Clinical Biomechanics 29 (2014) 170–176

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Maintenance of longitudinal foot arch after different mid/hind-foot arthrodesis procedures in a cadaveric model

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ARTICLE INFO

Article history:
Received 19 April 2013
Accepted 20 November 2013

Keywords:
Flatfoot
Longitudinal foot arch
Mid/hind foot arthrodesis
Biomechanical measurement
Cadaver

ABSTRACT

Background: Currently, the optimal treatment of flatfoot remains inconclusive. Our objectives were to understand the effect of different arthrodeses on maintenance of foot arch and provide experimental basis for rational selection in treatment of flatfoot.

Methods: Sixteen fresh-frozen cadaver feet amputated above the ankle along with a section of leg were studied from ten males and six females. We used standard clinical techniques and hardware for making the arthrodeses. Plantar pressure in the medial and lateral longitudinal arch distribution was measured with a plantar pressure mapping system under different loading conditions.

Findings: Values of plantar pressure reaction, mean and maximum dynamic peak pressure between all group pairs were statistically significant ($P < 0.05$). The plantar pressure reaction appeared at the load of 960 N in the medial arch of the unoperated foot, compared with 1080 N after subtalar arthrodesis, 1200 N after talonavicular arthrodesis, 1080 N after calcaneocuboid arthrodesis, 1320 N after double arthrodesis, and 1560 N after triple arthrodesis. The plantar pressure reaction appeared at the load of 360 N in the lateral arch of the unoperated foot, compared with 600 N after subtalar arthrodesis, 600 N after talonavicular arthrodesis, 840 N after calcaneocuboid arthrodesis, 960 N after double arthrodesis, and 1440 N after triple arthrodesis.

Interpretation: The triple arthrodesis provided the highest support to both arches; the double arthrodesis appeared to be similar to talonavicular arthrodesis in supporting the medial arch and similar to calcaneocuboid arthrodesis in supporting the lateral arch; subtalar arthrodesis was less effective in supporting both arches.

1. Introduction

Flatfoot is characterized by depression or absence of medial longitudinal arch. The prevalence was 6.6% (Kohls-Gatzoulis et al., 2009) for flatfoot deformity. Development of flatfoot may result in further joint and soft-tissue disorders and thus cause pain, lower limb weakness, and difficulty in mobility. Treatments for flatfoot aim to correct the deformity and eliminate the associated symptoms. A successful treatment should restore the biomechanical characteristics of a normal arch. Currently, the optimal treatment remains inconclusive. Among various options, selective mid/hind foot arthrodesis is widely performed because of its advantages in alleviating pain and maintaining the arch stability (O'Malley et al., 1995; Zaret and Myerson, 2003).

Commonly performed mid/hind foot arthrodesis procedures include subtalar, talonavicular, calcaneocuboid, double (talonavicular and calcaneocuboid), and triple (subtalar, talonavicular, and calcaneocuboid) arthrodesis. Subtalar arthrodesis was reported to be primarily suitable for medium to severe adult flatfoot accompanied by stage-3 or more advanced posterior tibial tendon dysfunction (PTTD), and especially effective for patients who experience lateral ankle pain and diagnosed by radiography to have osteoarthritis but generally confined to the subtalar joint (Cohen and Johnson, 2001; Johnson et al., 2000; Kitaoka and Patzer, 1997; Stephens et al., 1999). The procedure can normalize the connection between bones of the mid- and hind foot, correct the deformity without bone grafting, and has a high bone union rate. Talonavicular arthrodesis is suitable for flexible flatfoot deformity accompanied by talonavicular osteoarthritis (Fortin, 2001; Harper and Tisdel, 1996; Mothershed et al., 1999). It can correct forefoot abduction, elevate the arch, stabilize the medial column, prevent excessive intorsion of the subtalar joint, and alleviate pain. Calcaneocuboid distraction arthrodesis also can elevate the arch and correct flatfoot deformity (Hintermann et al., 1999; Phillips, 1983). Double arthrodesis can increase the midfoot stability and avoid the development of lateral column pain following talonavicular arthrodesis alone; it is particularly suitable for obese patients and patients with talonavicular or calcaneocuboid osteoarthritis (Mann et al., 1998). Triple arthrodesis is suitable for rigid flatfoot, flexible flatfoot accompanied by stage-3 or more advanced PTTD, and also flatfoot accompanied by severe osteoarthritis of the hindfoot (Graves et al.,

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http://dx.doi.org/10.1016/j.clinbiomech.2013.11.016

1993; Jarde et al., 2002; Sullivan and Aronow, 2002). It can correct subtalar eversion, talonavicular collapse, and forefoot abduction at the midtarsal joint. It can also prevent the development of joint osteoarthritis adjacent to the fused joints as a potential side-effect after a single-joint arthrodesis. Although effective, these procedures inevitably result in reduced mobility of the mid/hind foot. The reduced mobility results in degenerative changes of the unfused joints, which can progress into osteoarthritis and cause pain and impaired foot function due to rigidity. To date, most studies on flatfoot treatment investigated only one arthrodesis procedure. Moreover, the measurement of arch height and marker points varied among studies: the height measured dynamically or statically, and the marker points placed on the navicular or medial cuneiform. These limitations have prevented reliable comparisons among different studies.

The outcomes of these arthrodesis procedures have been systematically examined and their indications and key points have been analyzed. It was found that the chief disadvantage associated with these procedures is the loss of mid/hind foot mobility. The loss of mobility can induce the unfused joints to undergo degenerative changes, which may develop osteoarthritis and cause foot pain and loss of foot function due to rigidity (Astion et al., 1997; Deland et al., 1995; Fortin, 2001; Harper and Tisdel, 1996; Mann et al., 1998; Savory et al., 1998). Therefore, an optimum arthrodesis procedure that can maintain the arch stability and minimize the loss in mid/hind foot mobility remains to be investigated.

In this study, we simulated these popular arthrodesis procedures in human cadaveric models. In the model, a load was applied along the tibial diaphysis and the plantar pressure in the medial and lateral longitudinal arch distributions was measured after the foot was treated by each procedure. Our objectives were to understand the effect of different arthrodesis procedures on the maintenance of the foot arch and thereby provide experimental basis for rational selection of arthrodesis procedures in the clinic treatment of flatfoot.

2. Methods

2.1. Materials

Sixteen fresh-frozen cadaver feet amputated above the ankle along with a section of leg were studied from ten male and six female patients. Specimens had no evidence of previous injury, operations, osteoarthritis, or severe deformity by visual inspection and X-ray examination. Five were left and eleven were right feet. The mean age at the time of death was 37 years (range, 18–58 years). The tibia and fibula were amputated at the junction of the middle third and distal third. The skin, subcutaneous tissues, and muscle were dissected from the most proximal portion. The interosseus and ligaments of foot and ankle were kept intact. Specimens were stored frozen at −80 °C before the experiment and thawed to room temperature at the beginning of the experiment.

2.2. Ethics statement

Institutional Ethical Approval was obtained prospectively, and conforms to the provisions of the Declaration of Helsinki (Tongji Hospital Ethics Committee, Ethics number LL (H)-08-02). The subjects gave informed consent and patient anonymity has been preserved. All consent was written in nature, and where deceased, written consent was obtained from the next of kin of the deceased.

2.3. Arthrodesis procedures

There were normal conditions and five arthrodesis procedures at the hind foot to be studied were based on minimizing the damage to soft tissues in the mid/hind foot. We used standard clinical techniques and hardware (Kanghui Ltd, Changzhou, China) for making the arthrodesis, with the exception that the articular surfaces were left intact. The arthrodesis procedures included: I) Subtalar arthrodesis: The calcaneus was everted relative to the talus by 5°–10°. Three half-threaded cancellous screws (diameter: all 6.5 mm; length: 75 mm, 75 mm, and 70 mm) were inserted from the calcaneus, across the subtalar joint and into the talus. II) Talonavicular arthrodesis: The deep fascia was dissected and the tibial anterior tendon and the extensor hallucis longus were exposed. After elevating the muscles, three full-thread cancellous screws were inserted through the navicular bone, across the talonavicular joint and into the talus without opening the joint capsule. III) Calcaneocuboid arthrodesis: After dissecting the deep fascia, the peroneus brevis was retracted postero-laterally. The belly of the extensor digitorum brevis was bluntly separated and retracted superiorly without opening the joint capsule. With the foot maintained at a neutral position, the calcaneocuboid joint was fixed with a butterfly-shaped titanium plate and fully threaded cancellous screws. IV) Double and triple arthrodesis: These procedures were performed simply by combining the corresponding procedures described above (Fig. 1).

2.4. Biomechanical measurement

Plantar pressure distribution was measured with a plantar pressure mapping system (F-Scan Mobile, Tekscan, Boston, MA, USA). Considering that the pressure sensed in this system may be influenced by the actual pressure as well as the rate and duration of loading, a consistent loading profile was used in this study to ensure the comparability of the results. Specimens were mounted in a universal mechanical testing machine (CSS-44010, Changchun, China) which was fixed in a horizontal position to apply repeatable axial loads with the load downward along the tibial diaphysis. The foot was orientated in neutral position. The tibial diaphysis was vertical and parallel to the plumb line and perpendicular to the plantar plane as well as the platform surface. The line connecting the calcaneal tuberosity and the medial margin of the intermediate cuneiform bone was coronal. The loads were applied at a constant rate of 60 N/s to 1800 N in 30 s and released at the same rate in 30 s. During both loading and unloading, the horizontal displacement of tibial diaphysis was set and monitored by the built-in software to be restricted within 0–2 mm automatically; moreover, the sensor matt was placed on a laboratory-made fixture to prevent the matt from slipping during experiment. With the fixture, no matt slippage could be observed during any experiment. In addition, several pins were inserted to the bones near the fused joint(s). A three-dimensional coordinate measurement system (MicroScribe G2X, Immersion USA) was set up on the table near the specimen. The tips of the pins were touched by the stylus of the digitizer handled by the examiner. And rotation angles (Cardan angles, also called Tait–Bryan angles) of the joints were calculated. Application program was made for easy calculating and was hooked up to the software (Matlab 7.01, Mathworks Inc., Natick, MA, USA). The system has an accuracy of up to 0.2 mm to ensure the absence of abnormal joint movement during loading/unloading (Fig. 2).

Before experimenting with the arthrodesis procedures, the operated foot was loaded–unloaded and the resulting plantar pressures were measured. Then, the foot was sequentially treated by the arthrodesis procedures, and the corresponding pressure distributions were subsequently measured. During all experiments, the room temperature was maintained between 18 and 20 °C and the relative humidity was maintained at 40–50% to keep the cadavers moist.

2.5. Pressure data collection

After treatment with each arthrodesis procedure, the foot underwent three cycles of loading/unloading and the maximum peak pressures under the medial and lateral longitudinal arches were monitored during each cycle and averaged. For each measurement, the midfoot was divided into two regions representing the medial and