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Biomechanical Cadaveric Evaluation of the Role of Medial Column Instability in Hallux Valgus Deformity

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Abstract

Background: Medial column instability is a frequent finding in patients with flatfeet and hallux valgus, within others. The etiology of hallux valgus is multifactorial, and medial ray axial rotation has been mentioned as having an individual role. Our objective was to design a novel cadaveric foot model where we could re-create through progressive medial column ligament damage some components of a hallux valgus deformity.

Methods: Ten fresh-frozen lower leg specimens were used, and fluorescent markers were attached in a multisegment foot model. Constant axial load and cyclic tibial rotation (to simulate foot pronation) were applied, including pull on the flexor hallucis longus tendon (FHL). We first damaged the intercuneiform (C1-C2) ligaments, second the naviculocuneiform (NC) ligaments, and third the first tarsometatarsal ligaments, leaving the plantar ligaments unharmed. Bony axial and coronal alignment was measured after each ligament damage. Statistical analysis was performed.

Results: A significant increase in pronation of multiple segments was observed after sectioning the NC ligaments. Damaging the tarsometatarsal ligament generated small supination and varus changes mainly in the medial ray. No significant change was observed in axial or frontal plane alignment after damaging the C1-C2 ligaments. The FHL pull exerted a small valgus change in segments of the first ray.

Discussion: In this biomechanical cadaveric model, the naviculocuneiform joint was the most important one responsible for pronation of the medial column. Bone pronation occurs along the whole medial column, not isolated to a certain joint. Flexor hallucis longus pull appears to play some role in frontal plane alignment, but not in bone rotation. This model will be of great help to further study medial column instability as one of the factors influencing medial column pronation and its relevance in pathologies like hallux valgus.

Clinical Relevance: This cadaveric model suggests a possible influence of medial column instability in first metatarsal pronation. With a thorough understanding of a condition's origin, better treatment strategies can be developed.

Keywords: metatarsus varus, metatarsal pronation, medial column instability, flatfoot, hallux valgus, biomechanical analysis, cyclic loading

Introduction

Medial column instability is a frequent finding in patients with flatfeet, hyperlaxity, hallux valgus, and long-standing valgus deformity of the foot and ankle.[3,7,13,15,20,22] Even though it is a widely accepted concept and recognized component in different pathologies, there is no clear explanation, description, and/or understanding of its etiology and consequences on the foot.

The etiology of hallux valgus is multifactorial, and it is believed that the classic components of the deformity, that

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is, varus of the first metatarsal, pronation of the first ray, and valgus of the first toe, progress in sequential steps, considering unbalanced ligament constraints, joint incongruency, abnormal articular angles, and first tarsometatarsal instability.[15] No clear cause-effect association has been found between hallux valgus and first tarsometatarsal instability, so it would appear to be an oversimplification to consider the cuneometatarsal joint as the origin of the deformity.[1,13] Recently the concept of hallux valgus as a multiplanar deformity has been brought up to attention, giving more importance to medial column pronation as a factor to be considered when treating this deformity.[19] Metatarsal axial rotation has been mentioned as having an individual role in hallux valgus etiology.[16] The axial rotation of the first metatarsal has been shown to be part of a first-ray rotation, considering from the navicular proximally up to the first metatarsal distally.[10] If the medial column is rotating, we can suggest that midfoot ligament insufficiency occurs in midfoot joints allowing a change in alignment of the first ray. The role of midfoot ligament instability in hallux valgus etiology has not been analyzed before.

There are cadaveric protocols that progressively cut different ligaments on the medial arch of the foot, successfully re-creating a flatfoot [8,21] Nevertheless, there are no similar protocols that describe a medial column instability re-creating a hallux valgus. If this were to be achieved, hallux valgus origin would be clearer and, therefore, more appropriate treatment strategies would be applied. A model that could be of interest would be one that applies axial load and rotation to the foot, resembling the stress to which the medial column is subjected to in every step, that is, in the second ankle rocker of gait, where a plantigrade foot supports and absorbs all the impact through a controlled pronation of the foot with internal rotation of the tibia and talus.[11] A published model that used this concept was published in 2020, in a Lisfranc fracture model, where the authors included foot pronation-supination in addition to axial load delivering measurable bone diastasis in the midfoot area.[18]

Our objective was to design a cadaveric foot model where we could re-create through progressive medial column ligament damage some of the components of a hallux valgus deformity. We hypothesized that in this model we would be able to obtain a progressive varus inclination and pronation of the first metatarsal along with the progressive damage introduced.

Methods

Fifteen frozen cadaveric specimens of the lower leg were used, under 65 years old without known previous surgeries or trauma. They were thawed at room temperature for 16 hours before testing. All the manipulation, storage, and disposal of the specimens was performed according to approved protocols of our local Anatomy Department, following international standards. After an initial trial testing and evaluating the experimental setup, selecting reflecting markers positioning, how to damage ligaments without interfering with the Vicon system, and axial load capacity, 10 specimens were finally used. Each specimen was severed at a height of approximately 30 cm above the ankle joint. The tibial medullary canal was filled with a metallic rod with a truncated cone tip, ensuring adequate purchase inside the tibia. The ankle and talonavicular joints were fixed with 4.0-mm screws. The ankle was fixed in 30 degrees of plantar flexion to ensure load was applied on the forefoot area creating more torque in the midfoot region. The talonavicular joint was fixed in neutral alignment to maintain a stable hindfoot and to ascertain that we were not creating a flatfoot condition. The specimen's dorsal and medial skin was removed from the navicular up to the first metatarsophalangeal joint distally. The initial trial for this study included pull on the peroneus longus, extensor and flexor hallucis, tibialis posterior, Achilles, and tibialis anterior tendons. Except for the flexor hallucis longus (FHL), no evident change in bone position was observed, reason why only FHL pull was kept for the rest of the study. A dead weight equal to 50% of the stance phase force was applied to the FHL to add a valgus moment to the hallux[9] as it has been shown that is one of the factors contributing to the deformity.[14]

We used a similar setup as the one described by Wagner et al.[18] The specimen was mounted onto a specific frame designed for this experiment, allowing the specimen to remain vertical. On top of the jig, a special disc to support weight was incorporated, along with a set of bearings to allow a smooth axial rotation of the rod. Applying internal rotation to the rod (which was inserted in the tibia of each specimen) was able to produce pronation of the foot. Internal rotation of the rod (ie, foot pronation) was controlled through a pulley system attached between the rod and a tensile testing machine (Kinetecnics, Santiago, Chile). Five clusters with 3 reflective markers each were placed on the talus, dorsal surface of the navicular, medial, and intermediate cuneiforms and base of the first and second metatarsal (Figure 1, 2).

We recorded the spatial position of the clusters throughout the study. This was performed with a motion analysis system with 8 infrared cameras (Vicon Serie-T; Vicon Motion Systems Ltd) symmetrically positioned around the room, that detected (sample rate 50Hz) the reflective markers' movement throughout the testing. The measurement precision for this system is 1 mm.

Below every specimen, a force plate (FP-4000; Bertec Corp USA) was installed to control the amount of axial load applied. Our loading protocol consisted in applying 250 N

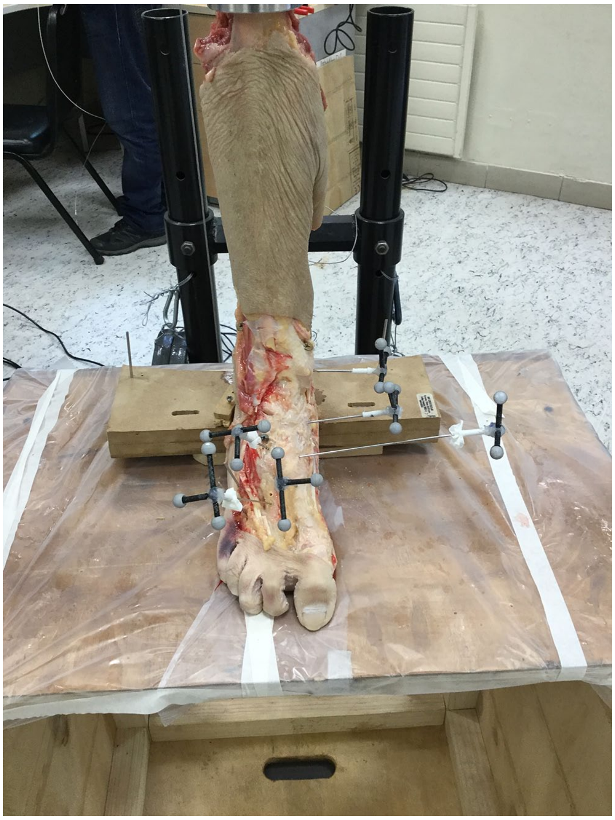

Figure 1. Frontal picture showing the biomechanical setting for the lower leg specimen. The cadaver feet were positioned in a frame that applies axial load and rotation. Axial pull on the FHL was applied as can be seen in this image (hallux interphalangeal flexion). The luminescent markers were applied on the talus, medial cuneiform, middle cuneiform, navicular, first metatarsal and second metatarsal.

of axial load and a variable torsional moment enough to obtain 30 degrees of internal rotation to the leg through the axial rod, simulating a pronation stress of the foot. Five cycles of internal rotation were applied holding the internal rotation for 5 seconds and allowing the foot to return to a neutral rotation, with a counterweight pulley.

We registered the alignment in the coronal plane (rotational alignment, pronation or supination) and in the axial plane (axial alignment, valgus or varus) of the following segments: talus and navicular (TN), talus and medial cuneiform (TC1), talus and first metatarsal (TM1), navicular and medial cuneiform (NC1), navicular and first metatarsal (NM1), medial and lateral cuneiform (C1C2), medial cuneiform and first metatarsal (C1M1), lateral cuneiform and second metatarsal (C2M2), and first metatarsal and second metatarsal (M1M2). Considering that the TN joint was fused, the TN segment was not expected to change as a result of midfoot ligament damage but was included to ascertain that we were not creating a flatfoot condition.

The spatial position of the different foot segments described in the previous paragraph were recorded along the rotational cycles with the motion analysis system.

We tested the specimens in 4 different conditions, that is, basal condition, first damage, second damage, and third damage. For the basal condition (first condition), we performed a distal medial metatarsophalangeal capsulectomy, from the neck of the first metatarsal bone to the base of the proximal phalanx, and laterally from the same aforementioned points, creating a rectangular window on both sides of the metatarsal head. This was performed to isolate any change in alignment of the foot segments to the midfoot joints and ligaments, eliminating any influence of the distal soft tissue attachments. The sequence of ligament damage was decided on the observation from trial specimens, where C1C2 and C1M2 ligament damage produced the most important kinematic changes. Therefore, we decided to apply the supposedly most important damage first, that is, the C1C2 and C1M2, followed by the less important damage, NC and C1M1. For the first damage (second condition), the dorsal intercuneiform and C1M2 ligaments were sectioned, using the whole length of a banana knife from dorsal to plantar. For the second damage (third condition), the naviculocuneiform ligaments were sectioned, using the same banana knife (Figure 3). Finally, the third damage (fourth condition) added a dorsal medial and lateral C1M1 damage. The previously mentioned loading protocol and registering protocol was applied under the 4 conditions described. For every condition tested, FHL pull was added or not, registering any change in the results obtained. Extreme caution was used when damaging the ligaments to ensure that the reflective clusters were not touched, and after every test we checked the integrity of the reflective markers.

Results were obtained per segment, showing the total alignment change in the frontal plane (ie, rotation, either pronation or supination) and in the axial plane (valgus or varus) relative to the basal condition along the cycles. We further analyzed the results per damage applied, showing which damage generated the biggest change in alignment.

Statistical analysis was performed with the SPSS software with the help of a statistician. Analysis of variance was performed for nested measures, estimated by mixed models. The statistical differences were considered with a P value $<.05$. The Bartlett test for equal variances was used to analyze the variability between specimens.

Results

The complete set of results are presented in Table 1 (angular values for rotational alignment) and Table 2 (angular values

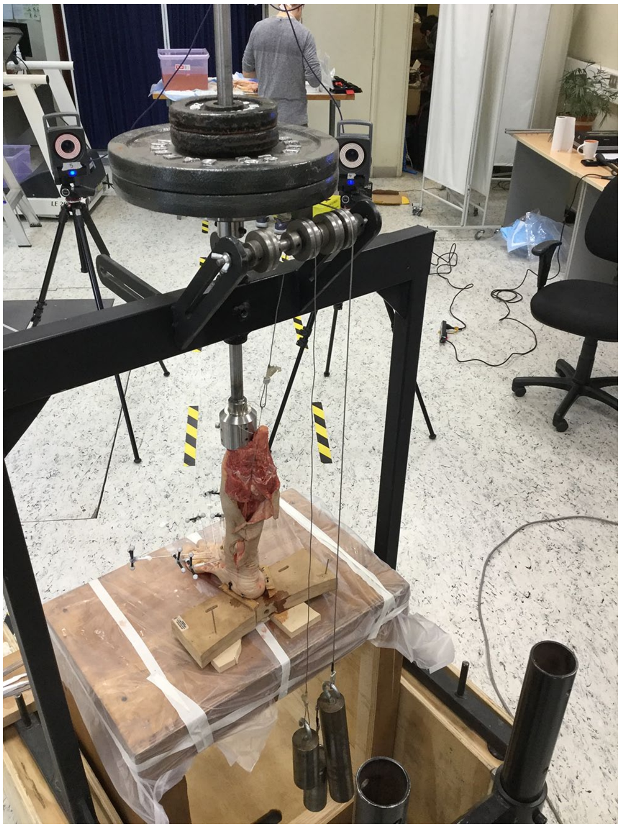

Figure 2. Posterior picture showing the setting of the lower leg specimen. The equinus ankle position can be seen. In addition, the flexor hallucis longus pulley can be seen, as well as the pulley that creates the tibial rotation movement (attached to the axial rod).

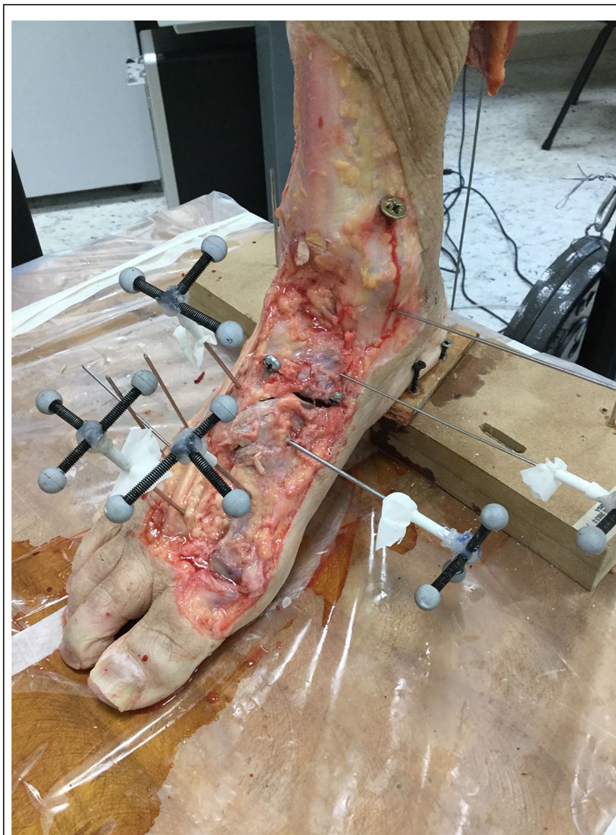

Figure 3. Magnified view of the specimen after the naviculocuneiform damage. The damage can be clearly seen. The screws that are visible are fusing the talonavicular and ankle joint.

for axial alignment). Figures 4 and 5 represent the results from Table 1 and 2, correspondingly.

Regarding frontal plane alignment or rotation (pronation or supination) separated by segment (Figure 4), with increasing damage a pronation change was registered in almost every segment, ranging between 2 and 8 degrees. Only segments C1M1, C2M2, and M1M2 showed almost no change in rotation after consecutive damage was applied. Flexor hallucis longus pull exerted a small change in the total registered values, without reaching statistical significance.

Regarding axial alignment or varus/valgus change, as it can be inferred from Figure 5, little change in segment motion was noted with increasing damage, ranging between 1 and 3 degrees of valgus, although statistical significance was observed in segments TC1, TM1, NC1, NM1, C1C2, and C2M2. C2M2 showed a varus movement initially during the cycles in the basal condition, changing to valgus changes after consecutive damages. Flexor hallucis longus pull exerted a small valgus change, significant only in segments TC1 and TM1.

Analyzing which damage created the biggest change in alignment, we analyzed the difference in degrees between conditions. This is presented in Tables 3 and 4 and re-presented graphically in Figures 6 and 7. In rotational alignment results, no statistical change was observed after the first damage. The main increase in pronation happened after the second damage, being statistically significant in TC1, TM1, NC1, NM1 and C1C2 segments, varying between 0.8 and 1.4 degrees of pronation. The third damage created small but significant supination changes in TC1, TM1, NC1, and C1C2 segments, varying between 0.25 and 0.5 degrees, finishing always in a more pronated situation compared to the basal condition.

Regarding segments axial alignment or varus/valgus change, when separated by damage (Figure 7), no statistical change was observed after the first damage. C2M2 shows a high angular change toward valgus but it did not reach statistical significance because of the standard deviation. Small valgus changes occurred after the second damage, varying between 0.2 and 0.5 degrees, being statistically significant in TC1, TM1, NC1, NM1, and C1C2 segments. It is

Table 1. Angular Values for Rotational Alignment, per Segment.[a]

Condition	TN	*P*/Cond.	TC1	*P*/Cond.	TM1	*P*/Cond.	NC1	*P*/Cond.	NM1	*P*/Cond.	C1C2	*P*/Cond.	C1M1	*P*/Cond.	C2M2	*P*/Cond.	M1M2	*P*/Cond.
Basal	2.80	ns	4.21	ns	6.93	ns	3.08	ns	5.52	ns	1.66	ns	3.73	ns	2.53	ns	1.66	ns
First damage	2.90	ns	4.33	ns	7.21	ns	3.12	ns	5.62	ns	1.81	ns	3.63	ns	2.51	ns	1.58	ns
Second damage	e2.70	ns	5.78	<.001/basal; .001/first	8.61	.001/basal; .049/ first	4.33	<.001/basal; <.001/first	6.90	ns	2.72	<.001/basal; <.001/first	3.72	ns	2.40	ns	1.85	ns
Third damage	2.86	ns	5.25	.006/basal; .047/second	8.32	.039/basal	4.07	<.001/basal; .002/first	6.90	0.013/basa l; 0.033/first	2.48	<.001/basal; .02/first	3.57	ns	2.68	ns	1.71	ns
Flexors, coeff.	0.29	ns	0.22	ns	–0.10	ns	0.26	ns	–0.17	ns	0.02	ns	–0.18	ns	–0.31	ns	–0.16	ns

Abbreviations: C1C2, medial and lateral cuneiform; C1M1, medial cuneiform and first metatarsal; C2M2, lateral cuneiform and second metatarsal; M1M2, first metatarsal and second metatarsal; NC1, navicular and medial cuneiform; NM1, navicular and first metatarsal; TC1, talus and medial cuneiform; TN, talus and navicular; TM1, talus and first metatarsal.
[a]Positive values represent pronation. For every segment measured, we present the statistical significance of the results against the corresponding group, presenting first the *P* value and then the condition against it was measured. Flexors coefficient: average increase or decrease in degrees for the corresponding segment when adding flexor hallucis longus pull.

Table 2. Angular Values for Axial Alignment, per Segment.[a]

Condition	TN	*P*/Cond.	TCI	*P*/Cond.	TMI	*P*/Cond.	NCI	*P*/Cond.	NMI	*P*/Cond.	C1C2	*P*/Cond.	CIMI	*P*/Cond.	C2M2	*P*/Cond.	MIM2	*P*/Cond.
Basal	2.43	ns	3.02	ns	3.11	ns	2.22	ns	2.23	ns	1.41	ns	1.17	ns	–0.75	ns	235	ns
First damage	2.56	ns	2.78		2.88		1.95	ns	2.07	ns	1.78	ns	1.53	ns	1.73	ns	2.32	ns
Second damage	2.35	ns	3.16	.013/first	3.08	.002/first	2.50	.024/basal; <.001/first	2.53	.015/basal; .001/first	1.95	.011/basal	1.42	ns	1.87	ns	2.66	ns
Third damage	2.35	ns	3.12	ns	2.72	.026/second	2.71	.016/first	2.76	.019/first	1.80	.04/basal	1.61		2.03	.033/basal	2.62	ns
Flexors, coeff.	0.32	ns	038	.03/basal	0.35	.04/basal	0.34	ns	0.29	ns	–02.0	ns	–0.02	ns	0.51	ns	–0.18	ns

Abbreviations: C1C2, medial and lateral cuneiform; C1M1, medial cuneiform and first metatarsal; C2M2, lateral cuneiform and second metatarsal; M1M2, first metatarsal and second metatarsal; NC1, navicular and medial cuneiform; NM1, navicular and first metatarsal; TC1, talus and medial cuneiform; TN, talus and navicular; TM1, talus and first metatarsal.
[a]Positive values represent valgus angulation. For every segment measured we present the statistical significance of the results against the corresponding group, presenting first the *P* value and then the condition against it was measured. Flexors coefficient: average increase or decrease in degrees for the corresponding segment when adding flexor hallucis longus pull.

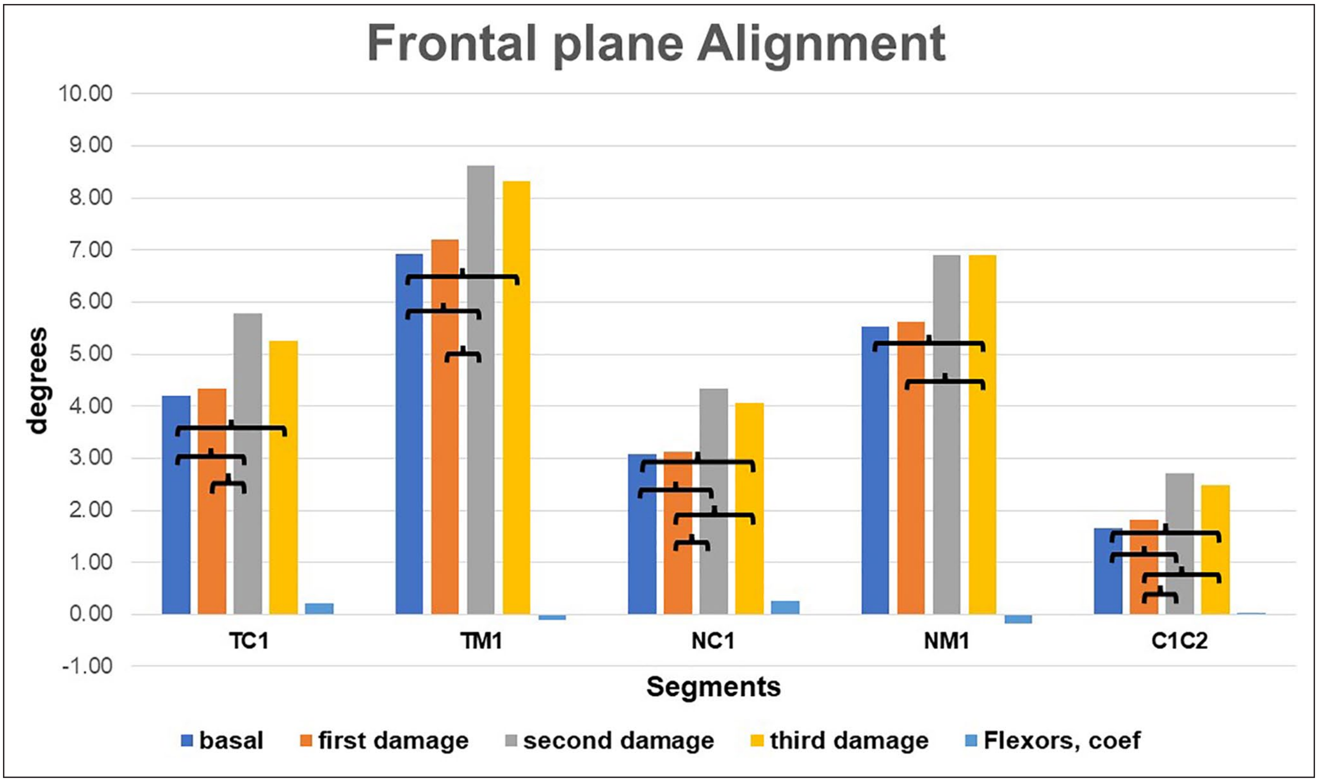

Figure 4. Angular values for rotational alignment of every segment measured, in degrees.
Frontal plane alignment per segment are represented by the vertical bars, in degrees, depending on the condition applied. Conditions are represented by different color bars. Positive values represent pronation. Only segments which showed statistically significant differences are presented. Segments: TC1: talus and medial cuneiform, TM1: talus and first metatarsal, NC1: navicular and medial cuneiform, NM1: navicular and first metatarsal, C1C2: medial and lateral cuneiform. Conditions: basal; first damage applied (C1C2 and C1M2 ligament sectioning); second damage applied (NC ligament sectioning); third damage applied (C1M1 ligament sectioning), Flexors coefficient: average increase or decrease in degrees when adding flexor hallucis longus pull. Each bracket starting and finishing position indicate in between which conditions there was a statistically significant change. [See online article for color figure.]

to be noted that after the third damage, as small additional valgus changes were observed in NC1 and NM1, small varus changes were observed in segments TM1 (going back to basal condition) and C1C2 (going back to first damage condition).

The analyses of variance between the specimens showed that they were comparable (Bartlett test).

Discussion

The development of hallux valgus deformity has been described to proceed in sequential steps, but there are many factors involved in the process, which makes it impossible to define which is/are the originating ones and which contribute the most.[15] For a long time, tarsometatarsal instability has been blamed to be responsible of the varus of the first metatarsal bone in hallux valgus, but no definitive cause or effect has been found yet.[1] A role for midfoot joint instability in the development of hallux valgus deformity has been suggested already in a cadaveric study, where positional changes along the first ray modifies the intermetatarsal angle and tibial sesamoid position.[3] A medial longitudinal arch collapse has been shown to be associated with metatarsal pronation, reinforcing the idea of a midfoot joint pathology in generating a hallux valgus.[7,13]

In our study, we achieved our objective as we were able to reproduce medial column pronation deformity. Our hypothesis was partially confirmed, as we did produce a progressive pronation deformity along with progressive ligament damage, but we were not able to generate a varus of the first metatarsal. To generate a varus deformity, we would probably need a model that damages multiple soft tissues, especially on the lateral aspect of the metatarsophalangeal joint. The intermetatarsal ligament, adductor tendon, and sesamoid apparatus were left intact in this model, being important lateral metatarsophalangeal stabilizers. We did not include them in the study to limit variables and restrict our results to depend on midfoot ligament damage. Surprisingly, naviculocuneiform ligament damage was the damage that produced the biggest change in segment alignment and not tarsometatarsal damage. It is

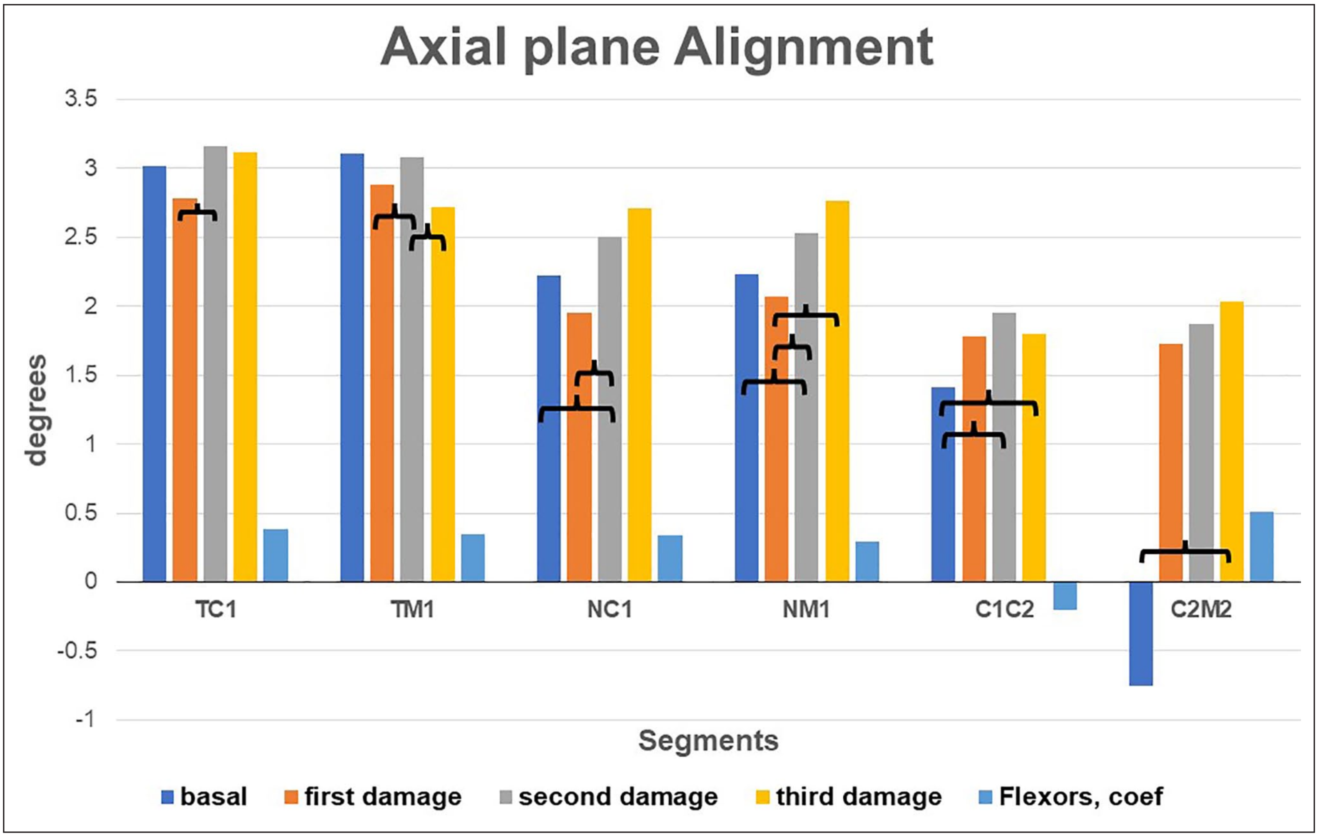

Figure 5. Angular values for axial alignment of every segment measured, in degrees.
Axial plane alignment per segment are represented by the vertical bars, in degrees, depending on the condition applied. Conditions are represented by different color bars. Positive values represent valgus. Only segments which showed statistically significant differences are presented. TC1: talus and medial cuneiform, TM1: talus and first metatarsal, NC1: navicular and medial cuneiform, NM1: navicular and first metatarsal, C1C2: medial and lateral cuneiform, C2M2: lateral cuneiform and second metatarsal. Conditions: basal; first damage applied (C1C2 and C1M2 ligament sectioning); second damage applied (NC ligament sectioning); third damage applied (C1M1 ligament sectioning). Flexors coefficient: average increase or decrease in degrees when adding flexor hallucis longus pull. Each bracket starting and finishing position indicate in between which conditions there was a statistically significant change. [See online article for color figure.]

Table 3. Change in Angular Values for Rotational Alignment, per Damage Applied, in Degrees.[a]

Segment	First Damage	Second Damage	Third Damage
TN	0.1	–0.2	0.16
TC1	0.12	1.45	–0.53
TM1	0.28	1.4	–0.29
NC1	0.045	1.21	–0.26
NM1	0.1	1.28	0
C1C2	0.15	0.91	–0.24
C1M1	–0.1	0.09	–0.15
C2M2	–0.02	–0.11	0.28
M1M2	–0.08	0.27	–0.14

Abbreviations: C1C2, intercuneiform; C1M1, medial cuneiform–first metatarsal; C2M2, middle cuneiform–second metatarsal; M1M2, intermetatarsal (first and second); NC1, naviculocuneiform; NM1, naviculo–first metatarsal; TC1, talocuneiform; TN, talonavicular; TM1, talo–first metatarsal.
[a]Positive values represent pronation.

Table 4. Change in Angular Values for Axial Alignment, per Damage Applied, in Degrees.[a]

Segment	First Damage	Second Damage	Third Damage
TN	0.13	–0.21	0
TC1	–0.24	0.38	–0.04
TM1	–0.23	0.2	–0.36
NC1	–0.27	0.55	0.21
NM1	–0.16	0.46	0.23
C1C2	0.37	0.17	–0.15
C1M1	0.36	–0.11	0.19
C2M2	2.48	0.14	–0.04
M1M2	–0.03	0.34	–0.04

Abbreviations: C1C2, intercuneiform; C1M1, medial cuneiform–first metatarsal; C2M2, middle cuneiform–second metatarsal; M1M2, intermetatarsal (first and second); NC1, naviculocuneiform; NM1, naviculo–first metatarsal; TC1, talocuneiform; TN, talonavicular; TM1, talo–first metatarsal.
[a]Positive values represent valgus.

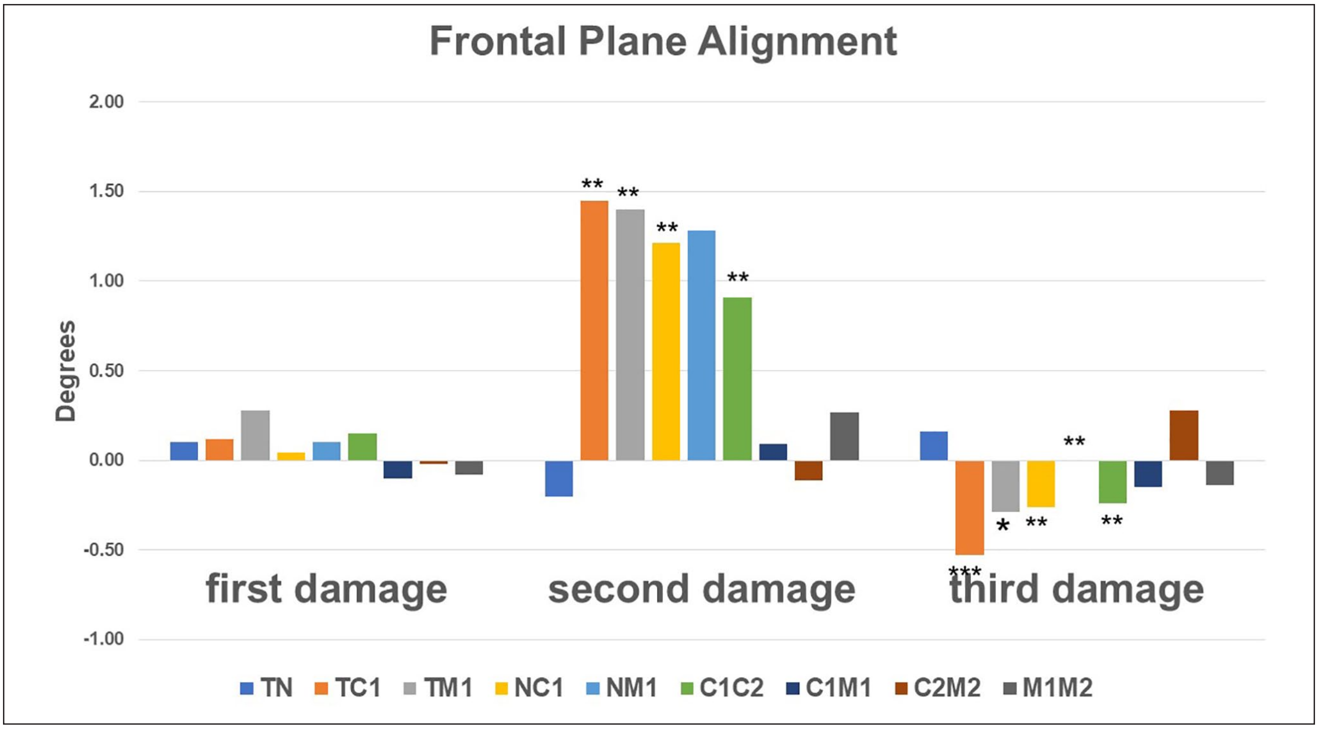

Figure 6. Change in Angular Values for rotational alignment, per damage applied, in degrees.
Rotational alignment changes per damage are represented by the vertical bars, in degrees, depending on the segment analysed. Segments are represented by different color bars. Positive values represent pronation. TN: talus and navicular, TC1: talus and medial cuneiform, TM1: talus and first metatarsal, NC1: navicular and medial cuneiform, NM1: navicular and first metatarsal, C1C2: medial and lateral cuneiform, C1M1: medial cuneiform and 1st metatarsal, C2M2: lateral cuneiform and second metatarsal, M1M2: first metatarsal and second metatarsal. Damage: first damage (C1C2 and C1M2 ligament sectioning); second damage (NC ligament sectioning); third damage (C1M1 ligament sectioning). The asterisks represent statistical significance between conditions. * = different against basal condition, ** = different against basal and first damage condition, *** = different against basal and second damage. [See online article for color figure.]

highly interesting that intercuneiform damage did not produce any significant change in alignment of the analyzed segments, as one could predict from Lisfranc damage literature that C1C2 and C1M2 damage were the most important midfoot ligaments connecting the forefoot to the midfoot.[18] Having said this, we were not interested in generating a midfoot collapse, and it can be possible that a complete plantar damage to the C1C2 and C1M2 ligaments with higher axial load could have shown alignment changes. To be noted too is the small effect damage over C1M1 generated on segment alignment, as it produced small supinating changes in the frontal plane and small variable changes in the axial plane. It could be possible that C1M1 ligaments were still connecting midfoot and first ray transmitting a pronation torque, and after releasing those ligaments, a "recoil" happens generating supination changes, but ending always in a more pronated situation compared to the basal condition. There are studies that have shown the importance of the C1M1 joint in hallux valgus. Nevertheless, no direct cause-effect relationship has been conclusively shown. Coughlin et al[2] showed how the instability measured with the Klaue device improved after a metatarsal osteotomy, stating that instability is secondary to the deformity and not a joint instability itself (it is a consequence and not the cause). Pasapula et al[12] recently showed how there appears to exist some relationship (independent risk factors) between hallux valgus, spring ligament insufficiency, and first-ray instability, thus suggesting a multi- ligament compromise in hallux valgus. The previous findings could make us suggest that some importance can be given to different joints in the medial column other than only the first tarsometatarsal one, when addressing hallux valgus pathology.[4]

Relative to tendon imbalance in hallux valgus deformity, it has been shown that peroneus longus pull increases pronation of the first metatarsal bone and decreases the intermetatarsal angle.[5] An important role in hallux valgus deformity has been suggested too for the flexor and extensor hallucis longus, both producing valgus torque at the metatarsophalangeal joint.[17] Because of this, we decided to add the flexor hallucis longus tendon pull to the analysis, finding a small, but significant, valgus effect over the talus–medial cuneiform and talus–first metatarsal segments. We can suggest that in a chronic situation with widespread

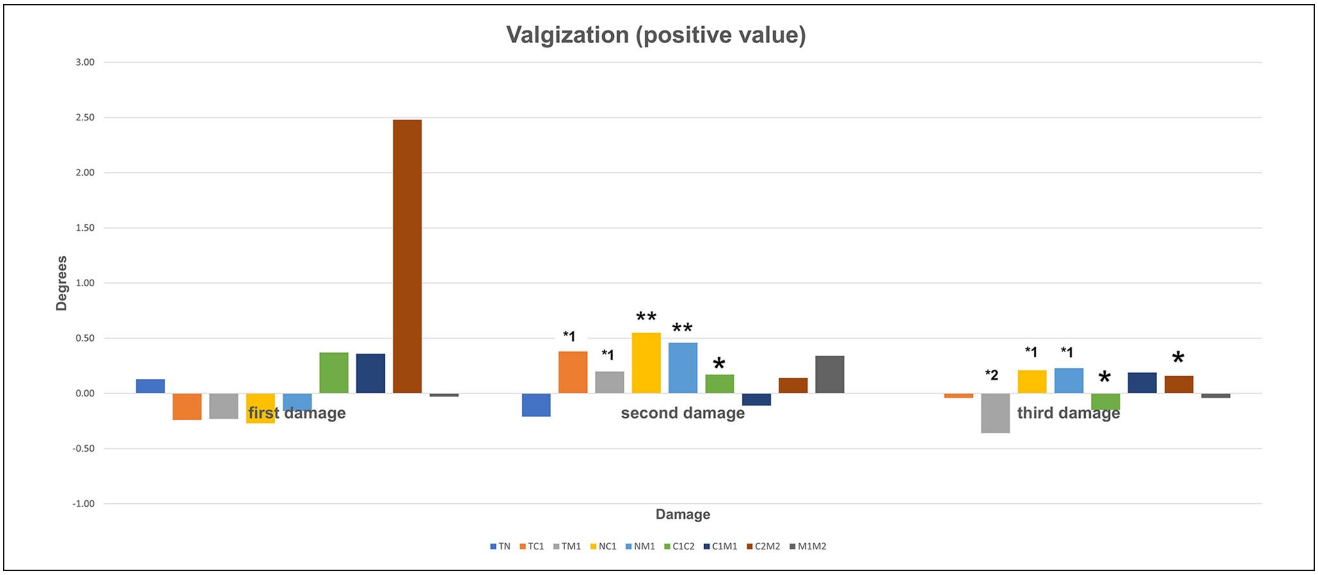

Figure 7. Change in Angular values for axial alignment, per damage applied, in degrees.
Axial plane alignment changes per damage are represented by the vertical bars, in degrees, depending on the segment analysed. Segments are represented by different color bars. Positive values represent valgus. Segments: TN: talus and navicular, TC1: talus and medial cuneiform, TM1: talus and first metatarsal, NC1: navicular and medial cuneiform, NM1: navicular and first metatarsal, C1C2: medial and lateral cuneiform, C1M1: medial cuneiform and 1st metatarsal, C2M2: lateral cuneiform and second metatarsal, M1M2: first metatarsal and second metatarsal. Damage: first damage (C1C2 and C1M2 ligament sectioning); second damage (NC ligament sectioning); third damage (C1M1 ligament sectioning). The asterisks represent statistical significance between conditions. * = different against basal condition, ** = different against basal and first damage condition, *** = different against basal and second damage, *1 = different against first damage, *2 = different against second damage. [See online article for color figure.]

damage over the metatarsophalangeal ligaments and tendon subluxation, a more evident effect of extrinsic tendons could be found, but this has yet to be studied.

Limitations of this study include the fact that it is a novel cadaveric model, in which we reproduced mainly the pronation component of hallux valgus. More development of this model is needed to be able to include degenerative and progressive damage to other soft tissues. Only including axial load and pronation in the model also limits our understanding of the etiology of hallux valgus, although as stated in the introduction, weightbearing and pronation are the most important load bearing instances where the foot is stressed. Including additional tendon pull such as posterior tibial, peroneal tendons, or Achilles could have added more information about their influence in bone rotation,[6] but as commented in the methods section, our preliminary trial made us choose only the FHL tendon pull. This study included a small number of cycles and thus no time for more significant and widespread damage to other soft tissues in the foot. We did not expect big angular changes in our results, as it has been seen in other midfoot cadaveric studies that when ligament damage is introduced, only millimetric changes are observed.[18]

In summary, our study shows that in a novel cadaveric model where axial load and pronation of the foot are applied, progressive damage of the medial column translates into significant pronation on the first ray. The naviculocuneiform joint ligament damage is the most significant one responsible for instability of the first ray, considering pronation and valgus deviation. The first tarsometatarsal joint ligament damage decreased the pronation deformity, somehow disconnecting the first ray from its corresponding metatarsal. No consistent change in valgus or varus was produced after first tarsometatarsal joint damage. Having said this, we must remember the importance of the first tarsometatarsal joint in stabilizing hallux valgus deformity. This is a novel model, so no definitive conclusions can be drawn from these results. Nevertheless, these findings should draw our attention to other joints along the medial column, besides the first tarsometatarsal joint, when investigating hallux valgus etiology and considering surgical treatment.

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