Biomechanics of calcaneus impacted by talus: a dynamic finite element analysis

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ABSTRACT

This paper aimed to investigate the biomechanical changes during the talus impact with the calcaneus at varying velocities. Various three-dimensional reconstruction software was utilized to construct a finite element model that consisted of the talus, calcaneus, and ligaments. The explicit dynamics method was used to explore the process of the talus impacting on the calcaneus. The velocity of impact was altered from 5 m/s to 10 m/s with a 1 m/s interval. Stress readings were collected from the posterior, intermediate, and anterior subtalar articular (PSA, ISA, ASA), calcaneocubic articular (CA), Gissane Angle (GA), calcaneal base (BC), medial wall (MW), and lateral wall (LW) of the calcaneus. The changes in the amount and distribution of stress in the different regions of the calcaneus that varied with velocity were analysed.

The model was validated through comparison with findings from the existing literature. During the process of impact between the talus and calcaneus, the stress in the PSA reached its peak first. Notably, stress was concentrated mainly in the PSA, ASA, MW, and LW of the calcaneus. At varying impact velocities of the talus, the mean maximum stress of the PSA, LW, CA, BA, and MW exhibited statistically significant differences (P values were 0.024, 0.004, <0.001, <0.001, and 0.001, respectively). However, the mean maximum stress of the ISA, ASA, and GA was not statistically significant (P values were 0.289, 0.213, and 0.087, respectively). In comparison with the velocity at 5 m/s, the mean maximum stress increases in each region of the calcaneus at a velocity of 10 m/s were as follows: PSA 73.81%, ISA 7.11%, ASA 63.57%, GA 89.10%, LW 140.16%, CA 140.58%, BC 137.67%, MW 135.99%. The regions of stress concentration were altered, and the magnitude and sequence of peak stress in the calcaneus also varied according to the velocity of the talus during impact.

In conclusion, the velocity of the talus during impact had a significant influence on the magnitude and distribution of stress within the calcaneus, which was a crucial factor in the development of calcaneal fractures. It was possible that the magnitude and sequence of stress peaks played a vital role in determining the emergence of fracture patterns.

Introduction

Fractures of the calcaneus make up nearly one-third of all foot injuries, with falls being the most frequent cause of such injuries (Herrera-Pérez et al. 2018). Understanding the mechanisms and patterns of injury was crucial for making informed surgical decisions (Galluzzo et al. 2018). Due to the complex anatomy of the calcaneus, as well as its susceptibility to infection, avascularity, and postoperative skin necrosis, treating calcaneal fractures was expensive and often resulted in complete disability for patients lasting up to 3–5 years (De Boer et al. 2015; Clare and Crawford 2017; Albin et al. 2020).

Axial compression was identified as the primary cause of calcaneal fractures (Gallenberger et al. 2013; Stephens and Grujic 2020). The fractures were caused by stress on the calcaneus when it was positioned between the ground and the talus during a fall. There were two classic theory on calcaneal fracture (Essex-Lopresti 1952; Carr et al. 1989). Carr et al. (1989) used eighteen cadaveric tibia specimens to model intra-articular calcaneal fractures and found that the fracture comprised of two basic fracture lines. The first fracture line divided the calcaneus into medial and lateral portions, extending to the calcaneocuboid joint and the anterior subtalar articular. The second fracture line divided the calcaneus into anterior and posterior parts, extending from the Gissane Angle to the medial wall of the calcaneus. Essex-Lopresti...
(1952) suggested that the primary calcaneal fracture line initially formed between the lateral talar process and lateral calcaneal margin, and that the lateral wall of the calcaneus and the body of the calcaneus were separated at the Gissane Angle, followed by an anterolateral fracture, a compression fracture, or a tongue-type fracture of the calcaneus. These findings were obtained through direct observation of the experiment. Biomechanics have been proposed as the basis for managing intra-articular calcaneal fractures (Lowery and Calhoun 1996; Lewis 1999; Rammelt and Zwipp 2004), but the stress changes associated with different types of calcaneal fractures were not yet fully understood.

Finite element analysis was a valuable method for estimating internal stress and strain that could not be obtained through experimentation alone. The use of finite element models to study the biomechanics of the foot allowed for the visualization of stress distribution in different regions of the calcaneus, which could help understanding the process of calcaneal fracture (Shin et al. 2012; Wong et al. 2016; Tsubone et al. 2019). However, it remains unclear how the stress changes in the calcaneus when it is impacted by the talus at different velocities. Wong et al. (2016) studied the stresses on the trabeculae bone within the calcaneus during heel strike at velocities of 2 to 7 m/s. Qian et al. (2013) conducted a dynamic finite element analysis of the human foot complex in the sagittal plane during level walking. However, these studies did not clarify the magnitude of stresses or the changes in the area of stress concentration during impact on the calcaneus associated with calcaneal fractures. As a result, biomechanical changes in this area have not yet been reported.

In this study, a finite element model including the talus, calcaneus, and ligaments was constructed. The explicit dynamics method was employed to analyze the impact of the talus’ velocity on the calcaneus. The study aimed to determine the stress changes in the calcaneus when impacted by the talus at different velocities, and to analyze the impact of these stress changes on calcaneal fractures.

**Material and methods**

**Model construction**

For this study, a healthy male volunteer (24 years old; height, 172 cm; weight, 65.3 kg) without heel deformities or a history of fractures, as confirmed by radiographic examination, was selected. The study was approved by the ethics committee of the hospital. The informed consent was obtained from the volunteer. The volunteer’s left ankle was scanned using a spiral computed tomography (CT) scanner while fixed in a neutral position with a brace. The scanning ranged from the bottom of the heel to 10 cm above the ankle, with a slice thickness of 0.625 mm. The CT images were stored in Dicom format and segmented using Mimics software (version 10.0, Materialise, Belgium) to generate three-dimensional (3D) images of the calcaneus and talus. The 3D images were optimized using Geomagic Studio software (version 12.0, Geomagic company, America) to create a high-quality Non-Uniform Rational B-Splines surface. The calcaneus and talus were assembled in the neutral position according to their anatomical position using Solidworks software (version 2010, Solidworks, France). The classification of cortical and cancellous bone was accomplished using Boolean operations with Ansys Workbench software (version 14.0, Ansys Inc, America), with the cortical bone thickness measured at 2.68 mm (Sabry et al. 2000). The posterior talocalcaneal ligament, medial talocalcaneal ligament, lateral talocalcaneal ligament, and intertalar calcaneal ligament were defined based on their attachment points on the bone.

**Material properties**

In accordance with previous studies, the Poisson’s ratio of the bone was set to 0.3, and the elastic modulus of cortical bone and cancellous bone was set to 7.5 GPa and 400 MPa, respectively (Nakamura et al. 1981; Morales-Orcajo et al. 2016). Both types of bone were treated as isotropic materials (Wang et al. 2016). The ligament stiffness was assigned to tension-only structures (Iaquinto and Wayne 2010; Spratley et al. 2013). The ligaments were simplified as isotropic linear beams. The elastic modulus and Poisson’s ratio of the ligaments were set to 80 MPa and 0.40, respectively (Wang et al. 2015). The areas of the posterior talocalcaneal ligament, medial talocalcaneal ligament, lateral talocalcaneal ligament, and intertalar calcaneal ligament were assigned 14.96, 14.91, 6.84, and 72.80 mm², respectively, based on the studies of Mkandawire et al. (2005) and Shin et al. (2012). The densities of cortical bone and cancellous bone were set at 538.5 mg/cm³ and 210.5 mg/cm³, respectively (Wu et al. 2009).

**Boundary and initial condition**

To simulate real-life scenarios, the talus was loaded vertically down with initial velocities of 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, and 10 m/s, as individuals were more susceptible to calcaneal fractures when falling freely from a
height of 1.25 m to 5 m with terminal velocities ranging from about 5 m/s to 10 m/s. Gravitational acceleration was set at 10 m/s\(^2\), and the end time was set to 1.5 ms.

The calcaneal tuberosity and calcaneocuboid articular were fully constrained, with the talus set up as a rigid body. The analysis method used was explicit dynamics, and the solver used was Autodyn (Figure 1).

**Validation of finite element model**

To validate the model, the construct stiffness of the intact calcaneus finite element model was applied to the experimental conditions of a 700 N vertical load to simulate the single-legged standing phase. The results were then compared with the cadaveric calcaneus experiment reported by Ni et al. (2018).

**Data analysis**

Two to six nodes on the posterior subtalar articular (PSA), intermediate subtalar articular (ISA), anterior subtalar articular (ASA), Gissane Angle (GA), lateral wall (LW), medial wall (MW), calcaneocubic articular

![Figure 1. Finite element model with boundary conditions. (A) Velocity; (B) Fixed support.](image)

![Figure 2. Select the nodes in each region to extract the stress of the calcaneus (A-C). Seven nodes were selected to analyze the stress changing with the time (Number1 to 7 in A-C).](image)
(CA), and base of the calcaneus (BA) were selected to investigate the stress changes, and one node from each region was selected to analyze the relationship between stress and time (as shown in Figure 2(A–C)). The maximum von-Mises stress value of these nodes during the end time was extracted to evaluate the stress changes in each region of the calcaneus. The data was expressed as mean ± standard deviation (x \pm s), and repeated measures ANOVA was used for data analysis. A \( p \) value less than 0.05 was considered statistically significant. Statistical analysis was performed using SPSS 13.0 software (SPSS Inc, Chicago, IL, USA).

**Results**

**Model validation**

A model consisting of talus, calcaneus and ligaments was constructed using three-dimensional reconstruction software and finite element analysis software. The model comprised 10,084 nodes and 30,686 elements. To validate the finite element model, it was compared with previous studies. As a result, the finite element model in this study predicted the highest vertical construct stiffness of the calcaneus to be 656 N/mm, which was similar to the stiffness of 634 N/mm reported in a published study (Ni et al. 2018).

**Stress variation**

As the velocity of the talus impact increased, so did the stress value in each region of the calcaneus, with varying intensity. Table 1 displays the mean maximum stress for each region of the calcaneus, with statistically significant differences found for the PSA, LW, CA, BA, and MW regions (\( p \) value were 0.024, 0.004, < 0.001, < 0.001, and 0.001 respectively), while no significant differences were observed for the ISA, ASA, and GA regions (\( p \) value were 0.289, 0.213, and 0.087 respectively). Comparing talus velocities of 5 m/s and 10 m/s, the mean maximum stress for each calcaneal region increased as follows: PSA 73.81%, ISA 7.11%, ASA 63.57%, GA 89.10%, LW 140.16%, CA 140.58%, BC 137.67%, MW 135.99%.

Additionally, with differing velocities, the high-stress area on the calcaneus varied (Figure 3). Furthermore, analysis of the selected nodes revealed that the order of maximum stress in each region changed simultaneously as the talus velocity changed, and the posterior talus joint reached peak stress first. Figure 4 showed the stress changes and sequence of maximum stress for each calcaneal region at different velocities over time. Table 2 specified the sequence of maximum stress for each region at each velocity. The stress distribution for the calcaneus at a velocity of 10 m/s was illustrated in Figure 5.

**Discussion**

Foot and ankle injuries are often the result of high-energy falls (Snoap et al. 2017). Calcaneal fractures, in particular, could generate considerable force between the foot and the ground, ranging from 8 to 14 times the weight of the human body (Mcnitt-Gray 1991). Fractures occur when the impact load exceeds the endurance limit of the bone. Understanding the biomechanics of calcaneal fractures during falls was
Figure 4. Stress of the calcaneus changed with velocity during 1.5 ms. (A) 5 m/s. (B) 6 m/s. (C) 7 m/s. (D) 8 m/s. (E) 9 m/s. (F) 10 m/s.
crucial for identifying the mechanism of high-energy trauma in the hindfoot. Finite element modeling was widely used to explore biomechanics on human skeletal injuries (Shin et al. 2012; Qian et al. 2013; Wong et al. 2016; Güvercin et al. 2022). It has been also proven useful in conducting the treatment of dental injuries, hip and ankle fractures, and ligament injuries (Nisanci et al. 2020; Terzi et al. 2021; Güvercin et al. 2022; Güvercin and Yaylalı 2023). Shin et al. (2012) developed a finite element model of the foot and leg to investigate the injury tolerance of the ankle under brake pedal loading for internally and externally rotated feet. Qian et al. (2013) performed explicit finite element simulations covering the entire stance phase and found that ground reaction forces, center of pressure, foot bone motion, and plantar surface pressure were in good agreement with gait measurement data over most of the stance phase. Wong et al. (2016) evaluated the risk of calcaneal and talus fracture and found that the axial compressive impact at 5.0 m/s could cause significant trabecular bone yielding in both the calcaneus and talus. The peak stresses appeared around the talocalcaneal articulation and the inferior calcaneal tuberosity. This was consistent with the results of this study.

The present study determined that an increase in velocity led to an increase in the amplitude of stress in all areas of the calcaneus, with the greatest increase observed in the medial wall, lateral wall, and calcaneocuboid joints. Calcaneal fractures were found to be significantly influenced by impact velocity, with stress on each area of the calcaneus potentially increasing by up to 50% for every 1 m/s increase in velocity. The velocity of foot impact on the ground was found to be related to the height of the fall, which ultimately determined the impact load on the heel during landing (Mcnitt-Gray 1993). For activities such as walking and running, impact velocities ranged from 0.52 m/s to 0.72 m/s, while in sports such as skiing the impact velocity could reach as high as 14.0 m/s at a fall height of 10 meters (Chi and Schmitt 2005; Hubbard et al. 2009). A study by Funk et al. (2002) found that the majority of calcaneal fractures occurred at an impact velocity of 5.0 m/s. Therefore, reducing the impact of the talus on the calcaneus during a fall should be the primary means of reducing calcaneal fractures.

The location of stress concentration in the calcaneus changed with the impact velocity of the talus. Yoganandan et al. (2000) conducted experimental studies on the loads required to cause calcaneal fractures and found that the greater the load, the higher the likelihood of calcaneal damage. Another study found that the risk of calcaneal injury increased with increasing impact velocity (Gallenberger et al. 2013). However, previous studies did not provide quantitative analysis on the changes in stress in the calcaneus. The present study not only demonstrated the relationship between velocity and stress, but also showed how stress changes with time. As the velocity of talus increased, the increase in stress in different regions of the calcaneus was not uniform due to anatomical differences. This could result in different areas of calcaneal fracture and different calcaneal fracture lines.

This study made another noteworthy discovery, indicating that the initial positions of calcaneal fractures might be correlated with the sequence of stress peaks. The different positions and directions of fracture lines, even primary fracture lines, remain controversial (Miric and Patterson 1998; Funk et al. 2002). Calcaneal fractures exhibit varied morphologies due to the fragmentation and displacement, as well as the combination of different fracture lines. Utheza et al. (1998) suggested that the main fracture line varies but was consistently centered on the sustentaculum tali. Warrick and Bremner (1953), however, argued that the fracture line traverses anteriorly and posteriorly from a point on medial calcaneal wall, to varied locations posterior to the sustentaculum tali. In the present research, areas of stress concentration were identified at the anterior, posterior, and intermediate subtalar joint, the medial wall, and the Gissane Angle. These locations of stress concentration remained the same as the fracture locations proposed by Carr et al. (1989). Clearly, if the stress peak occurred early and the localized stress exceeded the bone’s limit load, the calcaneal fracture could occur at that time. As the stress concentration areas of the calcaneus increased, there was an associated increase in the number of possible fracture sites, resulting in composite fracture lines.

There were several limitations with the simplified finite element model utilized in this study. Firstly, assumptions were made that trabecular and cortical

| Velocity | Sequence of peak stress |
|----------|-------------------------|
| 5m/s     | PSA CA, MW AS, IS, GA LW, BC |
| 6m/s     | PSA CA AS, MW IS, GA LW, BC |
| 7m/s     | PSA AS, MW CA IS, GA BC, LW |
| 8m/s     | PSA CA AS, MW IS, GA LW, BC |
| 9m/s     | PSA IS CA, MW IS, GA BC, LW |
| 10m/s    | PSA IS CA, MW CA IS, GA BC, LW |

Note. PSA, posterior subtalar articular; IS, intermediate subtalar articular; AS, anterior subtalar articular; GA, Gissane angle; LW, lateral wall; MW, medial wall; CA, calcaneocubic articular; BC, bottom of the calcaneus.
bone as well as ligaments were homogenous and isotropic. Additionally, soft tissues of the forefoot, midfoot, and heel were not incorporated. In reality, these soft tissues could serve as energy absorbers, where the damping properties of skin, muscles, and cartilage could potentially reduce stress, transmit, and consume energy generated during impact. Consequently, this might have resulted in some inaccuracies in the results obtained. Furthermore, the weight of the human body was not applied to the talus. This study only provided an approximate reflection of stress distribution and stress changes on the calcaneus, and therefore the interpretation of results could not be extended. External validity also posed a challenge in finite element analysis, thus making it difficult to generalize the results. Due to the laborious nature of creating a finite element model, most studies used a single-subject design, leading to possible errors in the results. Finally, the impact injury to the calcaneus was a very complicated process, and a more accurate finite element model with precise material properties and boundary conditions would be required to better reflect reality through simulation technology.

Conclusions

The impact velocity influences both the amount and distribution of stress in the calcaneus, which was a crucial determinant of calcaneus fractures. Specifically, a higher talus impact velocity led to an increase in stress in each area of the calcaneus. The regions of the calcaneus most prone to stress concentration were the posterior, intermediate, and anterior subtalar articular, the Gissane Angle, and the medial wall. The magnitude and timing of stress peaks played an essential role in determining the direction and onset of fracture lines.

Disclosure statement

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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