https://doi.org/10.1016/j.actbio.2021.09.010

Biomechanical analysis of minimally invasive crossing screw fixation for calcaneal fractures: Implications to early weight-bearing rehabilitation

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Abstract

Background

Minimally invasive fixation using crossing screws was believed to produce satisfactory clinical outcome whereas its stability in early weight-bearing remained controversial. This study aimed to analyze the biomechanical stability of minimally invasive fixation during balanced standing and walking stance, and provide evidence for early rehabilitation.

Methods

A finite element model of foot-ankle-shank complex was reconstructed based on computed tomography and magnetic resonance images, and validated by plantar pressure of the model participant. A Sanders III calcaneal fracture was created on the model, and then fixed using crossing screws. The predicted stress distribution, fracture displacement, Bohler's angle and Gissane's angle were compared between the intact calcaneus and fracture model with the fixation.

Findings

Postoperatively, the concentrated stress appeared at the junction of the calcaneus and its surrounding tissues (especially Achilles tendon, plantar fascia and ligaments) during standing and walking stances, and the stress exceeded the yield strength of trabecular bone. The longitudinal screws sustained the highest stresses and concentrated at the tips and the calcaneal tuberosity junction. The displacement of posterior joint facet, Bohler's angle, and Gissane's angle were within the acceptable range either standing or walking after the fixation.

Interpretation

Early weight-bearing standing and walking after minimally invasive fixation may cause high stress concentration thereby induce calcaneus stress fractures and other complications like plantar fasciitis and heel pain, so it should not be supported. The peri-calcaneus tendons, i.e., Achilles tendon and plantar fascia, play key roles in the stabilization of the calcaneal fracture after operation.

key word calcaneus fracture; internal fixation; walking; biomechanics; finite element analysis

1 Introduction

Calcaneal fracture with inter-articular displacement often requires surgery and the open reduction and internal fixation (ORIF) has been recommended as a gold standard (Weng et al., 2019). However, ORIF creates large incision leading to complications. The complication rate could be as high as 30% and increased the risk of re-operation (Howard et al., 2003). Minimally invasive fixation (MIF) has been introduced to repair calcaneal fractures at a lower risk of complications (Backes et al., 2017). Ebrahimpou et al. (2020) pointed out that MIF shortened inpatient days, reduced wound-related complications, and produced better patient satisfaction, compared with that of ORIF.

Early rehabilitation is imperative for fracture healing and function recovery. Patients after MIF could withstand full body weight under balanced standing condition (Ni et al., 2019), but the capability to start weight-bearing walking remains controversial. An analysis of the fracture site, including stability and alignment after surgery under walking loading conditions could provide more evidences to support or oppose early walking postoperatively.

Computational simulation using Finite Element (FE) method can analyze the internal stress changes of complicated structures under different boundary and loading conditions, otherwise infeasible to conduct through cadaveric experiments (Wang et al., 2016). Some simulations have been conducted on ORIF. Ni et al. (2016) compared the biomechanical stability between locking plate, crossing metallic and absorbable screw fixation using a single calcaneus model, whereas similar work was also conducted on the modified Calcanail system (Ni et al., 2019). Chen et al. (2017) improved the prediction by encompassing the full foot-and-ankle model complex, which comprised of bones, cartilages, and soft tissues. Despite, the biomechanical performance focusing on MIF requires further investigations.

To this end, the objective of this study is to construct a FE model of the foot-ankle-shank complex, modify it into a fracture model with MIF, and drive the simulation with the boundary and loading conditions of balanced standing and walking stance. The predicted stress distribution, fracture displacement, Bohler's angle and Gissane's angle were evaluated and compared between the intact calcaneus and fracture model with MIF procedure. We hypothesized that the outcome of these variables was negative and might suggested that early weight-bearing rehabilitation deem inappropriate.

2 Materials and Methods

2.1 Subject Information

A healthy female volunteer with the age of 63, height of 156 cm and weight of 64 kg was recruited. The participant was free of any musculoskeletal disorder, pain, and previous foot surgery. This study was approved by the Ethics Committee of Shanghai Pudong New Area Peoples' Hospital (No. 2019-16).

2.2 Geometry Reconstruction

Computed tomography (CT) imaging of the left lower limb were taken using a GE CT750 HD (750 High Definition), with 1-mm slice interval, and a pixel size of 0.5 mm. Meanwhile, sagittal MRI images were also obtained using a Siemens magnetic resonance imaging (MRI) Skyra 3.0 at a layer thickness of 1.25 mm and a pixel size of 0.68mm. The CT and MRI images were processed by medical image processing software (MIMICS 15.0, Materialise Leuven, Belgium) to reconstruct the geometry of the lower limb musculoskeletal model which comprised of 32 foot bones (tibia, fibula, talus, calcaneus with 5 fracture fragments, navicular, cuboid, 3 cuneiforms, 5 metatarsals, 12 phalanges), muscles (gastrocnemius and soleus), 46 ligament bundles with 127 truss units, 5 plantar fascia bundles, and encapsulated soft tissues, as shown in Fig.1a.

Fracture (Sanders III ab) was made on the model geometry by osteotomizing a 0.1 mm fracture gap (Fig. 1b). The fracture model then underwent a simulated MIF procedure using five crossing screws. As shown in Fig. 1c, two short cannulated screws (diameter: 3.5 mm) were inserted to the sustentaculum tali in transverse direction. Two longitudinal screws (diameter: 6.5 mm) were placed obliquely from the calcaneal tuberosity to the calcaneocuboid joint, and another screw was fixed to the fragment of the posterior joint facet.

2.3 Mesh Creation

The model was then processed in another software (Geomagic 2015, NC, USA) and proceeded for mesh creation (Hypermesh 13.0, Altair, USA), as shown in Fig.1d.

The bones, muscles and encapsulated soft tissues were modeled as four-node three-dimensional tetrahedron units (C3D4), and those of the plantar fascia and ligaments were 2-node Truss (T3D2) units. The ground support was meshed with an 8-node reduced integrated hexahedral element (C3D8R). The intact foot model comprised of 80,311 nodes, 455,104 elements and 137 truss units while the fracture model comprised of 369,551 nodes, 778,668 elements and 137 truss units.

2.4 Material properties

Muscles and encapsulated soft tissues were considered as hyperelastic materials. The hyperelastic materials properties were referred from the experimental results obtained by Lemmon et al. (1997) and Reeves et al. (2005), respectively, as shown in Table. 1. Material properties of other parts were idealized as homogeneous, isotropic and linearly elastic, as shown in Table. 1 (Cheung and Nigg, 2008; Cheung et al., 2005; Morales-Orcajo et al., 2016; Ramlee et al., 2014).

2.5 Loading and boundary conditions

During balanced standing condition, 320 N (half of body weight) was applied superiorly from the ground plate as the ground reaction force. The tensile force acting through the Achilles tendon was applied on the posterior superior calcaneal tuberosity. The superior surfaces of the tibia, fibula, Achilles tendon and soft tissues were fixed (Fig. 2). The plantar soft tissue and the ground were defined as hard contacts with a friction coefficient of 0.6 (Dai et al., 2006) while the fracture and the screw and different fracture bone pieces were defined as hard contacts with a friction coefficient of 0.2 (Bulaqi et al., 2015).

During walking stance condition, three featured instants were simulated, including heel-strike, midstance, and push-off. Ground reaction forces (GRFs) during gait were 704 N, 608 N and 738 N, which corresponded to 110%, 95% and 115% body weight. (Chen et al., 2015; Yu et al., 2016). The Achilles tendon forces were 480 N, 550 N, and 1100 N, respectively at heel-strike, midstance and push-off (Arnold et al., 2010; Fröberg et al., 2009; Gefen et al., 2000). The angle between the foot and ground was set to be 11° (Gefen et al., 2000).

2.6 Outcome Measures

The finite element simulation was carried out in Abaqus 6.13 (Dassault Systèmes, RI, USA). The coordinate system of the FE model, loading and boundary condition were set as shown in Fig. 2. The outcome between the intact model was compared to the fracture calcaneus model with MIF procedure.

3 Results

3.1 Model validation

To validate the FE model, the plantar preassure distribution predicted from FE analysis was compared with that measured on the same model participant under balanced standing condition (TPScan system, Biomecha, Korea). The peak plantar pressure were 0.262 MPa and 0.253 MPa respectively, which demonstrated good agreement (Figs. 3a and 3b). Forefoot contact area was 20.17 cm^2 and 20.97 cm^2, which was slightly lower than the measured value of 3.8 %. Rearfoot contact area was 39.83 cm^2 and 38.63 cm^2, which was slightly higher than the measured value of 3.1 %. In addition, the predicted navicular height dropped 8.1 mm, which fell within the suggested range of 7.3 mm to 9.0 mm (Giuliani et al., 2011).

3.2 Biomechanical comparison of intact calcaneus and fracture model

Under balanced standing, the maximum von Mises stress of the intact calcaneus was concentrated on the sustentaculum tali (9.125 MPa) and the junction between the plantar fascia and the calcaneus (6.095 MPa), as shown in Fig. 4a. The MIF procedure increased the maximum von Mises stress to 188.5 MPa at the junction between the plantar fascia and calcaneus (Fig. 4b). The maximum von Mises stress was 174.7 MPa at the junction between the calcaneus and the interosseous talocalcaneal ligament (Fig. 4b). In contrast, the stress was reduced at the sustentaculum tali (5.1 MPa) indicating potential disturbance of stability compromised by peri-calcaneus tendons and plantar fascia.

3.3 von Mises stress distribution

Under walking stance, for the calcaneus model with MIF procedure, the maximum von Mises stress concentrated at the plantar fascia junction during midstance and push-off but concentrated at the interosseous talocalcaneal ligament junction at heel strike. The values were 208.1 MPa, 350.3 MPa, and 375.7 MPa respectively at heel-strike, midstance and push-off instants (Fig. 5). There was an approximately one-fold stress elevation overall, as compared to that of the balanced standing. There was also some concentrated stress at the fracture end and screw connection.

Figure 6 shows the stress distribution of the fixation screws. The stress was mainly concentrated at the junction with the fractures, and the longitudinal screws (S3, S5) bore the stress substantially. The maximum von Mises stresses were 134.1 MPa, 169.0 MPa, 221.1 MPa, and 395.9 MPa respectively at balanced standing, heel-strike, midstance, and push-off instants. The maximum stress located at the tips of the longitudinal screws and transferred to the mid-shaft closed to the calcaneal tuberosity during push-off.

3.4 Fracture displacement and calcaneal angles

The maximum displacement of calcaneus was 3.735 mm, located at the sustentaculum tali during static standing. However, it was transferred to the calcaneal tuberosity, and decreased to 0.703 mm, 1.694 mm and 3.300 mm during stance at the three stance instants respectively (Fig. 7).

The fracture clearance of posterior joint facet was measured according to the previous report (Ni et al., 2016; Ni et al., 2019). The fracture clearance was 0.18 mm during balanced standing, and 0.14±0.036 mm, 0.26±0.020 mm, and 0.38±0.018 mm in the three stance instants. The Bohler's angle and Gissane's angles were 30.8 ° and 122.7 ° respectively during standing. During stance, the Bohler 's angle decreased, but the Gissane 's angle gradually increased. Regardless, the Bohler’s angle and Gissane’s angle in all stance instants were within acceptable range (Table. 2).

3.5 Contact pressure of the fragment interfaces

There were 7 contact pairs of bone-to-bone fragment, and 17 contact pairs of bone-to-implant interfaces. The maximum contact pressure on the bone-to-implant interface was higher than that between the bone-to-bone fragments. The former was 220.4 MPa in static standing and increased to 243.8 MPa, 259.0 MPa, and 278.5 MPa, respectively at the three gait instants. The latter was 75.6 MPa in static standing and 147.9 MPa at push-off.

4 Discussion

In this study, we have reconstructed and validated a FE model of the foot-ankle-shank complex, which could reveal the internal biomechanical characteristics of the intact calcaneus and fracture model with MIF. The models were loaded with the balanced standing condition and featured instants in walking stance, including heel-strike, midstance, and push-off. Our results showed that the calcaneal fracture would undertake higher stress compared with intact calcaneus. In addition, in calcaneal fracture model, the high stress was concentrated at the junctions of calcaneal tuberosity and surrounding tendons and ligaments. This indicates the peri-calcaneus tendons, i.e., Achilles tendon and plantar fascia, play key roles in the stabilization of the calcaneal fracture after operation.

Despite the fact that the critical calcaneal angles (Bohler's angle and Gissane's angle) were within acceptable range (Su et al., 2013), our prediction showed that MIF procedure induced excessive concentrated calcaneal stress which exceeded the ultimate stress (< 130 MPa) of calcaneal fracture (Frost, 1997), which supported our hypothesis that the outcome was negative. These undesirable biomechanical outcomes may indicate the risk of stress fracture and osteophyma development, thus the early weight-bearing rehabilitation with walking training may not be appropriate.

Crossing metallic screw fixation was believed to provide sufficient stability during balanced standing (Ni et al., 2016). However, relevant study did not consider the role of encapsulated soft tissue and adjacent structures in the model. The advantage of our study was to take a more comprehensive foot-ankle-shank model complex into consideration, which encompassed other soft tissues, as well as the simulation of walking stance using applied GRF and Achilles tendon force. Our study showed that the clearance of the posterior joint facet was less than 1 mm in both standing and walking stance that may not affect the stress distribution after fracture healing (Potter and Nunley, 2009). However, the peak stress of calcaneus was 188.5 MPa and even larger during walking. The value was likely to be underestimated since muscular adaptation response was not considered (Kiter et al., 2010). Nevertheless, the excessive stress may provoke stress fracture, plantar fasciitis, heel pain and other complications.

Crossing screws fixation is a common configuration of the MIF for calcaneal fractures (Ni et al., 2016). We found that the longitudinal screws undertook higher stresses concentrated on the tip and the junctions with the calcaneal tuberosity. The longitudinal screws acted as a bending cantilever and was leveled distally and superiorly upon the contraction of Achilles tendon. Furthermore, Achilles tendon force caused a greater shear force between the calcaneal tuberosity and the screws, resulting in stress concentration. Therefore, we suggest that the longitudinal screw should be placed to the articular surface as close as possible (Eichinger et al., 2019) to reduce the stress at the tip. A larger diameter screw could also be used to reduce the excessive stress in calcaneus which can help to start rehabilitation exercise early.

Clinical studies showed that patients after MIF were likely to develop heel pain and plantar fasciitis (Clare and Crawford, 2017; Koutserimpas et al., 2016; Lim and Leung, 2001). Our study supported the observation that high stress was concentrated at the junction of the soft tissue. Existing study found that concentrated stress appeared at the fracture sites (Ni et al., 2019) could be due to the ignorance of surrounding soft tissue structures. To this end, based on our findings, we discourage patients with pre-existing heel pain and plantar fasciitis underwent MIF so as to prevent aggravating the conditions. On the other hand, a certain amount of contact pressure at the fragment interfaces could facilitate an inter-fragmentary compression for bone healing and avoid non-union (Wong et al., 2015), despite that excessive pressure may lead to bone breakdown. Investigations on the appropriate pressure range are warranted.

This study had several limitations. We assumed that the material of the bone was homogeneous and isotropic. Taking account of the bone quality, heterogeneity and anisotropy could improve model accuracy and help predict the risk of periprosthetic fracture of the fixation. The ligaments were simplified as truss units and assumed the same cross-sectional area which may overestimate the joint stability of the forefoot. Besides, we assumed that the boundary and loading conditions between the intact and fracture model with MIF conditions were similar, under the premise that no notable overall structural change and thus adaptation gait response was anticipated (Wong et al., 2018). It shall also be noted that the ground reaction force and muscles forces were sensitive to the plantar pressure pattern and thus their measurement or estimation shall be adequately reliable (Akrami et al., 2018). In addition, finite element method pertains to a deterministic theoretical study such that single-subject approach is often adopted (Wong et al., 2016). We believed that our model participant was of typical physique and representative as viewed by orthopaedic surgeon. Model improvement can be carried out by solidifying the plantar fascia and consider a patient-specific loading profile (Wang et al., 2016). Future study can explore novel surgical interventions to minimize stress concentration and undesirable biomechanical environment to the foot and ankle.

5 Conclusions

In comparison to the intact calcaneus, the calcaneal fracture after MIF undertook higher stress concentration during standing and walking conditions. The peri-calcaneus tendons, i.e., Achilles tendon and plantar fascia, help preserve calcaneal stabilization after MIF and endure high stress concentration. All these would induce stress fractures, plantar fasciitis and other complications. Therefore, early weight-bearing rehabilitation after MIF should be avoided.

Funding

This study was funded by the Project of academic leader of health system in Pudong New Area, Shanghai (PWRd2019-05); General project of Shanghai Municipal Health Burean (201840137); Key R&D Program granted by the Ministry of Science and Technology of China (2018YFB1107000); General Program granted by the National Natural Science Foundation of China (11972315); Key Program granted by the National Natural Science Foundation of China (11732015); and General Research Fund granted by The Hong Kong Research Grant Council (PolyU152065/17E)

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Table. 1 Material parameters

Entity	Young's modulus E (MPa)	Poisson's ratio v	Density (kg/m^3)	Cross-sectional area (mm^2)
Bone	7300	0.3	1500	——
Plantar fascia	350	——	937	58.6
Ligament	260	——	937	18.4
Titanium	110000	0.3	4540	——
Ground	17000	0.1	5000	——
muscle	Hyperelastic (polynomial form) C_{10} = 0.08556, C_{01} = −0.05841, C_{20} = −0.039, C11 = −0.02319, C_{02} = 0.00851, D_1 = 3.65273			
Soft tissue and skin	C_{10} = 8.57000, C_{01} = 12.1000, C_{20} =936.000, C_{11} = 718.000, C_{02} =480.000, D_1 =0.00413			

Table. 2 Posterior joint facet fracture clearance, Bohler's angle and Gissane's angle of the fracture calcaneus after MIF

Parameter	Static standing	Heel-strike	Midstance	Push-off
Posterior joint facet fracture clearance/mm	0.18±0.021	0.14±0.036	0.26±0.020	0.38±0.018
Bohler’s angle	30.8	31.1	30.1	27.2
Gissane’s angle	123.7	121.4	123.1	125.2