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Morton's Extension on Hallux Rigidus Pathology

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Abstract: Study design, case-control study: Background, Morton's extension (ME) is a kind of orthotic that has been used as a conservative treatment of painful hallux rigidus (HR) osteoarthritis, but only their effects on first metatarsophalangeal joint (MPJ) mobility and position in healthy subjects have been studied, but not on its applied pulled tension forces neither in subjects with HR. Objectives: This study sought to understand how ME's orthotics with three different thicknesses could influence the kinematic first MPJ by measuring hallux dorsiflexion using Jack's test and a digital algometer with a rigid strip anchored to the iron hook's extremity and comparing subjects with healthy first MPJ mobility to those with HR. We aimed to clarify whether tension values were different between healthy and HR subjects. Methods: Fifty-eight subjects were selected, of whom thirty were included in the case group according to HR criteria and twenty-eight were included in the control group. A digital algometer (FPX®® 25, Wagner Instruments®®, Greenwich, CT, USA) was used to assess the pulled tension values (kgf) of the first MPJ during Jack's test. Results: The pulled tension values were highly reliable (ICC > 0.963). There were no statistically significant differences between the pulled tension values for the different ME conditions in the case ($p = 0.969$) or control ($p = 0.718$) groups. However, as it's expected, there were statistically significant differences comparing all pulled tension values between case and control group subjects ($p < 0.001$). Conclusions: Different ME's thicknesses had no influence on the pulled effort applied during the dorsiflexion Jack's test between the healthy and HR groups; therefore, it can be prescribed without joint-care danger. In addition, it is proven that there is greater resistance to performing Jack's test in the HR group than in the healthy group, regardless of ME's orthotics. Furthermore, it is shown that the digital algometer device is a valid tool to detect the first MPJ restriction and is more reliable than other tests.

Keywords: algometer; hallux rigidus; metatarsal bones; metatarsophalangeal joint

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1. Introduction

The limitation of the first metatarsophalangeal joint (MPJ) can be classified as functional hallux limitus or hallux rigidus [1] (HR) depending on the level of this limitation, reaching null movement on the last stage; this one, also called osteoarthritis, is a pathological condition referred to by other authors as hallux flexus [2] or hallux equinus [3] too. HR is the most common presentation with pain of the first MPJ, with an incidence of ~2.5% in people older than 50 years of age [4]. The main symptoms are pain with an active or passive load under manual dorsal and plantar mobilization of the first MPJ or during the heel off-phase of the gait cycle, or pain related to impingement of the medial branch of the superficial peroneal nerve from the dorsal osteophyte, as well as cartilage destruction and restricted joint mobility [5]. HR could disturb the normal gait cycle and thus affect other structures of the body, such as the knee, ankle, lower back, and hip [6]. Understanding gait as the different phases of the human displacement on the floor, which are divided into the phase of first contact, phase of full contact, phase of propulsion, and phase of push-off [7]. If this pathological status is not addressed, surgery will eventually be required to improve the symptoms and restore mobility [8].

Although most literature reviews have shown that non-surgical interventions cannot stop the degenerative progress of HR in the first MPJ [9], non-surgical management of symptomatic HR has been suggested as an early-stage (0–2) palliative solution [10]. Non-steroidal anti-inflammatory drugs, ultrasound therapy, shoe modifications, hallux strapping, and rigid insoles have been identified as the best options to reduce clinical pain [10–12], with a 60% success rate [13]. These rigid insoles with a modification on the first ray, which was also described as Morton's extension (ME) [6,13], have been used in orthopedics to treat restrictive pathologies like symptomatic HR. MEs are rectangular pieces of semi-rigid material (of varying thicknesses) that are placed under the insoles around the first MPJ. Morton [14] was the first author to argue for first-ray alteration as an etiology of overload disease under the second metatarsal bone, but it was Ebisui [14] and Kelso [15] who detected the relationship between the first-ray dorsiflexed position in the sagittal plane and the first MPJ's restrictive dorsiflexion motion and Dananberg [16] who related its biomechanical consequences.

The Windlass mechanism has been described as a spring system formed by a cable that is attached to a fat plantar pad and calcaneus bone on one end and the proximal phalanx of the hallux base and the first metatarsal head on the other. This cable is the plantar aponeurosis and—under normal conditions—stabilizes the medial arch of the foot during the gait cycle. The Windlass mechanism also rises and shortens the medial arch through the first MPJ's dorsiflexion during the heel-off phase of the gait cycle [17]. When the first MPJ's mobility is restricted by soft tissue structures or bone alterations [18,19], this windlass mechanism is altered, thereby affecting the normal propulsion of the body. One of these bone alterations is metatarsus primus elevatus [20,21], where the first metatarsal bone takes an elevated position in the sagittal plane relative to the second metatarsal bone and to the floor. In this way, simulated restriction of the first MPJ's dorsiflexion with a 4- or 8-mm acrylic platform under the first ray (e.g., a ME) was already demonstrated, using a classical goniometer, in healthy participants [22] However, it remains unclear if the first MPJ, in a metatarsus primus elevatus position induced by ME, would have the same reducing effects in subjects with the first MPJ restriction pathology (subjects with HR).

Nowadays, mobility assessment of the first MPJ is one of the most common methods to assess the biomechanical function of the foot, although a few more complicated kinematic parameters can also be useful [23]. Given this, Jack's test describes a passive, static, weight-bearing resting position (WRP) to assess the dorsiflexion mobility of the first MPJ, thereby simulating the push-off phase of the gait cycle by executing a simulated Windlass mechanism [17], pulling the hallux in the dorsal direction passively until the movement stops [24,25].

There are a few ingenious studies that assess the mobility [26–28] and the reliability [29,30] of the first MPJ grades of motion on non-WRP in healthy subjects but not with HR pathology or on WRP, a condition consistent with reality [31]. In addition, the pressure needed to reach the motion but not the pull tension necessary to perform the manual Jack test has been assessed, which is the most common maneuver in daily clinical practice. Furthermore, if the clinicians use ME to treat HR, it would be advisable to know the kinematic repercussions on the joint under different ME thicknesses.

On the other hand, it is remarkable to know that a lot of musculoskeletal pathologies do not show any mobility and/or visual restrictions, cause biomechanical forces moments do not always have kinematics behavior but also kinetics effects [32,33] and so that that's why it is hypothesized that tension values can represent better than mobility values what occurs inside the joint.

Therefore, the principal purpose of this research was to know the effects of three different ME insoles on the pulled tension values that were required to perform simulated dorsiflexion of the first MPJ, executing a validated [34] Jack's test, in subjects with normal and restricted ranges of motion of the first MPJ (i.e., HR). Secondary to this study, we sought to compare the tension values of healthy and HR subjects during Jack's test without any ME insoles. Knowing these force-inside-joint alterations, the ME insoles could be recommended to avoid overload inside the joint.

Due to their regular shape and the fact that healthy first MPJs have shown normal values of dorsiflexion grades during the final phase of the dynamic gait [35] and arthrosis first MPJs with osteoarthritis surfaces damage have shown important limitations of mobility [36], it was thought that the tension values needed to develop the dorsiflexion grades needed to perform the Jack test were greater for HR subjects than healthy participants. Hence, the hypothesis of the present study was that there was a difference in tension values between subjects with HR and healthy subjects in dorsiflexion mobility of the first MPJ during Jack's test with or without any of the ME insoles.

2. Methods

2.1. Study Design

A case-control study was carried out between January 2021 and March 2021, following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) requirements [37]. This research was approved by the Institutional Review Board of the Hospital Universitario Nuestra Señora de Valme affiliated with the authors in October 2020, ref number f7f4a6567676d7ba7163bce0d15e7f98c9f33355; the digital algometer used in the present research is non-dangerous and non-invasive. All legal permissions were obtained. All the participants had informed consent and data protection act forms to be signed by them if they were in agreement with the study. The standards of the Helsinki Declaration regarding human experimentation were respected; the experiments were performed in accordance with relevant guidelines and regulations or adhered' to the "Declaration of Helsinki 1964".

2.2. Participants

The research case group associated with HR consisted of participants, men and women, between 35 and 45 years old, who met the following inclusion criteria: (1) restricted first MPJ-assisted dorsal mobility, according to a validated active range of motion with the subject in a non-weight-bearing test, below 10 degrees of dorsal flexion to consider hallux rigidus [1]; (2) restricted non-weight-bearing-assisted plantarflexion of the first MPJ under 35° [38]; (3) pain during active and passive plantarflexion and dorsiflexion of the first MPJ [39]; (4) no trauma or injury in the lower limbs and feet for 1 year ago; (5) normal range of motion in the subtalar joint (30°), midtarsal joint (15° along the longitudinal axis), and ankle joint (at least 20° of dorsiflexion with the knee fully extended) [19] according to classical maneuvers [19] and (6) age between 30 and 60 years old. Subjects were excluded if they were under the effects of any drugs or had any hypermobility condition (e.g., ligamentous hyperlaxity). The control group consisted of healthy, age-matched subjects with a neutral foot posture index (between 0 and +5 points) according to validated tool criteria [40].

2.3. Measurement Procedures, Instruments, and Variables

To set the first metatarsal bone in the dorsiflexion position, flat insoles were selected in 30° shore-A material with ME thicknesses of 2, 4, and 8 mm [22] and made (Termofeet SL, Madrid, Spain) in 45° shore-A hardness of ethylene-vinyl acetate (EVA) (Figure 1), adjusted to the size of the subject's feet, and incorporated randomly into the right foot for each measurement and for each subject. The ME was a rectangular piece of EVA that was also placed inside the insoles under the area of the first MPJ. The proximal edge of the piece was located in the anatomical neck of the first metatarsal bone, and the distal edge was located in the middle of the proximal phalanx of the hallux. Three measurements were made for each condition to determine consistency. To avoid any imbalance, the same flat insole in the contralateral foot was placed.

Figure 1. Flat insoles with Morton's extension of 2, 4, and 8 mm.

To assess the effects of the three ME thicknesses on the first MPJ, a digital algometer tested previously [41] (FPX®® 25, Wagner Instruments®®, Greenwich, CT, USA) with a rigid strip anchored to the iron hook's extremity was used. This device had a 10 × 0.01 kgf (kilogram-force) capacity/graduation and an accuracy of 0.3% of the full scale. Previous studies have reported good reliability and validity for this device (intra-rater reliability: 0.895, 95% CI = 0.846–0.928; SEM = 2.36; MDC = 6.55) [42]. In the static WRP, the proximal phalanx of the hallux was pulled to its maximal dorsal position until the foot showed supination movement, which was evaluated through the Helbing sign axis [19,43] as the change in the Helbing lines, drawn before, verifying the supination movement of the rearfoot with a digital goniometer Preciva®® (Winkelmesser, Munich, Germany), during the performance of the hallux traction. This technique was developed by an experienced clinician (RS-G), transmitting the tension needed to perform Jack's test [25] through the rigid strip anchored to the algometer (Figure 2). To avoid bias, the verticality of the thrust was maintained to avoid the change in direction of the dorsal vector and always at the same height. The order between the WRP and ME's placing and between ME's thickness conditions was simple and randomized (Figure 3).

Figure 2. Digital algometer pulling hallux with Morton's extension flat insole.

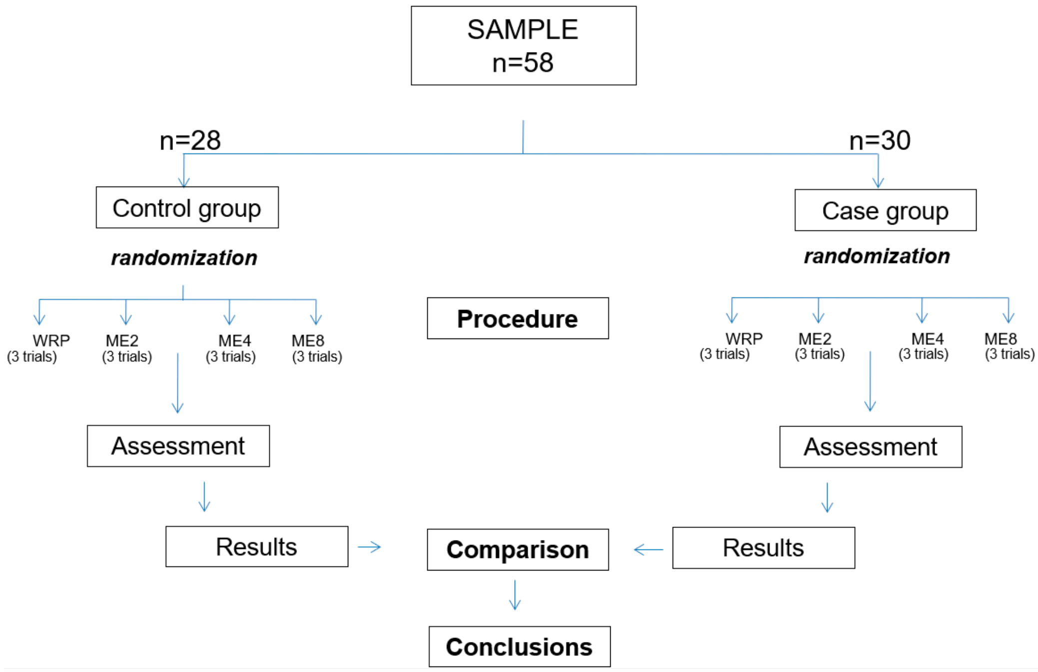


Figure 3. Work chart of the procedure. Abbreviations: CASES GROUP = participants with hallux rigidus; CONTROL GROUP = healthy participants, without hallux rigidus; ME = Morton's extension insoles; WRP = weight-bearing resting position (without insoles).

2.4. Sample Size

The sample size was calculated using software from the Epidemiology Unit of Biostatistics (www.fisterra.com, accessed on 20 May 2021) to detect differences in the kgf applied to the first MPJ during Jack's test between the case and control groups and between the different MEs. Previous measures in healthy subjects have shown that the mean strength with the 8 mm insole was 3.2 ± 0.7 kgf (mean ± SD) (personal observations). In another similar study, ten healthy subjects were recruited [22]. According to these data, we needed to include at least 46 subjects (23 in the control group and 23 in the case group) to detect a difference in the mean strength of 0.7 kgf using Student's t-test for independent samples with 80% power, in a bilateral contrast, and $\alpha = 0.05$. Considering that some subjects could be lost to follow-up, we established a final sample of 60 subjects (30 per group).

2.5. Statistical Methods

To validate the reliability across the measurement trials, the 25 intra-class correlation coefficients (ICCs) were evaluated according to the specifications of Landis and Koch: coefficients less than 0.20 represent a slight agreement; between 0.20 and 0.40, fair reliability; between 0.41 and 0.60, moderate reliability; between 0.61 and 0.80, substantial reliability; and between 0.81 and 1.00, almost perfect reliability. Coefficients of 0.90 or larger reflect sufficient reliability, given that reliability coefficients exceeding 0.90 increase the likelihood that a measure is also reasonably valid [43].

All the continuous data were studied for normality using the Kolmogorov–Smirnov test; normal distributions were noted for p-values > 0.05. Independent Student's t-tests were used to determine if there were significant differences between the case and control groups under the WRP and the three continuous variables used in the study. Similarly, ANOVA was used to test if there were significant differences in the applied tension values between the different conditions. Tukey's test was used for post hoc comparisons. The Spearman rank correlation coefficient was used to determine the correlation between the thickness of the ME insoles and the effect on the pulled applied tension. We present each descriptive summary as the mean ± SD. For all the analyses, we considered p-values < 0.05

(within a 95% confidence interval) as statistically significant. We analyzed the data using SPSS software, version 19.0 (SPSS Science, Chicago, IL, USA).

3. Results

A total of 58 subjects (34 females and 24 males) participated in the study; 28 subjects were recruited to the control group and 30 subjects were included in the case group (Figure 4).

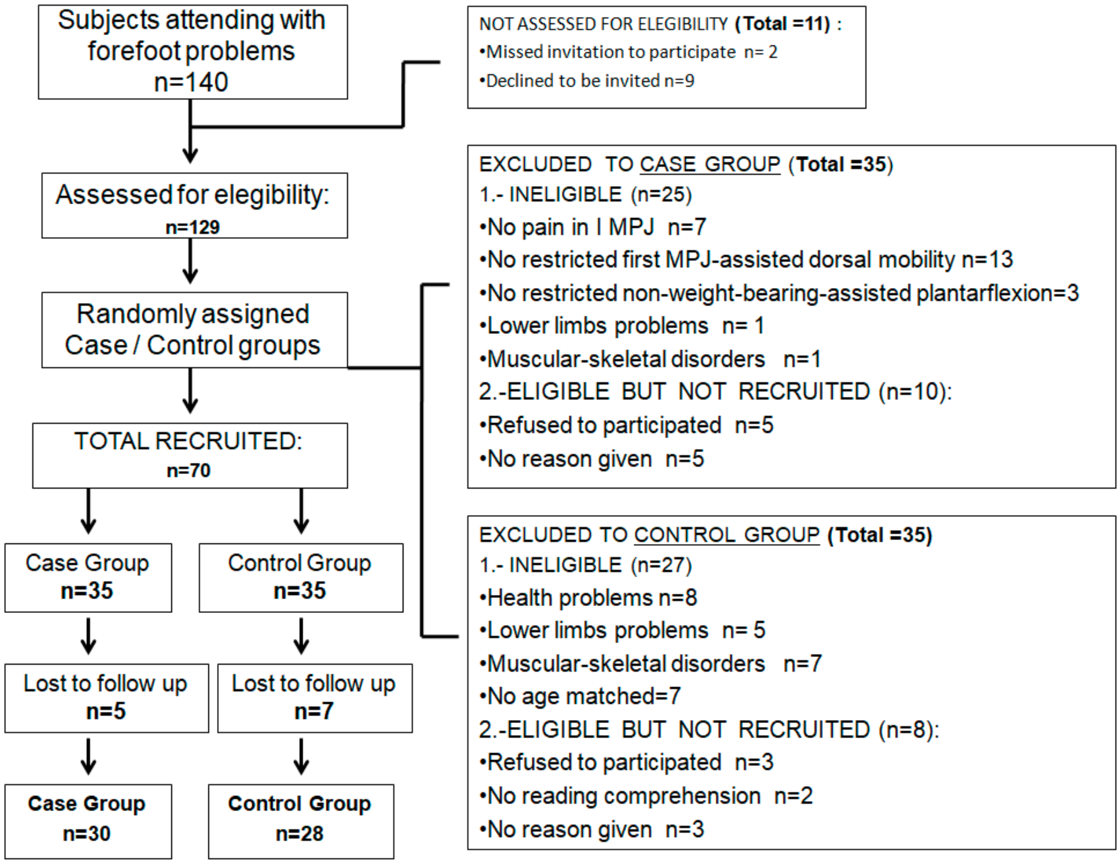


Figure 4. Flow chart. Representation of participants' recruitment. IMPJ = first metatarsophalangeal joint; n = population.

The sociodemographic characteristics of the case and control groups are shown in Table 1. The homogeneity of the four measured physical characteristics [weight, height, foot size, and body mass index (BMI)] guaranteed the applicability of the results to the sample. The distribution was normal ($p > 0.05$).

The reliability of the variables followed perfect ICC criteria and ranged from 0.963 to 0.989 (Table 2). According to our obtained values (Table 2), the control group required almost 1 kgf less effort than the case group to move the MPJ dorsally under the 4 mm ME [4.122 ± 0.162 kgf in the case group vs. 3.325 ± 0.139 kgf in the control group under WRP ($p < 0.001$); 4.211 ± 0.116 kgf in the case group vs. 3.538 ± 0.123 kgf in the control group under a 4 mm ME ($p < 0.001$)]. The differences were smaller for the 2 mm ME: 4.139 ± 0.142 kgf in the case group vs. 3.421 ± 0.133 kgf in the control group ($p < 0.001$) (Figure 5). Nevertheless, in the case group, the WRP and the different ME insoles had similar pulled tension values, which ranged from 4.122 ± 0.16 kgf in the WRP to 4.211 ± 0.116 kgf in the 4 mm ME condition (not statistically significantly different, $p > 0.05$); the differences were smaller with the 2 and 8 mm MEs (4.139 ± 0.142 kgf with a 2 mm ME and 4.179 ± 0.126 kgf with an 8 mm ME) (Table 2). For the controls, the WRP and different ME insole conditions showed similar pulled tension values, which ranged from 3.325 ± 0.139 kgf in the WRP to 3.538 ± 0.123 kgf with the 4 mm-thick ME; the 8-mm-thick ME (3.465 ± 0.134 kgf) and 2 mm-thick ME (3.421 ± 0.133 kgf) values were quite similar (Table 2) ($p > 0.05$). These data are shown in Figure 5, where it is possible to see the differences in tension values between the groups.

Table 1. Descriptive socio-demographics data of cases and control healthy group subjects.

	Total Population $n = 58$	CASES GROUP HR Participants $n = 30$	CONTROL GROUP Healthy Participants $n = 28$	
Variable	**Mean ± SD (95% CI)**	**Mean ± SD (95% CI)**	**Mean ± SD (95% CI)**	***p*-Value**
Age (years)	40.62 ± 1.12 (40.98–40.33)	42.53 ± 5.72 (44.57–40.48)	38.57 ± 1.12 (38.98–38.15)	0.9
Weight (kg)	67.44 ± 9.98 (70–64.87)	66.6 ± 9.37 (69.95–63.24)	68.35 ± 10.7 (72.31–64.38)	<0.001
Height (cm)	167.77 ± 10.01 (170.34–165.19)	167.53 ± 7.72 (170.29–164.76)	164 ± 12.14 (168.49–159.5)	<0.001
Foot Size (Es)	40.2 ± 1.9 (40.50–39.89)	38.2 ± 2.10 (38.95–37.44)	40.3 ± 0.35 (40.42–40.17)	<0.001
BMI (kg/m^2)	21.48 ± 1.47 (21.85–21.1)	20.2 ± 1.74 (20.82–19.57)	22.95 ± 2.58 (23.90–21.99)	<0.001

Abbreviations: N = sample size; CASES GROUP = participants with hallux rigidus; CONTROL GROUP = healthy participants, without hallux rigidus; SD = Standard Deviation; CI = confidence interval; *p*-value = level of significance; $p < 0.05$ (with a 95% confidence interval) was considered statistically significant; Es = number according to European mode size; BMI = body mass index.

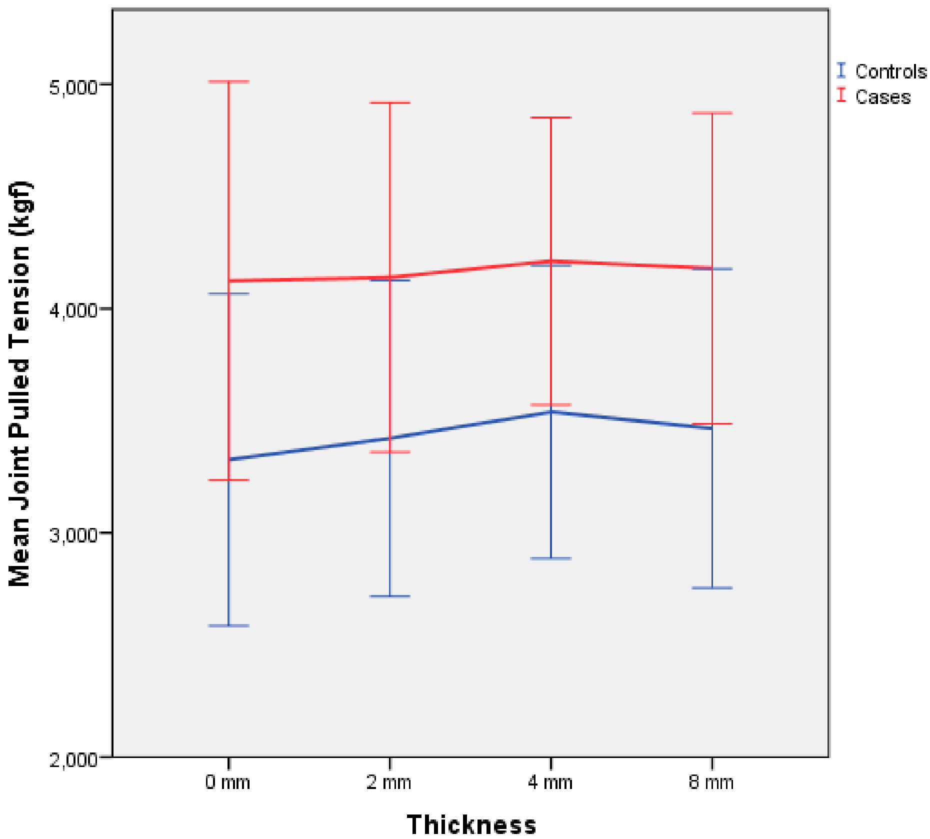


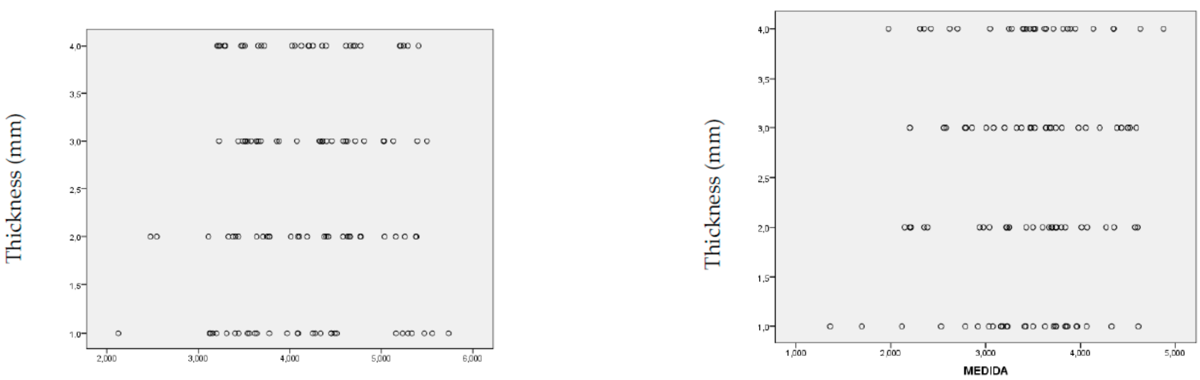
Figure 5. Difference in pulled joint tension applied (kgf) between the case group and the control group. Mean + SD data between cases (red lines) and control (blue lines) groups. The highest values of cases in the Hallux rigidus group showed a clear difference.

Table 2. Mean values and reliability of pulled tension for measurements of first MPJ under each Morton's extensions insoles thickness between cases and control groups.

	CASES GROUP *n* = 30		**CONTROL GROUP** *n* = 28		
Thickness ME Variable	**Mean (kgf) ± SD (95% CI)**	**ICC 95% IC (Li-Ls)**	**Mean (kgf) ± SD (95% CI)**	**ICC 95% IC (Li-Ls)**	***p*-Value**
I MPJ WRP	4.122 ± 0.162 (3.79–4.45)	0.989 (0.98–0.994)	3.325 ± 0.139 (3.03–3.61)	0.971 (0.948–0.98)	<0.001
ME 2 mm	4.139 ± 0.142 (3.84–4.43)	0.97 (0.94–0.985)	3.421 ± 0.133 (3.14–3.69)	0.963 (0.928–0.982)	<0.001
ME 4 mm	4.211 ± 0.116 (3.97–4.45)	0.969 (0.943–0.984)	3.538 ± 0.123 (3.28–3.79)	0.94 (0.88–0.97)	<0.001
ME 8 mm	4.179 ± 0.126 (3.92–4.43)	0.972 (0.939–0.987)	3.465 ± 0.134 (3.18–3.74)	0.971 (0.94–0.986)	<0.001
WRP vs. ME2 *p*-value	1	-	0.956	-	-
WRP vs. ME4 *p*-value	0.969	-	0.669	-	-
WRP vs. ME8 *p*-value	0.992	-	0.879	-	-
ME2 vs. ME4 *p*-value	0.983	-	0.924	-	-
ME2 vs. ME8 *p*-value	0.997	-	0.996	-	-
ME4 vs. ME8 *p*-value	0.998	-	0.98	-	-

Abbreviations: CASES GROUP = participants with hallux rigidus; CONTROL GROUP = healthy participants, without hallux rigidus; SD = standard deviation; CI = confidence interval; ICC= intraclass correlation coefficient; Li = inferior limit; Ls = superior limit; IMPJ = first metatarsophalangeal joint; ME = Morton's extension insoles; mm = millimeters; *p*-value= level of significance; $p < 0.05$ (with a 95% confidence interval) was considered statistically significant. WRP = weight-bearing resting position (without insoles).

Spearman's rho correlations between the ME thickness and the amount of pulled joint tension were not statistically significant for either group (case, $p = 0.715$; control, $p = 0.481$) (Figure 6).



(**A**) Cases. Joint pulled tension (kgf) (**B**) Control. Joint pulled tension (kgf)

Figure 6. The correlation between Morton's extension insoles thickness (mm) and pulled joint tension applied (kgf). (**A**) = Cases group; hallux rigidus participants. (**B**) = control group; healthy participants. Spearman's rho= level of significance; $p < 0.05$ (with a 95% confidence interval) was considered statistically significant; kgf = kilogram force.

4. Discussion

The main goal of the present research was to study the behavior of the first MPJ under the effects of three different kinds of ME orthoses on healthy subjects versus HR subjects in WRP, recording values of pulled tension with a digital algometer; a secondary goal was to compare the pulled tension values between healthy and HR subjects without any ME orthoses. Rigid MEs have been used as a conservative treatment for the first stages of HR [10,44], and their effects have been studied with respect to the position [22,45] and pressure [46] of the first ray on healthy subjects; this is the first research that studies the pulled tension forces applied in HR subjects on WRP, as Moisan et al. [28] proposed.

First MPJ is a rolling structure regulated by the rotational equilibrium theory described before [47], in which kinetic and kinematic forces are present in the different phases of the human gait. Taking into account that this study is not about the first MPJ's mobility or position, nor is it about pressure valves, but instead about kinetics inside the first MPJ, and considering that MEs have a direct implication on this rolling mechanism [48], it was essential to know the effects of that kind of orthosis on the first MPJ tension forces.

It is known that the thicker the MEs were placed, the wider the dorsal gap formed over the first MPJ as a result of the distance generated between the joint's bone surfaces and the more difficult it was to roll the proximal phalanx of the hallux over the head of the first metatarsal bone [21,22,49], so Jack's test performed with pulled tension would show higher values as much thickness beneath the first MPJ was placed. Surprisingly, our results showed that it did not matter how much thicker the MEs were, because the values of the tension applied did not increase statistically significantly, in contrast with those studies that argued that the dorsal first MPJ's mobility was influenced by the position of the first ray [14,15,22] cause were smaller as much thickness acrylic platform were placed below of it [22]. It was a highlight result because it emphasized the idea that (unseen) kinetics is more important than (visible) kinematics and that the forces inside the joint may not always have the measurable motion representation but have internal implications, in line with discoveries reached by other authors [50–53].

The hypothesis proposed at the beginning of the present study could not be confirmed according to the results because there was no statistically significant difference between the applied pulled tension in Jack's test for the case or control groups, regardless of the ME thickness. Moreover, the differences that were detected were small. In our study, the pulling force applied on the first MPJ during the measurements did not show any proportional correlation with the ME thickness, as opposed to the results of Roukis et al. [22], who showed a 19.3% incremental restriction on the first MPJ's mobility in proportion to 4 mm first-ray simulated dorsiflexion. The data revealed that, regardless of the external ME's restrictions, the pulling force needed to perform Jack's test was the same after reaching the joint stop movement through the thickness of the ME.

On the other hand, it is mandatory to consider the variations of the first ray function when some pieces are placed beneath it, and how these variations are poorly correlated with the real dorsiflexion angle during gait [54,55]. For example, the total amount of dorsal mobility of the first ray in WRP, with the ground reactions forces acting under the foot, was set at 4.9 mm [56], which is lower than that achieved with the foot in resting non-weight bearing position; this is due to the increased tension on the plantar aponeurosis related to the windlass mechanism [17,57], as it has been shown previously by the intrinsic correlation between first MPJ, the rearfoot supination and the triceps surae activation [58,59]. The ME thicknesses used in the present experiment were 2, 4, and 8 mm [22]. In our results, the 4 mm ME orthotic produced the greatest tension effort on the first MPJ, which could be linked as a rough comparison with the mobility results of Grady [56], but without any statistical significance.

The "artificial dorsal-opening" of the first MPJ got through the ME's effects placed under the first MPJ and could be used to avoid pain inside the joint, pushing away the phalanx and metatarsal dorsal surfaces during the push-off phase; however, it has been shown that these MEs had no effects on the kinetic data because the exerted tension was enough to produce the needed dorsiflexion of the first MPJ before to achieve the "stop" point determined by supination of the rearfoot. Further dynamic research is now needed to clarify if the present data could be applied to functional gait and if our kinetics results would be similar to the results of examining the kinematics variables under similar conditions.

Nevertheless, according to our data, the authors could hypothesize that the case group had more difficulty achieving peak mobility in Jack's test than the control group, as shown by the greater force values applied, regardless of the ME's thickness. As expected, this is in accordance with the field's current knowledge about the mobility of the first MPJ [16,22,48]. Grebing et al. [56] detected a decrease in the first-ray simulated dorsiflexion when comparing healthy versus first MPJ arthrodesis subjects, which explains the increase in pulled force we observed in the HR group compared to the healthy control group.

There are controlling orthoses for hyper-pronated feet [60], and these have been shown to restore the mobility of first MPJs with restricted dynamic mobility (named functional hallux limitus) at the 5-month follow-up. It is also possible to improve this mobility in real time using cut-out orthoses [61]. Nevertheless, the objective of the present research was to assess the tension values of the ME on a totally restricted first MPJ, not just dynamic-functional restriction. Moreover, Reina et al. [62] showed no statistical difference in the X-ray of first-second intermetatarsal angles and HAV-angle values between custom-made foot orthoses and no orthoses in subjects with HAV, indicating that kinematics data are not always related to kinetics values, which is in line with our results.

The first MPJ dorsiflexion resistance test or similar has already been proven in healthy subjects, showing the ICC intra-rater reliability of 0.77 ($p < 0.001$) [28], 0.814 ($p = 0.784$) [29], and 0.568 [26] in contrast to the 0.989 ($p < 0.001$) obtained in this research. Then, the authors proposed the digital algometer as a valid tool to detect HR in healthy subjects.

Limitations

The present device had a 10 × 0.01 kgf capacity/graduation and an accuracy of 0.3% of the full scale; furthermore, the small effect sizes throughout the results between the WRP and MEs inside each control and case group are in line with another comparative kinetic and kinematic study with small effect sizes between the case and control groups [63]. Therefore, the reported values should be considered with caution.

This is a novel force–kinetic study related to pulled tension and did not focus on the first MPJ's mobility or position; therefore, further investigations are needed to be able to make comparisons with these results. Moreover, further dynamics measurements will be required to verify the ME effects discovered in the present simulated research. In addition, future research with X-ray assessments to correlate the elevation of the first metatarsal bone with ME and how it changes the forces of dorsiflexion could be interesting. There is no reliable method for determining the final position of the proximal phalanx of the hallux during Jack's test.

5. Conclusions

The orthopedic use of rigid ME as a palliative treatment for HR has been studied regarding mobility, but not force–kinetic effects. In the present study, the authors showed that with the use of different MEs, the tension values detected during the simulated toe-off phase of the gait cycle (i.e., Jack's test) in healthy individuals and subjects with HR had no correlation with the ME's thickness. Although we were able to confirm that performing Jack's test in individuals with HR required higher kgf tension values than in healthy individuals, the data showed that the prescription of bigger MEs did not affect tension forces inside the first MPJ, and thus its prescription can be made free of joint damage. In addition, the digital algometer is a valid tool to detect HR pathology versus healthy subjects.

Future research will be needed to assess the kinetic and force effects of ME on the shoes to check the first MPJ's behavior.

6. Clinical Relevance

This is the first study that assesses the first MPJ motion using tension force values with a valid tool as a digital algometer to discriminate HR pathology versus healthy subjects with a high level of accuracy and reliability. In addition, it has been proven that subjects with HR store more tension forces inside the first MPJ during the simulated push-off phase of gait (i.e., Jack's test) than healthy subjects, proving the etiology of joint disruption caused by kinetics and not only by kinematics and therefore alerting clinicians to consider both biomechanical forces when applying their orthopedic treatments.

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References

1. Stuck, R.M.; Moore, J.W.; Patwardhan, A.G.; Sartori, M. Forces under the hallux rigidus foot with surgical and orthotic intervention. *J. Am. Podiatr. Med. Assoc.* **1988**, *78*, 465–468. [PubMed]
2. Cotterill, J.M. Stiffness of the Great Toe in Adolescents. *Br. Med. J.* **1887**, *1*, 1158. [CrossRef] [PubMed]
3. Rzonca, E.; Levitz, S.; Lue, B. Hallux equinus. The stages of hallux limitus and hallux rigidus. *J. Am. Podiatr. Med. Assoc.* **1984**, *74*, 390–393. [CrossRef]
4. Colò, G.; Fusini, F.; Samaila, E.M.; Rava, A.; Felli, L.; Alessio-Mazzola, M.; Magnan, B. The efficacy of shoe modifications and foot orthoses in treating patients with hallux rigidus: A comprehensive review of literature. *Acta Biomed.* **2020**, *91*, e2020016.
5. Caravelli, S.; Mosca, M.; Massimi, S.; Pungetti, C.; Russo, A.; Fuiano, M.; Catanese, G.; Zaffagnini, S. A comprehensive and narrative review of historical aspects and management of low-grade hallux rigidus: Conservative and surgical possibilities. *Musculoskelet. Surg.* **2018**, *102*, 201–211. [CrossRef]
6. Dananberg, H.J. Gait style as an etiology to chronic postural pain. Part I. Functional hallux limitus. *J. Am. Podiatr. Med. Assoc.* **1993**, *83*, 433–441.
7. Jamari, J.; Ammarullah, M.I.; Santoso, G.; Sugiharto, S.; Supriyono, T.; Permana, M.S.; Winarni, T.I.; van der Heide, E. Adopted walking condition for computational simulation approach on bearing of hip joint prosthesis: Review over the past 30 years. *Heliyon* **2022**, *8*, e12050. [CrossRef]
8. Coughlin, M.J.; Shurnas, P.S. Hallux Rigidus. *J. Bone Joint. Surg.* **2004**, *86 Pt 2*, 119–130. [CrossRef]
9. Drago, J.J.; Oloff, L.; Jacobs, A.M. A comprehensive review of hallux limitus. *J. Foot Surg.* **1984**, *23*, 213–220.
10. Shurnas, P.S. Hallux Rigidus: Etiology, Biomechanics, and Nonoperative Treatment. *Foot Ankle Clin.* **2009**, *14*, 1–8. [CrossRef]
11. Gould, N. Hallux rigidus: Cheilotomy or implant? *Foot Ankle* **1981**, *1*, 315–320. [CrossRef] [PubMed]
12. Smith, R.W.; Katchis, S.D.; Ayson, L.C. Outcomes in Hallux Rigidus Patients Treated Nonoperatively: A Long-Term Follow-Up Study. *Foot Ankle Int.* **2000**, *21*, 906–913. [CrossRef]
13. Grady, J.F.; Axe, T.M.; Zager, E.J.; Sheldon, L.A. A Retrospective Analysis of 772 Patients with Hallux Limitus. *J. Am. Podiatr. Med. Assoc.* **2002**, *92*, 102–108. [CrossRef] [PubMed]
14. Ebisui, J.M. The first ray axis and the first metatarsophalangeal joint: An anatomical and pathomechanical study. *J. Am. Podiatr. Med. Assoc.* **1968**, *58*, 160–168. [CrossRef]
15. Kelso, S.F.; Richie, D.H.; Cohen, I.R.; Weed, J.H.; Root, M. Direction and range of motion of the first ray. *J. Am. Podiatr. Med. Assoc.* **1982**, *72*, 600–605. [CrossRef]

16. Dananberg, H.J. Functional hallux limitus and its relationship to gait efficiency. *J. Am. Podiatr. Med. Assoc.* **1986**, *76*, 648–652. [CrossRef]
17. Hicks, J. The mechanics of the foot. II. The plantar aponeurosis and the arch. *J. Anat.* **1954**, *88*, 25–30.
18. Lyritis, G. Developmental disorders of the proximal epiphysis of the hallux. *Skelet. Radiol.* **1983**, *10*, 250–254. [CrossRef]
19. Root, M.L.; Orien, W.P. *Normal and Abnormal Function of the Foot*; Corp, C.B., Ed.; Clinical Biomechanics Corp.: Los Angeles, CA, USA, 1977; Volume II.
20. Lambrinudi, C. Metatarsus Primus Elevatus. *Proc. R. Soc. Med.* **1938**, *31*, 1273. [CrossRef]
21. Ohara, K.; Tanaka, Y.; Taniguchi, A.; Kurokawa, H.; Kumai, T.; Yamada, H. Is metatarsus primus elevatus truly observed in hallux rigidus? Radiographic study using mapping methods. *J. Orthop. Sci.* **2018**, *24*, 312–319. [CrossRef] [PubMed]
22. Roukis, T.; Scherer, P.; Anderson, C. Position of the first ray and motion of the first metatarsophalangeal joint. *J. Am. Podiatr. Med. Assoc.* **1996**, *86*, 538–546. [CrossRef]
23. Kim, H.K.; Mirjalili, S.A.; Fernandez, J. Gait kinetics, kinematics, spatiotemporal and foot plantar pressure alteration in response to long-distance running: Systematic review. *Hum. Mov. Sci.* **2018**, *57*, 342–356. [CrossRef] [PubMed]
24. Downey, M. Tarsal coalitions. A surgical classification. *J. Am. Podiatr. Med. Assoc.* **1991**, *81*, 187–197.
25. Jack, E.A. Naviculo-cuneiform fusion in the treatment of flat foot. *J. Bone Jt. Surg.* **1953**, *35-B*, 75–82. [CrossRef]
26. Heng, M.L.; Chua, Y.K.; Pek, H.K.; Krishnasamy, P.; Kong, P.W. A novel method of measuring passive quasi-stiffness in the first metatarsophalangeal joint. *J. Foot Ankle Res.* **2016**, *9*, 41. [CrossRef] [PubMed]
27. Molyneux, P.; Bowen, C.; Ellis, R.; Rome, K.; Jackson, A.; Carroll, M. Ultrasound Imaging Acquisition Procedures for Evaluating the First Metatarsophalangeal Joint: A Scoping Review. *Ultrasound Med. Biol.* **2021**, *48*, 397–405. [CrossRef] [PubMed]
28. Moisan, G.; McBride, S.; Isabelle, P.; Chicoine, D.; Walha, R. Intrarater and interrater reliability of the first metatarsophalangeal joint dorsiflexion resistance test. *Musculoskelet. Care* **2022**, *14*, 1–6. Available online: https://pubmed.ncbi.nlm.nih.gov/35833706/ (accessed on 7 February 2023). [CrossRef]
29. Leow, Y.; Kong, P.W.; Liu, Y.; Pan, J.W.; Fong, D.T.; Chan, C.C.; Heng, M.L. Test-retest reliability of a clinical foot assessment device for measuring first metatarsophalangeal joint quasi-stiffness. *Foot* **2020**, *45*, 101742. [CrossRef]
30. Curran, S.; Jones, A. Intrarater and interrater reliability of first metatarsophalangeal joint dorsiflexion: Goniometry versus visual estimation. *J. Foot Ankle Res.* **2010**, *3*, P5. [CrossRef]
31. Mens, M.; Bouman, C.; Dobbe, J.; Bus, S.; Nieuwdorp, M.; Maas, M.; Wellenberg, R.; Streekstra, G. Metatarsophalangeal and interphalangeal joint angle measurements on weight-bearing CT images. *Foot Ankle Surg.* **2023**, *23*, S1268-7731. Available online: https://pubmed.ncbi.nlm.nih.gov/36641368/ (accessed on 9 February 2023). [CrossRef]
32. Desmyttere, G.; Hajizadeh, M.; Bleau, J.; Begon, M. Effect of Foot Orthosis Design on Lower Limb Joint Kinematics and Kinetics during Walking in Flexible pes Planovalgus: A Systematic Review and Meta-Analysis. In *Clinical Biomechanics*; Elsevier Ltd.: Amsterdam, The Netherlands, 2018; Volume 59, pp. 117–129. Available online: https://pubmed.ncbi.nlm.nih.gov/30227277/ (accessed on 20 May 2021).
33. Kirby, K.A. The medial heel skive technique. Improving pronation control in foot orthoses. *J. Am. Podiatr. Med. Assoc.* **1992**, *82*, 177–188. [CrossRef] [PubMed]
34. Sánchez-Gómez, R.; Becerro-de-Bengoa-Vallejo, R.; Losa-Iglesias, M.E.; Calvo-Lobo, C.; Navarro-Flores, E.; Palomo-López, P.; Romero-Morales, C.; López-López, D. Reliability Study of Diagnostic Tests for Functional Hallux Limitus. *Foot Ankle Int.* **2020**, *41*, 457–462. [CrossRef] [PubMed]
35. Dananberg, H.J. The Kinetic Wedge. *J. Am. Podiatr. Med. Assoc.* **1988**, *78*, 98–99. [CrossRef] [PubMed]
36. Ho, B.; Baumhauer, J. Hallux rigidus. *EFORT Open Rev.* **2017**, *2*, 13–20. [CrossRef] [PubMed]
37. Vandenbroucke, J.P.; von Elm, E.; Altman, D.G.; Gøtzsche, P.C.; Mulrow, C.D.; Pocock, S.J.; Poole, C.; Schlesselman, J.; Egger, M. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and elaboration. *Int. J. Surg.* **2014**, *12*, 1500–1524. [CrossRef]
38. Shereff, M.J.; Bejjani, F.J.; Kummer, F.J. Kinematics of the first metatarsophalangeal joint. *J. Bone Jt. Surg.* **1986**, *68*, 392–398. [CrossRef]
39. Mann, R.A.; Coughlin, M.J.; Duvries, H.L. Hallux rigidus: A review of the literature and a method of treatment. *Clin. Orthop. Relat. Res.* **1979**, *142*, 57–63. [CrossRef]
40. Redmond, A.C.; Crosbie, J.; Ouvrier, R.A. Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index. *Clin. Biomech.* **2006**, *21*, 89–98. [CrossRef]
41. Sarcevic, Z.Z.; Tepavcevic, A.P. Association between abductor hallucis abductory force and navicular drop index, a predictive correlational study. *J. Pediatr. Orthop. B* **2020**, *30*, 484–487. [CrossRef]
42. Kelly-Martin, R.; Doughty, L.; Garkavi, M.; Wasserman, J.B. Reliability of modified adheremeter and digital pressure algometer in measuring normal abdominal tissue and C-section scars. *J. Bodyw. Mov. Ther.* **2018**, *22*, 972–979. [CrossRef]
43. Portney, L.; Watkins, M. Foundations of Clinical Research: Applications to Practice. In *Survey of Ophthalmology*, 3rd ed.; Hall, P.P., Ed.; Prentice Hall Health: Upper Saddle River, NJ, USA, 2009; Volume 47, 598p.
44. Park, C.H.; Chang, M.C. Forefoot disorders and conservative treatment. *Yeungnam Univ. J. Med.* **2019**, *36*, 92–98. [CrossRef] [PubMed]
45. Kunnasegaran, R.; Thevendran, G. Hallux Rigidus Nonoperative Treatment and Orthotics. In *Foot and Ankle Clinics*; W.B. Saunders: Philadelphia, PA, USA, 2015; Volume 20, pp. 401–412.

46. Rambarran, K.K. Reduce Relative Plantar Pressure—Search Results—PubMed. Available online: https://pubmed.ncbi.nlm.nih.gov/?term=Rambarran+KK%2C+reduce+relative+plantar+pressure (accessed on 10 February 2023).
47. Kirby, K.A. Subtalar Joint Axis Location and Rotational Equilibrium Theory of Foot Function. *J. Am. Podiatr. Med. Assoc.* **2001**, *91*, 465–487. [CrossRef] [PubMed]
48. van Gheluwe, B.; Dananberg, H.J.; Hagman, F.; Vanstaen, K. Effects of hallux limitus on plantar foot pressure and foot kinematics during walking. *J. Am. Podiatr. Med. Assoc.* **2006**, *96*, 428–436. [CrossRef]
49. Horton, G.A.; Park, Y.-W.; Myerson, M.S. Role of Metatarsus Primus Elevatus in the Pathogenesis of Hallux Rigidus. *Foot Ankle Int.* **1999**, *20*, 777–780. [CrossRef]
50. Fuller, E.A. Center of pressure and its theoretical relationship to foot pathology. *J. Am. Podiatr. Med. Assoc.* **1999**, *89*, 278–291. [CrossRef]
51. Huerta, J.P.; Moreno, J.M.R.; Kirby, K.A. Static Response of Maximally Pronated and Nonmaximally Pronated Feet to Frontal Plane Wedging of Foot Orthoses. *J. Am. Podiatr. Med. Assoc.* **2009**, *99*, 13–19. [CrossRef] [PubMed]
52. Mills, K.; Blanch, P.; Chapman, A.R.; McPoil, T.G.; Vicenzino, B. Foot orthoses and gait: A systematic review and meta-analysis of literature pertaining to potential mechanisms. *Br. J. Sport. Med.* **2009**, *44*, 1035–1046. [CrossRef]
53. Nigg, B.M. The Role of Impact Forces and Foot Pronation: A New Paradigm. *Clin. J. Sport Med.* **2001**, *11*, 2–9. [CrossRef]
54. Gatt, A.; Mifsud, T.; Chockalingam, N. Severity of pronation and classification of first metatarsophalangeal joint dorsiflexion increases the validity of the Hubscher Manoeuvre for the diagnosis of functional hallux limitus. *Foot* **2014**, *24*, 62–65. [CrossRef]
55. Halstead, J.; Redmond, A.C. Weight-Bearing Passive Dorsiflexion of the Hallux in Standing Is Not Related to Hallux Dorsiflexion During Walking. *J. Orthop. Sport. Phys. Ther.* **2006**, *36*, 550–556. [CrossRef]
56. Grebing, B.R.; Coughlin, M.J. The Effect of Ankle Position on the Exam for First Ray Mobility. *Foot Ankle Int.* **2004**, *25*, 467–475. [CrossRef] [PubMed]
57. Durrant, M.N.; Siepert, K.K. Role of soft tissue structures as an etiology of hallux limitus. *J. Am. Podiatr. Med. Assoc.* **1993**, *83*, 173–180. [CrossRef] [PubMed]
58. Maceira, E.; Monteagudo, M. Functional Hallux Rigidus and the Achilles-Calcaneus-Plantar System. *Foot Ankle Clin.* **2014**, *19*, 669–699. [CrossRef] [PubMed]
59. Sánchez-Gómez, R.; Romero-Morales, C.; Gómez-Carrión, Á.; De-La-Cruz-Torres, B.; Zaragoza-García, I.; Anttila, P.; Kantola, M.; Ortuño-Soriano, I. Effects of Novel Inverted Rocker Orthoses for First Metatarsophalangeal Joint on Gastrocnemius Muscle Electromyographic Activity during Running: A Cross-Sectional Pilot Study. *Sensors* **2020**, *20*, 3205. [CrossRef]
60. Munuera, P.V.; Domínguez, G.; Palomo, I.C.; Lafuente, G. Effects of rearfoot-controlling orthotic treatment on dorsiflexion of the hallux in feet with abnormal subtalar pronation: A preliminary report. *J. Am. Podiatr. Med. Assoc.* **2006**, *96*, 283–289. [CrossRef]
61. Becerro de Bengoa Vallejo, R.; Gomez, R.S.; Losa Iglesias, M.E. Clinical improvement in functional hallux limitus using a cut-out orthosis. *Prosthet. Orthot. Int.* **2016**, *40*, 215–223. [CrossRef]
62. Reina, M.; Lafuente, G.; Munuera, P.V. Effect of custom-made foot orthoses in female hallux valgus after one-year follow up. *Prosthet. Orthot. Int.* **2012**, *37*, 113–119. [CrossRef]
63. Sung, P.S.; Zipple, J.T.; Andraka, J.M.; Danial, P. The kinetic and kinematic stability measures in healthy adult subjects with and without flat foot. *Foot* **2017**, *30*, 21–26. [CrossRef]