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Original Research

Comparison of Extraosseous Talotarsal Stabilization Implants in a Stage II Adult-Acquired Flatfoot Model: A Finite Element Analysis

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ABSTRACT

Subtalar arthroereisis has been proved to be an efficient method for correcting flexible adult flatfoot. However, the optimal sinus tarsi implant is still debated and yet to be determined. In the present study, we compared the biomechanical effects of type I and II sinus tarsi implants in stage II adult-acquired flatfoot deformity (AAFD). First, a finite element model of stage II AAFD was established in which virtual surgery of subtalar arthroereisis was simulated. The indexes of plantar stress distribution, peak von Mises of the medial and lateral columns, strain of the medial ligaments and plantar fascia, arch height, talo-first metatarsal angle, calcaneus pitch angle, talonavicular coverage angle, and hindfoot valgus angle were all compared and analyzed. The results of the present study have validated the stage II AAFD finite element model by comparing the simulation results with the same parameters measured from weightbearing radiographs in the midstance phase. All the indexes showed that both types of arthroereisis can lower the plantar pressure and the strain of the medial ligaments that support the medial longitudinal arch and can shift the load of the medial column to the lateral column. They can also help to correct the deformity and restore the arch. However, the type II sinus tarsi implant design exhibited a more obvious effect than that of type I.

Adult-acquired flatfoot deformity (AAFD) is a progressively developing foot and ankle problem characterized by medial longitudinal arch lowering, hindfoot eversion, plantar and medial talus rotation, and/or forefoot abduction. Stage II AAFD is highly common with patients presenting with a normal medial arch under non-weightbearing conditions but an absence of the medial arch accompanied by a calcaneus valgus position and medial protrusion of the talar head under weightbearing conditions (1). The treatment of stage II AAFD remains controversial owing to various therapeutic methods available.

Subtalar arthroereisis, a technique for treating flexible flatfoot, has undergone >50 years of evolution. Subtalar arthroereisis aims to alter the subtalar joint (STJ) alignment through prosthesis insertion into the sinus tarsi (2). Subtalar arthroereisis was first used in 1946 by Chambers (3), who attempted to restrict STJ eversion through insertion of a bone graft into the anterior edge of the posterior STJ facet. Considerable progress has been made in the techniques, materials, and device designs for flexible flatfoot treatment, which allowed arthroereisis to become an acceptable form of treatment. In 2005, the clinical practice guideline for AAFD indicated that subtalar arthroereisis should only be used for stage IIA (4). In 2013, Bresnahan et al (5) expanded STJ application to children aged >3 years and adults aged >18 years. However, subtalar arthroereisis treatment remains controversial, especially regarding the effects, indications, and the best type to use.

In recent years, Graham and Jawrani (6) have classified sinus tarsi implants into 3 types according to the shape, implanting direction, fixation location, and biomechanical mechanism (Table 1). Types IA and IB sinus tarsi implants are almost the same, except that type IB closely resembles the sinus tarsi shape. However, type II is completely different from type I in all aspects. Graham et al (7) performed research on 83 AAFD patients, with 117 feet treated with type II sinus tarsi implants. Of the 83 patients, ≤52% experienced total pain relief, 69% showed significant improvement in feet function, and 80% were fully

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J. Xu and X. Ma contributed equally to this research.

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Table 1
Types of subtalar arthroereisis according to Graham and Jawrani (6)

Type	Design	Orientation in Sinus Tarsi	Anchoring	Biomechanical Function
IA	Cylinder	Laterally to medially	Lateral	Talar impingement mechanism
IB	Cone	Laterally to medially	Lateral	Talar impingement mechanism
II	Cylinder plus cone	Anteriorly, laterally, distally to posteriorly, medially, proximally	Medial	Allows normal talar helicoidal motion

satisfied with this type of surgery. Graham et al (8–11) also found that type II sinus tarsi implantation can relieve the strain on the posterior tibial tendon, posterior tibial nerve, and plantar fascia and increase the navicular position height. This research proved the benefits of type II sinus tarsi implantation. However, the effects of type I and II sinus tarsi implants in the same AAFD model have yet to be compared. In the present study, we compared the biomechanical effects of type I and II sinus tarsi implants using a finite element analysis model. The results of the present study could provide guidelines for orthopedic surgeons in the selection of the sinus tarsi implant type.

Patients and Methods

The protocol of the present study conformed to the guidelines set forth in the Declaration of Helsinki and the ethics committee of Fudan University approved the study. All the patients provided written informed consent before the study was performed.

Reconstruction of 3-Dimensional Finite Element Stage II AAFD Model

A 32-year-old male volunteer with stage IIA AAFD who was 175 cm tall and weighed 60 kg was enrolled in 2014 (Fig. 1). He had no ankle fractures and no foot and ankle tumors, which was verified by a radiographic examination under one-leg weightbearing conditions. A computed tomography scan was also taken of the foot and ankle in a neutral position, and Digital Imaging and Communications in Medicine formation data were collected.

The images were distinguished in MIMICS, version 13.0 (Materialise, Leuven, Belgium), to reconstruct the bone geometry that composes most of the foot and ankle: tibia, fibula, talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals, and 2 sesamoids. The reverse engineering software Geomagic Studio, version 12.0 (Geomagic Inc., Research Triangle Park, NC) was used to reduce the noise levels of the STL formation point cloud data, smooth the bone model surfaces, and generate nonuniform rational B-spline format models. Subsequently, the models were imported into the preprocessing finite element software HyperMesh, version 13.0 (Atlair Co., Troy, MI) to complete the reassembly and extraction of the cartilage models. The bones were connected by the cartilaginous joints. The tendons and ligaments were established using truss units in Abaqus software, version 6.12 (Abaqus Inc., Pawtucket, RI). One finite element model, consisting of 16 bones, 56 ligaments, and soft tissues, was finally established (Fig. 2).

Material Properties

The properties (Young's modulus and Poisson's ratio) of the bone, soft tissue, and cartilage were assigned in accordance with published data (12,13). However, some of the ligament properties in stage II AAFD, including the spring, deltoid, short plantar, and long plantar ligaments and plantar fascia, were not similar to those in the normal foot. Thus, these ligaments were assigned properties according to the reported data (14).

Loading and Boundary Settings

Two reference points were set just on the top of the tibia and fibula. The coupling relationship between the points and the upper end of the tibia and fibula was established. The ligaments were represented by 2-node truss units with noncompression characteristics that can only bear traction powers. The ligament functions were simulated with coupling units and changeable vector loads. Joint surface contacts were simulated with face-to-face nonlinear universal interaction. The surface contacts abided with tangential Coulomb friction, and the friction coefficient was 0.1.

The midstance phase was simulated in these models. Vertical loads that were five sixths and one sixth of the body weight were applied to the 2 reference points to pass the load to the upper tibia and fibula surfaces. The triceps surae, flexor hallucis longus tendon, peroneus longus muscle, peroneus brevis muscle, and flexor digitorum longus tendon in both models received reaction forces of 50%, 10.5%, 10%, 8.8%, and 6% of the corresponding body weight (14). A 3-dimensional analysis was performed after all the material properties and boundary conditions were properly set up.

Model Validation

The finite element model was validated through comparison of the simulation results with the same parameters measured from weightbearing radiographs in the midstance phase.

Subtalar Arthroereisis Simulation

Types IB and II sinus tarsi implant models with different sizes were built and simplified (Fig. 3) using SOLIDWORKS software (Dassault Systèmes SA, Vélizy-Villacoublay, France).

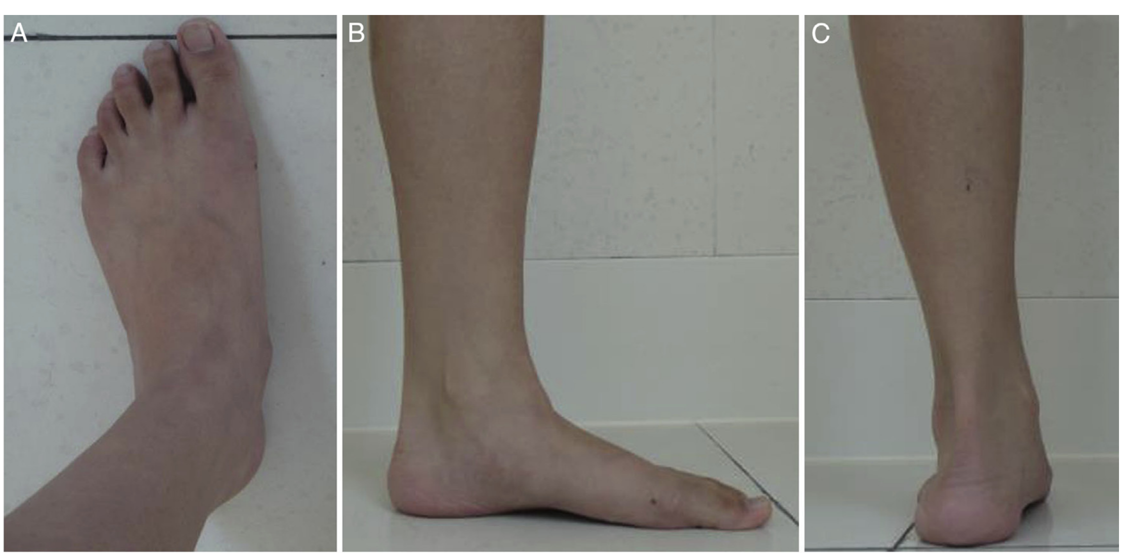

Fig. 1. Appearance of the foot of the enrolled patient with stage II adult-acquired flatfoot deformity. (*A*) Anteroposterior view of the foot. (*B*) Lateral view with weightbearing showing the collapsed medial arch. (*C*) Posterior view showing the valgus hindfoot.