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Biomechanical study on surgical fixation methods for minimally invasive treatment of hallux valgus

Rui Mao[a,1], Junchao Guo[b,1], Chenyu Luo[a], Yubo Fan[a,b], Jianmin Wen[c,*], Lizhen Wang[a,*]

[a] *Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, 100191 Beijing, China*
[b] *Key Laboratory of Human Motion Analysis and Rehabilitation Technology of the Ministry of Civil Affairs, National Research Centre for Rehabilitation Technical Aids, 100176 Beijing, China*
[c] *Wangjing Hospital, China Academy of Chinese Medical Sciences, Beijing, China*

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A B S T R A C T

Hallux valgus (HV) was one of the most frequent female foot deformities. The aim of this study was to evaluate mechanical responses and stabilities of the Kirschner, bandage and fiberglass fixations after the distal metatarsal osteotomy in HV treatment. Surface traction of different forefoot regions in bandage fixation and the biomechanical behavior of fiberglass bandage material were measured by a pressure sensor device and a mechanical testing, respectively. A three-dimensional foot finite element (FE) model was developed to simulate the three fixation methods (Kirschner, bandage and fiberglass fixations) in weight bearing. The model included 28 bones, sesamoids, ligaments, plantar fascia, cartilages and soft tissue. The peak Von Mises stress (MS) and compression stress (CS) of the distal fragment were predicted from the three fixation methods: Kirschner fixation (MS = 6.71 MPa, CS = 1.232 MPa); Bandage fixation (MS = 14.90 MPa, CS = 9.642 MPa); Fiberglass fixation (MS = 15.83 MPa, CS = 19.70 MPa). Compared with the Kirschner and bandage fixation, the fiberglass fixation reduced the relative movement of osteotomy fragments and obtained the maximum CS. We concluded that fiberglass fixation in HV treatment was helpful to the bone healing of distal fragment. The findings were expected to guide further therapeutic planning of HV patient.

1. Introduction

Hallux valgus (HV) with the lateral deviation of great toe and the medial displacement at distal portion of the first metatarsal is a common disease in foot deformities, with an incidence rate of 12%–33% [1–3]. Female HV has a higher prevalence rate because of heredity and high heel shoes [4–6]. The complications with the callus, bunion and deformity seriously affect the gait and foot health [7].

For therapeutic intervention of HV, the conservative and surgical treatments have been reported in past decades. The conservative HV treatment includes foot orthosis devices, special insoles and toe spacers. However, surgery treatment was more effective and the main method to correct the metatarsal deformity [8]. About 150 methods of operative treatments have been reported because of the postoperative complications [9]. As the surgical technology developing, minimally invasive techniques with advantages of reductive operating time, shorter recovery period and less cost were gradually received by HV patients [10]. Giannini and Bösch techniques with Kirschner fixation would improve foot function in 4–6 weeks [11–13]. However, infection, mal-union and recurrence have been reported after Kirschner fixation [14–16]. Except for a high rate of residual valgus, Wen's method with bandage fixation reinforced stability of the fixation and reduced the recovery period [17,18]. However, little quantitative information exists about the different fixation methods in minimally invasive HV treatment.

In HV treatments, to investigate the stability of the osteotomy fragments different fixations in open surgeries have been well reported [19,20]. Bozkurt compared the stability of cannulated screw and Kirschner fixation after the proximal crescentic osteotomy by the testing machine [21]. Both Khuri and Jacobson quantified the biomechanical effect of different screw types or quantities on stability of foot [22,23]. But this testing neglected the ambient conditions in vivo. As two methods in HV postoperation Kirschner and bandage fixations have been applied in minimally invasive surgery

* Corresponding authors: School of Biological Science and Medical Engineering, Beihang University, No.37, Xueyuan Road, 100191 Beijing, China.
E-mail addresses: wjm5734@263.net (J. Wen), lizhenwang@buaa.edu.cn, bmewlz@foxmail.com (L. Wang).
[1] Both authors have equally contributed to this work.

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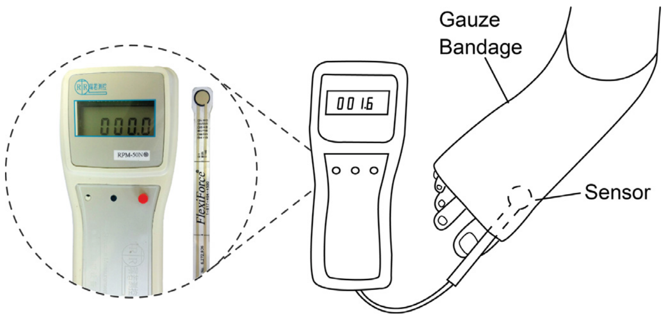

Fig. 1. Pressure measurement under bandage fixation condition.

Table 1
Pressure measurement under bandage fixation condition.

Region	Pressure value (MPa)
The first metatarsal	0.0216
Other part of forefoot	0.0116
Proximal part of hallux	0.0420

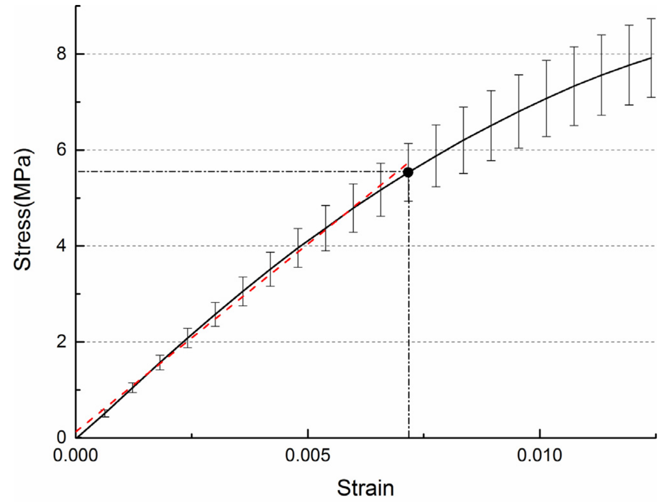

Fig. 2. Stress-strain curves of fiberglass bandage in mechanical testing.

[11–13]. Moreover, fiberglass bandage with advantage of the excellent bonding, light weight, good X-ray transmission and fast reaction time was widely used in orthopedics [24,25]. However, the relationship between the different fixation methods and loading of distal fragment has not been well established in the literature. In addition, it is difficult for HV patient to measure the biomechanical response of the osteotomy fragments in vivo. So the foot finite element (FE) model had been widely used in clinical assessment of HV treatment [26–28].

Therefore, a three-dimensional foot FE model would be developed to compare the biomechanical behavior of Kirschner, bandage and fiberglass fixation in minimally invasive HV treatment. This could provide a suggestion for optimal design of the minimally invasive surgery for HV patients.

2. Methods

2.1. Experiment testing

Pressure values between location of bandage fixation and metatarsophalangeal joints in balanced standing were obtained by a pressure sensor device (Shanghai, Ruiruo Company, China) (Fig. 1). The device displays the value of force loading on the sensor with a radius of 5 mm. The region covered by bandage was divided into three parts: hallux, great/second toe web space and other forefoot region. Average pressure values of these regions were recorded in Table 1. The value was applied as loading condition in FE model.

Material mechanical properties of fiberglass bandage were achieved by the mechanical testing. Ten uniform fiberglass bandage samples (25 mm width, 185 mm length and 1 mm thickness) after curing for 24 h were obtained from Suzhou Connect medical technology Company. Each sample was assessed from uniaxial tensile test at the speed of 2 mm/min (Shimadzu AUTOGRAPH, Japan) [25]. The strain–stress curve for each specimen was recorded and the tensile modulus was obtained by the initial slope of the curve (Fig. 2). The average tension modulus of 791.9MPa ± 66.8 for fiberglass bandage was applied to FE model.

2.2. Foot FE model

The foot FE model was developed from CT images of a female HV patient (35 years old; 160 cm height; 62 kg weight) in neutral unloaded position. The images were segmented to obtain the boundaries of each bone and skin surface in Mimics 10.01 software (Materialise, Belgium). The skeletal and soft tissue components were processed using Geomagic Studio 2012 (Geomagic, USA). The whole model included 28 bones (tibia, fibula and 26 foot bones), sesamoids, plantar fascia, 25 main ligaments, cartilages, and soft tissue. All components were then imported and assembled in FE package (ABAQUS 6.13, SIMULIA Inc, US). Muscles around the first metatarsal including the flexor hallux brevis, extensor hallux brevis, abductor hallucis and adductor hallucis were inactive in balanced standing [29]. The models were developed by axial connector element in ABAQUS. The elasticity was assigned 20.6 MPa for abductor hallucis and adductor hallucis, 264.8 MPa for flexor hallux brevis and extensor hallux brevis, respectively [30,31]. The element types and material mechanical properties in FE model were shown in Table 2. To simplify the model, the forefoot bones except for the first metatarsal ray were fused together as cartilaginous joint by solid element in ABAQUS (Fig. 3a). Surface-to-surface contact was defined among other internal bones to simulate the relative articulating movement.

Kirschner, bandage and fiberglass fixation models were simulated and shown in Fig. 3: (b) Kirschner wire was designed in CATIA software (Dassault Systèmes, France) and inserted in osteotomy fragments; (c) In bandage fixation model, pressure loading obtained from experimental testing was used in surface traction of forefoot regions; (d) Bandage of fiberglass fixation was developed around the metatarsophalangeal joints regions.

All bones and tissues were idealized as homogeneous, isotropic and linearly elastic material. Medical grade steel named 316 LVM Stainless Steel was used for Kirschner [32]. Material mechanical properties were cited from literature (Table 2). The mechanical property of fiberglass bandage was obtained by the material test.

For the subject in this study (62 kg), each foot was loaded about half of body weight. About 300 N of the ground reaction force (GRF) was applied to plantar though ground. The upward vertically force of the Achilles tendon was about 150 N to simulate the equivalent force vectors at the posterior extreme of the calcaneus [37] (Fig. 4). Friction coefficient of 0.6 between osteotomy segments was measured by experiment [38]. Articular surfaces were defined by frictionless [39]. The contact between foot plantar and ground was divided into forefoot-ground, midfoot-ground, hindfoot-ground [40]. Coefficient of friction of 0.6 was used in interface between foot surfaces and ground [41].

In FE model, the relative displacements of osteotomy fragments were used to quantify the Kirschner, bandage and fiberglass