Am J Transl Res 2021;13(11):12834-12842
www.ajtr.org /ISSN:1943-8141/AJTR0137352

Original Article

Isolated medial column stabilization surgery does not benefit adult acquired flatfoot stage IIa nor IIb by three-dimensional finite element biomechanical analysis

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Received July 13, 2021; Accepted October 11, 2021; Epub November 15, 2021; Published November 30, 2021

Abstract: The surgical treatment for stage II adult acquired flat foot deformity (AAFD) remains controversial. Biomechanical effects of medial column stabilization remain unclear. No study has biomechanically assessed the effect of medial column arthrodesis on the whole foot. Our study aimed to mechanically analyze the advantages and disadvantages of this. Stage IIa and IIb AAFD three-dimensional finite element models were established. The application of Geomagic software, Solidwork software, and Abaqus software was used to simulate a medial column stabilization operation (navicular-cuneiform joint fusion, metatarsal-cuneiform joint fusion, or both). The maximum pressure on plantar soft tissue, medial column bone, and medial ligaments was compared before and after simulated single-foot weight loading. Several data were measured to carry out a comprehensive comparison. The maximum plantar stress was located under the first metatarsal head after the simulated medial column stabilization operation. It increased significantly after medial column stabilization in a stage IIa flatfoot model, but did not change significantly after medial column stabilization in stage IIb model. Therefore, after medial column fusion, the stress of the corresponding joint was reduced, but it was increased in the adjacent joints of the medial column. The stresses on medial ligaments and plantar fascia were also not alleviated after medial column fusion. Our results showed isolated medial column stabilization surgery cannot help patients with stage IIa nor IIb flatfoot from the biomechanical point of view, and such stabilization increases stress on the sole, the joints around the fusion sites, medial soft tissue, and ligaments. It can only be used as a combined surgery to stabilize joints with excessive motion and correct the deformity of supination of the forefoot.

Keywords: Flatfoot, medial column stabilization, three-dimensional finite element analysis, biomechanics

Introduction

Flatfoot deformity is a common disease in foot and ankle surgery. Its most prominent feature is the collapse of the medial longitudinal arch of the foot. Most patients also have hind foot valgus and forefoot abduction, accompanied by pain in the medial aspect of the foot and ankle. At present, it is considered that tibialis posterior tendon dysfunction is one of the main causes of flatfoot disease. It is reported in the literature that one out of six adults over 30 years old has flatfoot [1-3]. The degree of adult acquired flatfoot can vary from flexible deformity to rigid deformity. It is classified into 4 stages according to Myerson et al. in 1997 [2]. Stage II is the most common stage seen in clinical practice, but its treatment is still controversial [4]. Stage II is when the deformity is still flexible and is in transition from flexible deformity to rigid deformity [5].

Medial column instability in stage II flat foot, is an important cause of collapse of the arch and has been added to the classification by Bluman et al. in 2007 [6]. At present, a variety of treatments have been applied to stabilize the medial column and treat valgus deformities [7-10]. It is a common practice to treat flat foot by fusion surgery, tendon transfer, or combined surgery. Many patients with flat foot may have excessive instability of the medial column and some scholars [8, 11] recommend medial column stabilization to restore the height of the medial longitudinal arch and to correct the pronation of the forefoot. However, though arthrodesis can correct the deformity, the motion between the fused joints is lost, the adjacent joints' stress rises, and the normal physiologic movement of the foot changes accordingly [12, 13]. At present, there is no detailed biomechanical experiment in the literature to comprehensively assess the effect of medial column arthrodesis on the whole foot. Our study aims to mechanically analyze the advantages and disadvantages of medial column arthrodesis to reflect clinical practice.

Methods and materials

Subjects and softwares

One volunteer 32-year old male with stage IIa flat foot deformity had height 175 cm and weight 60 kg. Another volunteered 27-year old male with stage IIb flat foot had height 175 cm, weight 59 kg. These volunteers approved and signed consent for this study. Our study was approved by the ethics committee of the Fourth Affiliated Hospital of Guangxi Medical University, Liuzhou Workers' Hospital, Liuzhou, Guangxi, China with an approval number of LW2021011. Three-dimensional (3D) reconstruction software was Mimies 17.0 (Material, Belgium); reverse engineering software: Geomagic Studio 13.0; interactive CAD/CAM (Computer Aided Design and Computer Aided Manufacturing) Software: Solidwork 2012 (UGS Corporation, USA); Finite Element Analysis Software: ABAQUS 6.14 (SIMULIA, USA).

Experimental procedure

The stage IIa flatfoot volunteer reported a history of pain in his left tibialis posterior tendon area for 6 months. The arch of his foot was present when the foot was relaxed. During weight bearing, the medial arch collapsed, the hindfoot went into valgus deformity, and no forefoot abduction was seen (**Figure 1A-C**). In the stage IIb flat foot volunteers, there was left foot forefoot abduction, loss of the medial arch of the foot, and his hindfoot demonstrated valgus deformity (**Figure 1D-F**). X-ray examination confirmed that there was no evidence of fracture or tumor in his foot or ankle. The Philip/Brilhance 256-row spiral CT was used to scan the foot in neutral position. The scanning parameters were: tube voltage 100 kV, tube current 100 mA, foot was scanned up to 10 cm above the ankle joint with layer thickness of 0.67 mm. 454 layers of 2D CT image were acquired, and the data were exported as DICOM format. Using the Mimics software (Materialise, Belgium) to process the imported DICOM format and set the appropriate smoothing coefficients, a corresponding bone 3D model can be obtained. The model is generated and exported into STL (Stereo lithography) format. However, the model generated is only a cavity structure, which needs to be further processed by Geomagic Studio 13.0 software (Raindrop Geomagic, USA) to generate a solid model, which facilitates the later 3D finite element analysis. The Geomagic software was applied for each bone block STL model generated by Mimics software, and these small burrs or bumps were smoothed under the premise of highly retaining the integrity of the model. The software can fit a continuous NURBS (Non-uniform Rational B-splines) surface model on the model surface and was finally exported as a solid model in STEP (Standard for the Exchange of Product Data) format (**Figure 2A**). Each bone and soft tissue model exported by STEP recorded with their respective position information. They are saved in a slprt part format supported by Solidwork. The skeleton model is assembled in Solidwork 2012 (UGS Corporation, USA) software and each ligament anatomical originate and insertion points was drawn, to establish the anterior inferior tibiofibular ligament, posterior inferior tibiofibular ligament, interosseous ligament, lateral ligament (anterior talofibular ligament, posterior talofibular ligament and calcaneofibular ligament), Achilles tendon, medial deltoid ligament, the spring ligament, talus ligaments, plantar fascia, short and long plantar ligament, and many interosseous ligaments on the superior and inferior surface (**Figure 2B**).

According to Spratley [14], in stage II flat foot patients with weight-bearing, the tibialis posterior tendon is dysfunctional, its reaction force in the foot is negligible, and the reaction forces that are considered are the rest of the foot muscles acting against the external reaction

Figure 1. Gross appearance of a stage IIa flat foot volunteer (A-C) and a stage IIb flat foot volunteer (D-F). (A) No abnormal abduction. (B) Medial arch collapse. (C) Hindfoot valgus deformity. (D) Left forefoot abduction. (E) Medial arch collapse. (F) Hindfoot valgus deformity.

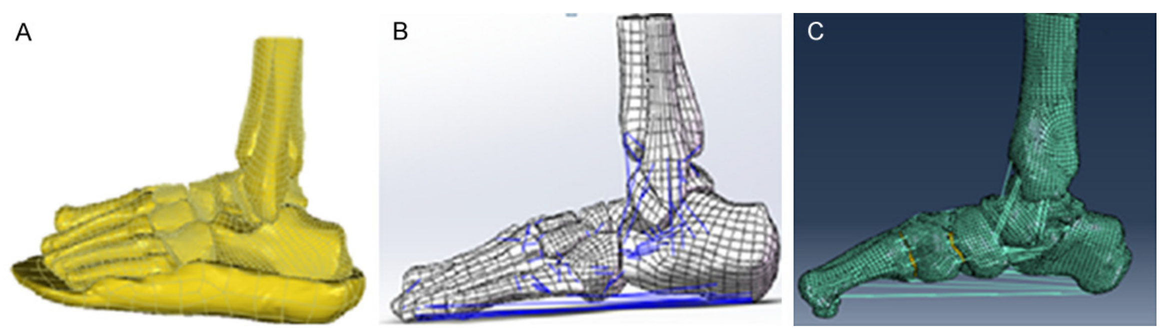

Figure 2. A. 3D model surfaces fitting of bone and soft tissue in Geomagic software. B. Establishing ligament solid models in Solidwork software. C. Medial column stabilization of bone grafting was simulated and properties were applied.

force to the body weight. The tendon model is established based on the specific anatomic location and orientation of the tendon. The method is also used to establish a solid curve through the reference point to represent the corresponding tendon effect vector.

Table 1. Bone and soft tissue cartilage material parameter settings

Component	Elastic modulus E (MPa)	Poisson's ratio μ
Bone	7300	0.30
Soft tissue	1.15	0.49
Articular cartilage	10	0.49

Following completing the creation and assembly of all solid models in Solidwork software, STEP format was exported and was imported into Abaqus finite element analysis software. In order to simplify the calculation of the model, we only retain the model from the lower part of the tibia and fibula to the whole foot without affecting the result. The attributes were assigned to various types of tissues in the 3D finite element model before loading operations.

In order to simplify the calculation and not affect the accuracy of the results, bone and soft tissue material are set to be isotropic homogeneous elastic material, provided the material is isotropic cartilage homogeneity, incompressible hyperelastic material. The specific performance parameters of these three materials are shown in **Table 1**. In stage II flat foot model, the ligament tissue is weakened to some extent. Therefore, in this model, the parameters of these ligaments have special settings based on the specific reference [14].

In the Abaqus software, the corresponding plane is established by the lowest point of the soft tissue of the foot to act as the ground, and the relationship between the model and the ground is set to be impenetrable and non-interfered. The weight bearing in neutral position is simulated. Therefore, 500 N is applied to the upper surface of the tibia of the 60 kg IIa flat foot and perpendicular to the pressure of the sole of the foot (5/6 of the weight of the human body), and 100 N downward loading pressure is applied to the upper surface of the ipsilateral tibia (1/6 of the human body weight). At the same time, the reaction force of the calf triceps (soleus, gastrocnemius), flexor hallucis longus tendon, peroneal longus tendon, peroneal brevis tendon and flexor digitorum longus are 50%, 10.5%, 10%, 8.8% and 6% of the body weight respectively. Validity verification of 3D finite element model and virtual surgery simulation of medial column fusion is performed. The validity of this 3D finite element model has been verified in previous publications by Xu J et al. [4]. For the establishment of the medial column stabilization model, Solidwork software can be used for processing a fusion simulation between joints (**Figure 2C**).

Results

Isolated fusion of navicular cuneiform (NC) joint

In the stage IIa and IIb flat foot models, the weight was simulated after the isolated NC joint fusion. The maximum plantar stress was located underneath the first metatarsal head. The maximum plantar stress in stage IIa model increased from 111.5 Kilopascal (kPa) to 126.7 kPa (**Figure 3**), and the maximum stress of stage IIb phase also increased from 77.9 Kpa to 78.8 Kpa (**Figure 4**). In stage IIa flat foot model, the maximum stress values of the talus, navicular, medial cuneiform, the first metatarsal, calcaneous, cuboid, and the fifth metatarsal stress changed from 5.29, 4.4, 2.1, 3.2, 4.15, 2.58, 3.5 Megapascals (MPa) to 5.68, 3.97, 1.92, 3.4, 3.97, 2.19, 3.5 MPa after simulation. The corresponding bone in the stage IIb flat foot model was also changed from 4.8, 2.79, 2.88, 1.94, 3.2, 3.1, and 3.08 MPa to 5.3, 1.34, 1.32, 2.26, 3.94, 2.98, and 3.07 MPa after simulation respectively. The maximum stress values in the stage IIa model of the anterior talofibular ligament, posterior talofibular ligament, tibiocalcaneal ligament, tibionavicular ligament, the spring ligament, and plantar fascia was changed from 0.93, 0.36, 0.74, 1.66, 3.48, and 2.0 MPa to 0.61, 0.49, 0.59, 1.42, 4.39, and 1.71 MPa after simulation respectively. The maximum stress values of the corresponding ligament and the plantar fascia in stage IIb flat foot model also changed from 3.94, 0.88, 1.55, 4.72, 4.50, and 1.52 MPa to 3.54, 0.98, 1.49, 4.66, 5.40, and 1.40 MPa post-simulation. The Meary angle, the calcaneous pitch angle, talonavicular coverage angle changed from 8.3°, 14.4°, and 11.7° to 5.2°, 15.6°, and 8.2°. The arch height restored from 10 mm to 15 mm. The Meary angle, the calcaneus pitch angle, talonavicular coverage angle in stage IIb model changed from 25.0°, 9.0°, and 19.6° to 20.5°, 8.9°, and 15.4° after simulation respectively. The arch height was restored from 4 mm to 10 mm (**Table 2**).

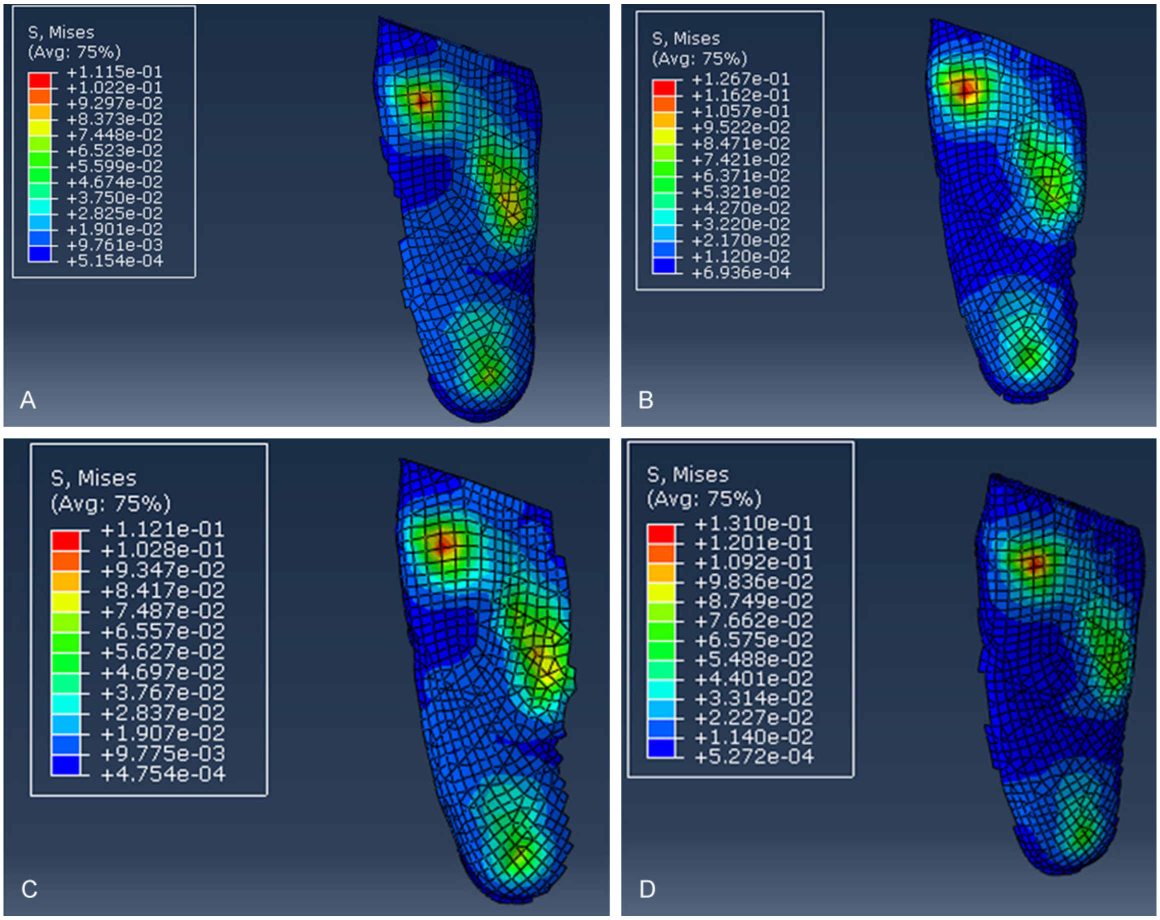

Figure 3. Plantar stress distribution before and after medial column stabilization in the stage IIa flat foot model. A. Plantar stress distribution of the stage IIa flat foot model after simulated weight-bearing. B. Plantar stress distribution of in the stage IIa flat foot model with the navicular cuneiform joint fusion after the simulation of weight bearing. C. Plantar stress distribution of in the stage IIa flat foot model with metatarsal cuneiform joint fusion after the simulation of weight bearing. D. Plantar stress distribution of the stage IIa flat foot model with both the navicular cuneiform joint and the metatarsal cuneiform joint fusion after the simulation of weight-bearing.

Isolated fusion of metatarsal cuneiform (MC) joint

In the stage IIa and IIb flat foot models, the weight bearing after the MC joint fusion was simulated, and the maximum stress of the foot was found under the first metatarsal head. The maximum stress of the plantar surface in stage IIa model also increased to 112.1 Kpa after simulation (**Figure 3**). The plantar stress on the stage IIb model decreased slightly to 76.6 Kpa after the simulation (**Figure 4**). After metatarsal cuneiform joint fusion, the maximum stress values of the talus, navicular, medial cuneiform, first metatarsal, calcaneus, tibia, fibula, and the fifth metatarsal changed to 5.27, 4.0, 3.0, 4.5, 4.1, 2.1, and 3.6 MPa. The corresponding bone in stage IIb flat foot model changed to 4.9, 2.87, 3.25, 2.4, 4.0, 3.1, and 3.07 MPa respectively. The maximum stress values of the anterior talofibular ligament, posterior talofibular ligament, tibiocalcaneal ligament, tibionavicular ligament, the spring ligament, and the plantar fascia also changed to 0.92, 0.35, 0.72, 1.64, 3.5, and 2.0 MPa, respectively. The maximum stress values of the corresponding ligament and tendon fascia in stage IIb flat foot model changed to 3.82, 0.88, 1.52, 4.67, 4.73, and 1.47 MPa, respectively. In the stage IIa model, the Meary angle, the calcaneus pitch angle, and the talonavicular coverage angle changed to 7.8°, 14.5°, and 10.8°, and the arch was restored to 14 mm. In the stage IIb model, the corresponding measured angle changed into 21.9°, 8.8°, and 17.2°, and the arch was restored to 8 mm (**Table 2**).

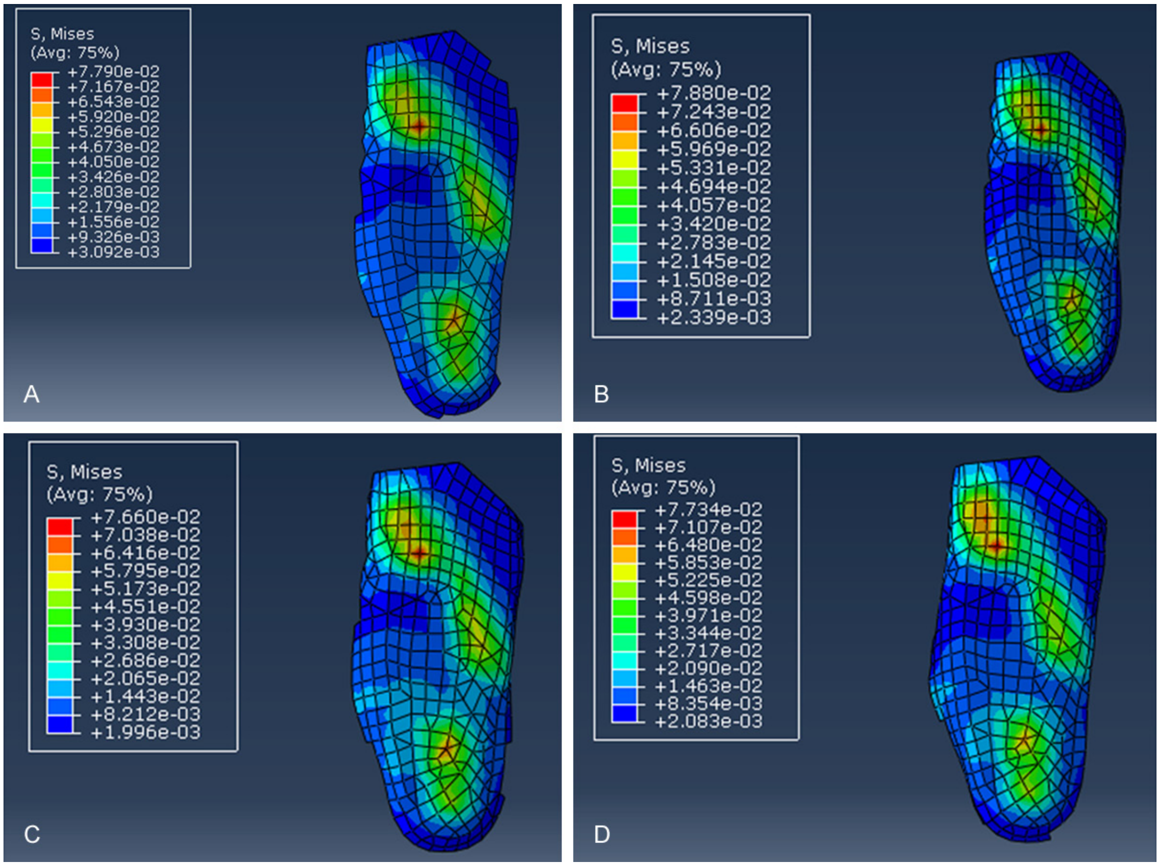

Figure 4. Plantar stress distribution before and after medial column stabilization in the stage IIb flat foot model. A. Plantar stress distribution of the stage IIb flat foot model after simulated weight-bearing. B. Plantar stress distribution of in the stage IIb flat foot model with the navicular cuneiform joint fusion after the simulation of weight bearing. C. Plantar stress distribution of in the stage IIb flat foot model with the metatarsal cuneiform joint fusion after the simulation of weight bearing. D. Plantar stress distribution of in the stage IIb flat foot model with both the navicular cuneiform joint and the metatarsal cuneiform joint fusion after the simulation of weight bearing.

Fusion of both NC and MC joints

In the stage IIa and IIb flat foot models, weight bearing was simulated after the NC and MC joints fusion, and the maximum plantar stress located below the first metatarsal head. The maximum value of the plantar stress in the stage IIa model increased to 131.0 Kpa (**Figure 3**). The maximum value of the plantar stress in the stage IIb model had a slight reduction to 77.3 Kpa (**Figure 4**). The maximum stress values of the talus, navicular, medial cuneiform, first metatarsal, calcaneus, tibia, fibula and fifth metatarsal changed to 5.83, 3.57, 1.96, 4.45, 3.9, 2.2, and 3.46 MPa. In the stage IIb model the corresponding bone changed to 5.2, 4.4, 3.07, 2.09, 4.1, 2.57, and 3.5 Kpa. The maximal stress values of the anterior talofibular ligament, posterior talofibular ligament, tibionavicular, tibiocalcaneal ligament, tibionavicular ligament, the spring ligament, and the plantar fascia changed to 0.56, 0.45, 0.55, 1.35, 4.6, and 1.67 MPa respectively in stage IIa flatfoot model. The maximum stress values of the corresponding ligaments and the plantar fascia in the stage IIb flat foot model were 3.76, 0.76, 1.43, 4.76, 4.87, and 1.43 MPa, respectively. The Meary angle, the calcaneus pitch angle, and the talonavicular coverage angle were 6.5°, 15.9°, and 7.8°, and the arch was restored to 14 mm. In the stage IIb model, the corresponding measurement angles were 18.9°, 9.1°, and 15.3°, and the arch was restored to 9 mm (**Table 2**).

Discussion

There are many controversial treatments for stage II adult acquired flatfoot deformities, but the accepted view is that conservative treat-

Table 2. Maximum stress values in MPa of the bones and soft tissue, and measurements at baseline and following simulated fusions in IIa and IIb flatfeet models

Index	Stage Model							
	IIa loading baseline	IIa NC fusion	IIa MC fusion	IIa NC & MC fusion	IIb loading baseline	IIb NC fusion	IIb MC fusion	IIb NC & MC fusion
Talus	5.29	5.68	5.27	5.83	4.8	5.3	4.9	5.2
Navicular	4.4	3.97	4	3.57	2.79	1.34	2.87	4.4
Medial Cuneiform	2.1	1.92	3	1.96	2.88	1.32	3.25	3.07
First Metatarsal	3.2	3.4	4.5	4.45	1.94	2.26	2.4	2.09
Calcaneus	4.15	3.97	4.1	3.9	3.2	3.94	4	4.1
Cuboid	2.58	2.19	2.1	2.2	3.1	2.98	3.1	2.57
Fifth Metatarsal	3.5	3.5	3.6	3.46	3.08	3.07	3.07	3.5
Anterior Tibiotalar Ligament	0.93	0.61	0.92	0.56	3.94	3.54	3.82	3.76
Posterior Tibiotalar Ligament	0.36	0.49	0.35	0.45	0.88	0.98	0.88	0.76
Tibiocalcaneal ligament	0.74	0.59	0.72	0.55	1.55	1.49	1.52	1.43
Tibionavicular Ligament	1.66	1.42	1.64	1.35	4.72	4.66	4.67	4.76
Spring ligament	3.48	4.39	3.5	4.6	4.5	5.4	4.73	4.87
Plantar Fascia	2	1.71	2	1.67	1.52	1.4	1.47	1.43
The Meary angle (°)	8.3	5.2	7.8	6.5	25	20.5	21.9	18.9
Calcaneal Pitch angle (°)	14.4	15.6	14.5	15.9	9	8.9	8.8	9.1
Talonavicular covering angle (°)	11.7	8.2	10.8	7.8	19.6	15.4	17.2	15.3
Arch height (mm)	10	15	14	14	4	10	8	9

ment is a first choice, while surgery is considered a second choice [15, 16]. Surgical procedures include fusion surgery and non-fusion surgery. The instability in the medial column in patients with second stage flat foot, is an important cause of the collapse of the arch [17-20]. Many patients with stage II flat foot, especially those with stage IIb flatfoot, may have rigid hind foot valgus with forefoot pronation which necessitates supplemental stabilization of the medial column in the form of joint arthrodesis. The degree of influence of the isolated medial column arthrodesis surgery on the stress distribution of the whole foot as well as the stress on the individual bones, soft tissue and ligament of the foot has not been studied from the biomechanical point of view.

A variety of treatment modalities have been used to stabilize the medial column and to treat hindfoot valgus deformities [7, 21, 22]. It is very common to treat stage II flat foot by surgery, such as joint fusion, osteotomy and tendon transposition or reconstruction, or combinations of these procedures [23, 24]. As an option, medial column arthrodesis can correct the deformity to a considerable extent, but there is no detailed biomechanical experiment in the literature to comprehensively assess the effect of medial column arthrodesis on the whole foot. Our study aims to mechanically analyze the advantages and disadvantages of medial column arthrodesis in a reflection to clinical practice. The arthrodesis sacrifices the motion between the fused joints, the adjacent joints stresses should increase, and the normal physiological movement of the foot should change accordingly. Roling et al. [25] have shown that the NC joint has the largest mobility in the medial column, accounting for about 50% of the sagittal plane activity of the first array. The metatarsal cuneiform joint and the talonavicular joint account for 41% and 9% of sagittal activity respectively. Another cadaveric study showed that fusion from the talonavicular joint also reduced the movement of the hindfoot by 80%-90% [26]. Many scholars believe that the treatment of stage II flat foot should try to retain the hindfoot three joints [18, 21, 27]. Although the medial column stabilization could correct the varus deformity of the forefoot and stabilize the midfoot, our research shows that NC joint fusion or MC joint fusion only reduces the maximum stress on the corresponding fusion joints. It fails to reduce the pressure on the plantar soft tissue and even increases the maximum stress on the soles in both stage IIa and IIb flatfoot. This is especially true in the stage IIa flatfoot model following NC and MC fusions where the maximum stress on the plantar surface is increased by 17.5%.

In this study, isolated NC arthrodesis merely reduces the maximum stress on the navicular and the medial cuneiform bones, but increases the maximum stress on the first metatarsal and the talus. There was no change on the maximum stress of the medial column following MC joint arthrodesis. This may be due to the fusion of the MC joint which increased the stress of the NC joint. After the fusion of the NC and MC joints, there was no reduction of plantar stress over the medial column nor the medial ligaments. This study also showed that the maximum stress value of the spring ligament after the fusion of the NC and MC joints is actually higher than its baseline value before surgery, which might be related to the instability of the TN joint, and the sinking of the talus head that causes an increase in the force over the spring ligament. According to the parameters we measured at various angles, the NC and/or MC fusion can partially restore the medial arch, thus preventing the talus head from sinking while weight-bearing. However, despite having some effects in correcting the deformities, the effect is not ideal. Thus we conclude that the isolated medial column stabilization surgery cannot help patients with stage IIa nor IIb flatfoot relieve the stress on the medial column, but can aggravate the pressure on the adjacent joints and the plantar sole.

Conclusions

Isolated medial column stabilization surgery cannot help patients with stage IIa nor IIb flatfoot from the biomechanical point of view, and such stabilization increases the stress on the sole, the joints around the fusion sites, the medial soft tissue and the ligaments. It can be used only as a combined surgery to stabilize joints with excessive motion and correct a deformity of supination of the forefoot.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (81902303, 82102632, 82160412), Guangdong Basic and Applied Basic Research Foundation (2020A151501048), Medical Research Fund by Guangdong Provincial Health Commission (B2019085), Guangxi Natural Science Foundation (2020GXNSFBA297089), Shenzhen Science and Technology Project (JCYJ20190806164216661, RCBS20200714114856299), Liuzhou Science and Technology Project (2021CBB0106), and Clinical Research Project of Shenzhen Second People's Hospital (20203357028).

Disclosure of conflict of interest

None.

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