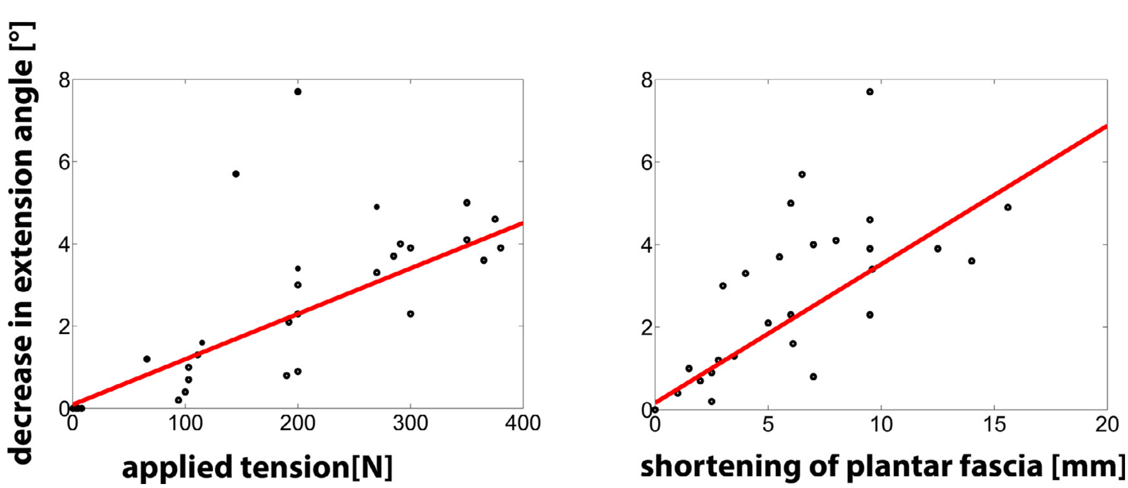

Fig. 3. Restriction in dorsal extension at the first metatarsophalangeal joint depending on applied tension (left) to the plantar fascia and shortening of the plantar fascia (right). The red line depicts linear regression. We found a positive correlation between tension and restriction in dorsal extension ρ = 0.87 ($p < .001$) and shortening of the fascia and dorsal extension (r = 0.84, $p < .001$) (N = 28 [4 tests in 7 specimens]).

Table
The alteration of tension and the corresponding shortening of the plantar fascia (N = 7 specimens)

Tension level	0	1	2	3	4
Tension, N	0	99 ± 16.1	197 ± 4.7	288 ± 14.8	364 ± 13.9
Shortening, mm	0	2.8 ± 1.7	5.7 ± 2.4	8.7 ± 3.8	10 ± 3.3
Decrease in extension angle, °	0	1.2± 0.99	3.0 ± 2.3	3.8 ± 1.1	4.2 ± 0.7

Angle significantly decreases ($p < .001$)

With increased tension, the reduction in first metatarsophalangeal joint-dorsiflexion increases as well. The decrease is significant for all levels referred to 0 ($p < .001$).

mean decrease of the extension angle of the first toe from 5.1 ± 3.5° of dorsiflexion by 4.8 ± 0.7° (Table and Fig. 4) to a mean dorsiflexion of 0.2 ± 4.3°. The decrease in extension of the first toe in relation to the applied tension (slope in Fig. 3) varied between the specimens. The maximum decrease in extension angle of 7.7° was found with an applied tension to the plantar fascia of 200 N, whereas for another specimen an applied tension of 365 N resulted in a decrease in extension angle of only 3.6°. The maximum additional force applied ranged within the reported physiological range for dorsiflexion angles of the great toe between 0° and 15° and an applied Achilles tendon force of 500N (11).

The applicable shortening to the fascia varied between the specimen with a maximum tension force below 350 N (270 and 200 N, respectively) in 2 specimens.

Equivalent results were obtained regarding the correlation between plantar fascial tightness and the dorsiflexion angle of the greater toe (Fig. 5). The regression analysis demonstrated a Pearson's r = 0.84 for a Gaussian distribution (D'Agostino and Pearson omnibus normality test); the t test confirmed a significant correlation ($p < .001$). For almost all specimens, tightening of the plantar fascia resulted in a depression of the forefoot leading to a functional cavus foot; however, the quantitative deformity could not be determined by the current setup.

Discussion

Our results demonstrate that increased tension of the plantar fascia results in a decrease of first MTPJ dorsiflexion. In the present study, the greater toe dorsiflexion has almost been nullified (0.24°) when maximally tightening the plantar fascia using a load of 364 N (i.e., 10 mm shortening). The overall decrease in dorsiflexion was 4.2°.

The study supports the hypothesis that an increased tension of the plantar fascia leads to an impaired dorsiflexion at the first MPTJ joint during stance phase. The mechanism could be due to a reversed windlass mechanism. The windlass mechanism has originally been described as tensioning of the plantar fascia resulting from toe extension (9). Besides this, as a result of the shortened distance between the metatarsal heads and the calcaneus a decrease in arch length is noted (9,14). By so doing, the plantar fascia commences to stabilize the medial longitudinal arch during gait and stores energy by elongation (9,14); however, additional load or contracture of the gastrocnemius muscle was identified as increasing the tension in the plantar fascia (17), a mechanism that may not be seen as the so-called "classic windlass" mechanism. It is known that any contracture of the Achilles tendon increases forefoot pressure and that increased tension of the plantar fascia will alter the plantar pressure in the terminal stance phase (15,16).

Based on those statements, it sounds logical that any contracture of the triceps surae muscle is likely to increase plantar fascia tension. The anatomical relation and connection between plantar fascia and Achilles tendon may also add important facts to this finding (16).

The impaired dorsiflexion at the first MTPJ during stance phase provides a plausible explanation for the development of HL. The authors

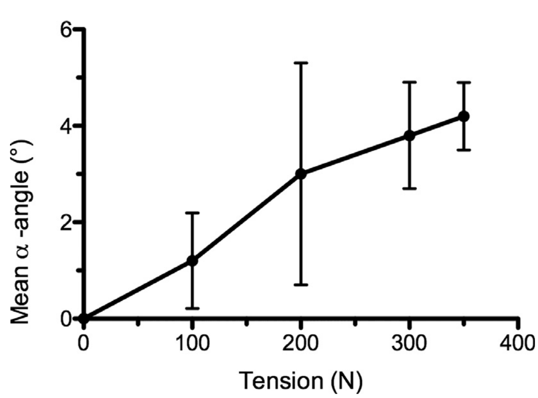

Fig. 4. Mean angle of deviation (°) in relation to applied tension of 100, 200, 300, and 350 N. Error bars indicate standard deviation (N = 7 specimens). The differences are significant but for changes from 200 to 350 N and 300 to 350 N (p = .345 and p = .686, respectively).

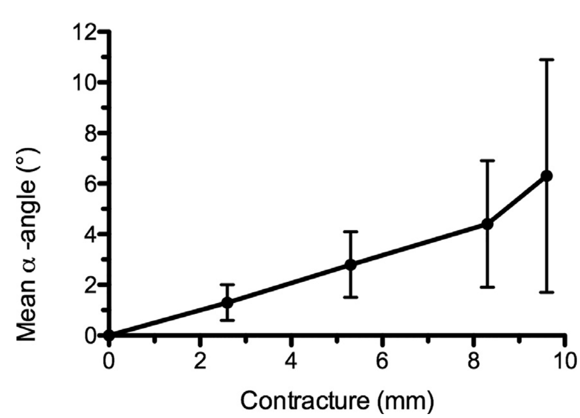

Fig. 5. Mean angle of deviation (N = 7 specimens) compared with applied shortening of the plantar fascia of 2.6, 5.3, 8.3, and 9.6 mm. Error bars indicate standard deviation. The differences are significant but for changes from 5.3 to 9.6 mm and 8.3 to 9.6 mm (p = .345 and p = .686, respectively).

also noted a decrease of longitudinal arch height when adding further tension onto the plantar fascia. This finding agrees with former studies, which showed a decrease of longitudinal arch height and arch length as well from the windlass mechanism during gait (9,13,18,19).

The measurement of the first MTPJ dorsiflexion in the literature references to the first metatarsal bone or the plantar plate (20). As a limitation of this study, first MTPJ-dorsiflexion referenced to the first metatarsal was not measured and changes in dorsiflexion might be due to a less horizontal position of the metatarsal bone resulting from a limitation of longitudinal arch height rather than true impairment of first MTPJ-extension. For propulsion during gait the extension of the first toe relative to the ground is important; therefore, we are convinced that the measured angle between the ground and the greater toe is of clinical interest.

Other limitations of the present study are the in vitro setup with a simplified static simulation of the stance phase neglecting dynamic forces and the intrinsic muscles; therefore, the current results must be seen with respect to experimental loading conditions simulating stance phase. Despite the small sample size, a significantly increasing restriction of the dorsal extension of the first toe for a force applied to tension the plantar fascia for all specimens could be detected. Furthermore, the present study cannot predict if the applied additional force to the plantar fascia can be found in patients with HL.

Besides these limitations, the presented data help to understand the role of the plantar fascia in the stance phase and provides a possible explanation to understand the evolution of HL. The current study adds relevant information because it supports the treatment of HL, which includes stretching of the triceps surae muscle and plantar fascia structure and surgical lengthening of the Achilles-calcaneal-plantar system (e.g., release of plantar fascia) if nonoperative treatment fails (21).

In conclusion, further clinical and experimental studies are necessary to address the question if stretching exercises are enough to ameliorate symptomatic HL disease or if other treatment options should be considered (e.g., corrective osteotomies, release of plantar fascia).

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