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Biomechanical Role of Bone Grafting for Calcaneal Fracture Fixation in the Presence of Bone Defect: A Finite Element Analysis

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Abstract

Background

The purpose of this study was to compare the biomechanical stress and stability of calcaneal fixations with and without bone defect, before and after bone grafting, through a computational approach.

Methods

A finite element model of foot-ankle complex was reconstructed, impoverished with a Sanders III calcaneal fracture without bone defect and with moderate and severe bone defects. Plate fixations with and without bone grafting were introduced with walking stance simulated. The stress and fragment displacement of the calcaneus were evaluated.

Findings

Moderate and severe defect increased the calcaneus stress by 16.11% and 32.51%, respectively and subsequently decreased by 10.76% and 20.78% after bone grafting. The total displacement was increased by 3.99% and 24.26%, respectively by moderate and severe defect, while that of posterior joint facet displacement was 86.66% and 104.44%. The former was decreased by 25.73% and 35.96% after grafting, while that of the latter was reduced by 88.09% and 84.78% for moderate and severe defect, respectively.

Interpretation

Our finite element prediction supported that bone grafting for fixation could enhance the stability and reduce the risk of secondary stress fracture in cases of bone defect in calcaneal fracture.

Keywords： Stress fracture; Hindfoot; Ankle; Finite element method; in silico simulation

Introduction

Calcaneal fractures are the most common tarsal bone fractures, typically caused by high-energy injuries, such as traffic accidents and falls, and more than two-thirds of them are displaced intra-articular calcaneal fractures (DIACFs) (Schepers et al., 2008). They account for approximately 1% to 2% of all body fractures and are prevalent among young and middle-aged adults (Zwipp et al., 2004). Calcaneal fractures could induce life-changing injuries with serious disability that might not be restorable (Spierings et al., 2019). Patients might have a rehabilitation period more than six months, imposing a significant burden on themselves, their families, and society (Jiang et al., 2012). Besides, the majority of these severe and compound calcaneal fractures involve displacement of articular fragments and collapse of posterior articular, leading to bone defects that adversely impact fixation outcomes (Park et al., 2021b). Stabilizing these fractures present a challenge because of the “neutral zone” of bone defects, particularly in cases of impaction fractures (Andermahr et al., 1999; Richter et al., 2005). The use of bone grafting in fracture fixation for cases with bone defects remains popular, despite the lack of substantial evidence to support its efficacy and benefits (Bulut et al., 2018; Longino and Buckley, 2001; Luo et al., 2022; Zheng et al., 2018).

The need for bone grafting to fill the defect has been a question for a long time (Diniz et al., 2019; Park et al., 2021b). Although it was believed that bone grafting may repair bone defects to prevent late-stage collapse and post-traumatic arthritis (Elsner et al., 2005; Jiang et al., 2008), the idea remains controversial (Diniz et al., 2019). Research has shown that fixation procedures can achieve similar functional and radiological outcomes with or without grafting and bone grafting might be reserved for cases where the bone defect is pronounced (Gusic et al., 2015; Khorbi et al., 2006; Longino and Buckley, 2001; Park et al., 2021b; Rammelt and Zwipp, 2004; Yang et al., 2012). Singh and Vinay (2013) showed that bone grafting induced a higher infection rate and worse AOFAS (American Orthopaedic Foot and Ankle Society) score, though the findings were not significant, while bone grafting might also lead to a significant occurrence of postoperative pain (Cao et al., 2018). Bone grafting, as an additional procedure, increases the cost and duration of the procedure, as well as necessitate more intensive postoperative care and rehabilitation.

Conversely, the need of bone graft was argued by the risk of secondary stress fractures in cases of bone defects, where the absence of grafting may lead to increased stress on the calcaneus, potentially compromising the stability of fixation and the quality of bone healing (Duymus et al., 2017; Singh and Vinay, 2013). Evidence suggested that bone grafting is crucial for maintaining better fracture reduction (Singh and Vinay, 2013). Inadequate reduction or unstable fixation may result in malunion, potentially leading to subsequent development of post-traumatic arthritis (Rammelt and Zwipp, 2013). A meta-analysis has demonstrated that bone grafts resulted in better AOFAS scores compared to non-grafting, without an elevated risk of postoperative complications (Zheng et al., 2018). Although recommended treatment algorithms exist to guide the choice between conservative or surgical interventions, as well as the type of surgical interventions for various severities and classes of calcaneal fractures (Salameh et al., 2023), there is no consensus regarding the use of bone grafting. Definitive guidelines based on patient characteristics, fracture patterns, or imaging findings are lacking. Further investigation into the role of bone defects and their biomechanical interaction with bone grafting is essential for informed surgical decision-making.

Evaluating the biomechanical stability of calcaneal fixation in the presence of bone defects could enhance our understanding of the need for bone graft. Computational methods, or in silico approaches, offer a versatile platform for analyzing the internal biomechanical environment under controlled conditions. The use of in silico finite element models has been extensively employed to investigate foot and ankle biomechanics, pathomechanics, and the assessment of interventions (Behforootan et al., 2017; Talbott et al., 2023; Wang et al., 2016). However, existing in silico studies have primarily concentrated on evaluating various calcaneal fixation techniques and/or implants (Lv et al., 2022; Ni et al., 2016a; Ni et al., 2019a; Xu et al., 2022; Zhang et al., 2020). The novelty of this study lies in its focus on a bone defect model that addresses the research question concerning the relationship between bone integrity and the stability of calcaneal fixation, thereby offering insights into the necessity of bone grafting.

This study aimed to investigate how moderate and severe bone defects and the application of bone grafting influence the stress and biomechanical stability of the calcaneus using computational (in silico) methods. We hypothesized that larger bone defects would increase the stress and decrease biomechanical stability of the calcaneus. Furthermore, we hypothesized that the application of bone grafting could reduce the elevated stress and restore stability.

Methods

Model Participant

We recruited a healthy male volunteer aged 30, 172 cm tall, and weighed 60 kg. He had no foot deformities, history of trauma and surgery. The participant was informed of the research and signed an informed consent. The study was approved by the Ethical Committee of Shanghai Pudong New Area People's Hospital (reference number: 2021.K12).

FE Modeling

Computed tomography (CT) imaging of the left lower leg was taken using a GE CT 750 HD (750 High Definition), with 1-mm slice interval and 0.5-mm pixel size. Sagittal Magnetic Resonance (MR) images were also acquired using Siemens Skyra 3.0 with a slice thickness of 1.25 mm and a pixel size of 0.68 mm. They were processed using Mimics 15.0 (Materialize, Leuven, Belgium) to reconstruct the model geometry. The FE model (Fig. 1) included 30 bones (tibia, fibula, talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals, 14 phalanges, and 2 sesamoids). Ligaments and plantar fascia were drawn as truss units. The cartilaginous structures were created by filling up the volume between the articular joint space.

We considered the calcaneus fracture plating system (Gorilla® Calc Fracture Plating System, Paragon 28® Incorp., Englewood, United States), which consisted of 15 locking screws and a perimeter plate (locking plate). It was modeled by Solidworks 2021 (Dassault Systèmes, Concord, USA). The screw threads were simplified and replaced by a "tie" operation to fasten the bone-thread interface.

Sanders Type III fracture was plotted and generated on the reconstructed intact model with an osteotomized gap of 0.1 mm by an orthopaedic surgeon (Fig. 2) (Ni et al., 2021). Thereafter, we created two different sizes of irregular geodesic dome-shaped cavities on the common location of bone defects (i.e., under the posterior facet) to resemble moderate and severe levels of bone defect based on previous report (Fig. 2) (Demcoe et al., 2009). The moderate defect was approximately 4500 mm^3 in volume, whereas that of the severe case was 9000 mm^3 (Lykoudis et al., 2013; Park et al., 2021b). Bone grafts were formed by filling the one defect and secured with screws. A "tie" contact is performed to secure the interface between the calcaneus and the bone graft.

The material properties are shown in appendix (Table A1) (Cheung and Nigg, 2008; Cheung et al., 2005; Morales-Orcajo et al., 2016; Ramlee et al., 2014). Bones were assumed to be homogeneous, isotropic, and linearly elastic. The material properties of encapsulated soft tissue were considered hyperelastic (Lemmon et al., 1997; Reeves et al., 2005).

As shown in Table 1, three representative walking stance instants were simulated by applying a tilting on the ground plate, ground reaction forces, and muscle forces (Bulaqi et al., 2015; Morales-Orcajo et al., 2017; Peng et al., 2021a; Wong et al., 2021b; Yu et al., 2016b). The proximal ends of the tibia and fibula were fully fixed. The friction coefficient between the plantar tissues and ground support was set at 0.6 (Dai et al., 2006), while it was set at 0.2 between the bone fragments (Bulaqi et al., 2015). The simulation was performed using Abaqus (Dassault Systèmes, Vélizy-Villacoublay, France).

Mesh Creation and Verification

Bones, cartilaginous structures, and the encapsulated soft tissue were meshed using four-node tetrahedral elements (C3D4). The plantar fascia and ligaments were assigned tension-only two-node truss elements (T3D2), while the ground supports were mapped with eight-node reduced integral hexahedral elements (C3D8R). Accordingly, the model incorporating a bone defect comprised 140,013 nodes, 815,320 elements, and 145 trusses, while that without bone defect comprised 141,121 nodes, 865,401 elements, and 145 trusses.

A mesh convergence test was conducted on the intact model under a balanced standing condition (GRF: 300 N; tendon Achilles force: 225 N). The test involved reducing the mesh size by about 10% (global mesh size from 3.2 mm to 2.88 mm.) This mesh size reduction changed the peak plantar pressure, the peak compressive principal stress of the first metatarsal shaft and talonavicular joint by 2.36%, 0.26%, and 1.48%, respectively. It was determined that the mesh size was adequately fine, as the outcome changes converged to less than 5% (Wong et al., 2018).

Outcome Measure and Data Analysis

The primary outcome measures were the maximum total displacement and posterior joint facet displacement of the calcaneus. To determine the changes of joint facet displacement, ten paired nodes from both sides of the fragments were identified with their average distance (Ni et al., 2016b; Ni et al., 2019b). The total and facet displacement served as indicators of fracture site stability, and their magnitudes reflected the risk of nonunion or malunion. The secondary outcome measure was the maximum von Mises stresses of bone fragments. High stress in the calcaneus indicated a risk of stress fracture.

We compared these outcome measures of the fixation on the calcaneus with and without defects, as well as before and after bone grafting.

Results

Model validation

Model validation was carried out by comparing the FE predicted plantar pressure (intact, balanced standing) with plantar pressure measured from the model participant using a pressure plate (TPScan System, Biomechanics Co. Ltd., Goyang-Si, South Korea). Both measured and simulated plantar pressures concentrated at the rearfoot, with peak values of 0.253 MPa and 0.257 MPa, respectively, accounting for a difference of 1.56%. The plantar contact areas were 56.84 cm^2 and 59.06 cm^2, respectively, for measurement and FE prediction, with a difference of 3.80% (Fig. 3).

Total Displacement and Facet Displacement

Fig.4 illustrates that the maximum displacement in the calcaneal fracture model with fixation, both with and without bone defect or bone graft, occurred at the calcaneal tuberosity. This can be attributed to the tension applied to the Achilles tendon. During the push-off instant, compared to the calcaneus without defects, the total displacement of the calcaneus with moderate and severe defects increased by 3.99% and 24.26% respectively, which then decreased by 25.73% and 35.96% respectively after bone grafting (Table 2).

The trend of the posterior joint facet displacement was the same as that of the total displacement. During the push-off instant, compared to the calcaneus without defects, the posterior joint facet displacement of the calcaneus with moderate and severe defects increased by 86.66% and 104.44% respectively, which then decreased by 88.09% and 84.78% respectively after bone grafting (Table 2).

von Mises Stress of Calcaneus

The distribution of stress predominantly localizes to the posterior articular surface of the calcaneus, the screw junction, and the ligament connection (Fig. 5). During the three gait instants, the maximum stress experienced by the calcaneus under defect conditions demonstrated an increase when compared to the non-bone defect calcaneus, as follows: moderate defect at 16.11%, severe defect at 32.51%. After bone grafting, the maximum stress in the calcaneus with moderate and severe defects decreased by 10.76% and 20.78%, respectively (Table 2).

Discussion

Calcaneal fractures could induce collapse in the posterior articular surface and misalignment (White et al., 2019), especially in cases with bone defects. Bone density in the trabecular core center was relatively low in calcaneus that may have contributed to the development of bone defects upon fractures. The bone defect problem might not be able to be solved by surgical reduction alone (Sarkar et al., 2002), and bone grafting might be intervened at a cost of potential complications (Park et al., 2021b). While bone grafting was carried out in one-fifth of the cases routinely (Schepers et al., 2008), a meta-analysis reported that there was no significant difference in Böhler angle and Gissane's angle between the graft and non-graft groups. This could be among the first few studies that endeavored to investigate the biomechanical variations of calcaneal fracture fixation with and without bone defect by a computational approach to support future research on whether bone grafting is essential.

The merit of this study lies in its comprehensive representation of both the bones and the encapsulated soft tissue, which contrasts with some prior studies that often resorted to oversimplification, such as employing solely the calcaneus model (Gu et al., 2015; Ni et al., 2016a; Ni et al., 2019a; Ouyang et al., 2017; Pînzaru et al., 2023; Xu et al., 2022; Yu et al., 2016a). These models typically neglected the dynamic interactions of the forefoot regions and the load transmission from these areas, which are crucial for a thorough analysis of the biomechanics of the foot and ankle complex (Wang et al., 2018). Qiang et al. (2020) extended their model to include the hindfoot and encompassed the deltoid ligaments to evaluate the influence of sustentaculum screw placement on joint contact area, stress, and displacement. Additionally, some studies have reconstructed the complete foot model, incorporating all bones, the plantar fascia and encapsulated soft tissue, yet omitting ligaments (Chen et al., 2018; Chen et al., 2017). The simplification of loading condition might affect the model accuracy and clinical interpretation. For example, Pînzaru et al. (2023) investigated implant stability by applying vertical loading to the subtalar joint surfaces to simulate weight-bearing conditions. Gültekin et al. (2021) examined the relationship between Böhler's angle and calcaneal strength by applying a 500 N axial load to the tibia alone. In contrast, our model more accurately simulates the walking stance, providing a better representation of physiological conditions.

Our FE predictions suggested that bone grafting could enhance the stability of calcaneal fractures with bone defects. Primary outcome measures, the total displacement and posterior joint facet displacement of the calcaneus, demonstrated marked improvements. Post-grafting, calcaneal total and posterior facet displacements with moderate and severe defects decreased by 25.73%, 35.96% and 88.09%, 84.78% respectively, compared to calcanei with defect. We observed increased displacement in calcanei with defects, suggesting higher instability compared to those without defects. However, bone grafting substantially improved this instability, as evidenced by reductions in both total and joint facet displacement post-grafting. Interestingly, these reductions led to displacements even lower than those in calcanei without defects. We attribute this enhanced stability to the bone cement acting as an internal splint within the calcaneus, effectively limiting micro-motion at fracture sites and providing a favorable mechanically stable environment for bone union. As for the secondary outcome measure, maximum von Mises stresses in the bone fragments, our analyses showed that defects increased peak stress, potentially exceeding the bone's fracture stress (120 MPa) (Frost, 1997). This suggested an increased risk of stress fractures in calcanei with defects. However, bone grafting significantly reduced peak stress on the calcaneus and the implant, hence lowering the risk of stress fractures. We also observed that severe bone defect calcanei demonstrated better stability after grafting than moderate defect calcanei. This could be due to the larger contact surface between the bone cement, bone fragments, and implants after cement solidification in severe defects, which may enable superior stress distribution.

Another notable finding in this study is that the biomechanical data of the calcaneus after bone grafting is even superior to that of the calcaneus without bone defect. Findings from a cadaveric study indicated that, when compared to conventional fixed-angle locking plate osteosynthesis, cemented-augmented screw osteosynthesis significantly outperformed in aspects of primary stability and range of motion during cyclic testing (Rausch et al., 2014). The application of bone cement appears to facilitate an improved biomechanical load distribution at the interface of the bone and osteosynthesis material, while concurrently mitigating the shear stresses experienced at the fracture locus (Belaid et al., 2018). Bone cement, when applied to fractures with a collapsed articular surface, may function as a biomechanical prop, offering essential support and stabilization.

The success of surgical fixation in calcaneal fractures can be significantly influenced by the choice of bone graft or filling. Different types of grafts, such as autografts (from patient’s own bone stock), allografts (from cadaveric bone stock), and synthetic substitutes, each possess distinct biomechanical and biological properties that impact the stability and success of the bone repair and fixation (Beaman et al., 2006). Essential properties to consider when selecting an appropriate bone graft include biocompatibility, biodegradability, osteoconductivity, and the capability to promote bone formation and osteogenesis (Beaman et al., 2006; Kolk et al., 2012). While Pan et al. (2018) have recommended the use of collagen artificial bone putty due to its lower complication rates, it is crucial to recognize that each bone graft or biomaterial has its own set of drawbacks. For instance, autografting can lead to new trauma and bone defects (García-Gareta et al., 2015); allografts or xenografts carry a high risk of immunologic rejection or infection (Pomajzl et al., 2016; Simonds et al., 1992); bioceramics are non-degradable and offer limited osteoconductivity (Conz et al., 2011); and synthetic biopolymers (e.g. polylactic acid, polyglycolic acid, etc.) may produce acidic degradation products that are detrimental to bone degeneration (Barber et al., 2011). In terms of finite element analysis, while it cannot directly account for the biological processes, it can provide insights into how the varying stiffness of bone grafts might influence the mechanical performance of surgical fixation. Additionally, the moldability of bone grafts over irregular defects can also be considered within finite element simulations to predict the mechanical stability post-surgery.

There are some limitations in this study. Studies using finite element models often lacked external validity, because only one subject-specific representative model was reconstructed and did not account for the variation in fracture patterns (Ni et al., 2021; Wong et al., 2021a). Particularly, our calcaneal fracture and fixation model was reconstructed and impoverished from a healthy individual, which might lose some necessary clinical features, such as irregularities between the fracture surfaces. From a modeling perspective, model geometry has been simplified for ligaments and plantar fascia (as trusses) and therefore, their interactions with encapsulated soft tissue were also neglected (Peng et al., 2021c). Material properties were assumed to be isotopic and homogeneous, in addition to the fact that the trabecular core and cortical shell were not segmented, which might overestimate the strength of the bone in the simulation. With respect to the boundary and loading conditions, the information was acquired from existing literature. Loading profile acquired from the same model participant was recommended to predict the muscle forces via musculoskeletal (multibody) modelling and to drive the patient-specific finite element model (Peng et al., 2021b).

Furthermore, inherent limitations arise from the methodological nature of in silico studies, finite element method in our case. Finite element analysis excels at simulating complex physiological conditions from a mechanical point perspective and predicting the mechanical behavior of tissues or implants under a variety of scenarios, offering insights that may be challenging or impossible to obtain through experimental methods or clinical trials. However, finite element analysis cannot fully replicate the intricate biological processes and patient-specific variations and responses that occur in vivo.

The outcomes of finite element studies suggest potential clinical implications from a biomechanical perspective. For example, surgeons can predict the mechanical behavior of the repair construct by inputting the patient-specific geometries and loading conditions and make informed choice about screw placement, graft material selection, and other surgical variables. Manufacturers can use the finite element model to evaluate the mechanical performance of their designs under a range of conditions before prototyping and clinical trials. Nonetheless, it is important to recognize that finite element methods cannot account for certain factors, including the biocompatibility of grafts, rehabilitation protocols (Park et al., 2021a), delayed treatments (Cao et al., 2018), physical activity levels (Schindler et al., 2021), comorbidities (SooHoo et al., 2011), and concurrent injuries (Schindler et al., 2021). As such, the role of finite element analysis is to supplement, not supplant, the clinical decision-making process and to provide a biomechanical framework that support, but not direct, clinical practice and patient care (Wong et al., 2021a).

Conclusion

In conclusion, our in-silico study has provided evidence that bone grafting can mitigate stress on the calcaneus and minimize fragment displacement, thereby enhancing stability and reducing the risk of secondary fractures. Future studies should expand on this work to investigate the biomechanical impacts of screws, external fixation, and other methods in conjunction with bone grafting, which would be crucial for a more comprehensive understanding of the optimal approaches to calcaneal fracture treatment.

Statements & Declarations

Declaration of Completing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figure legend

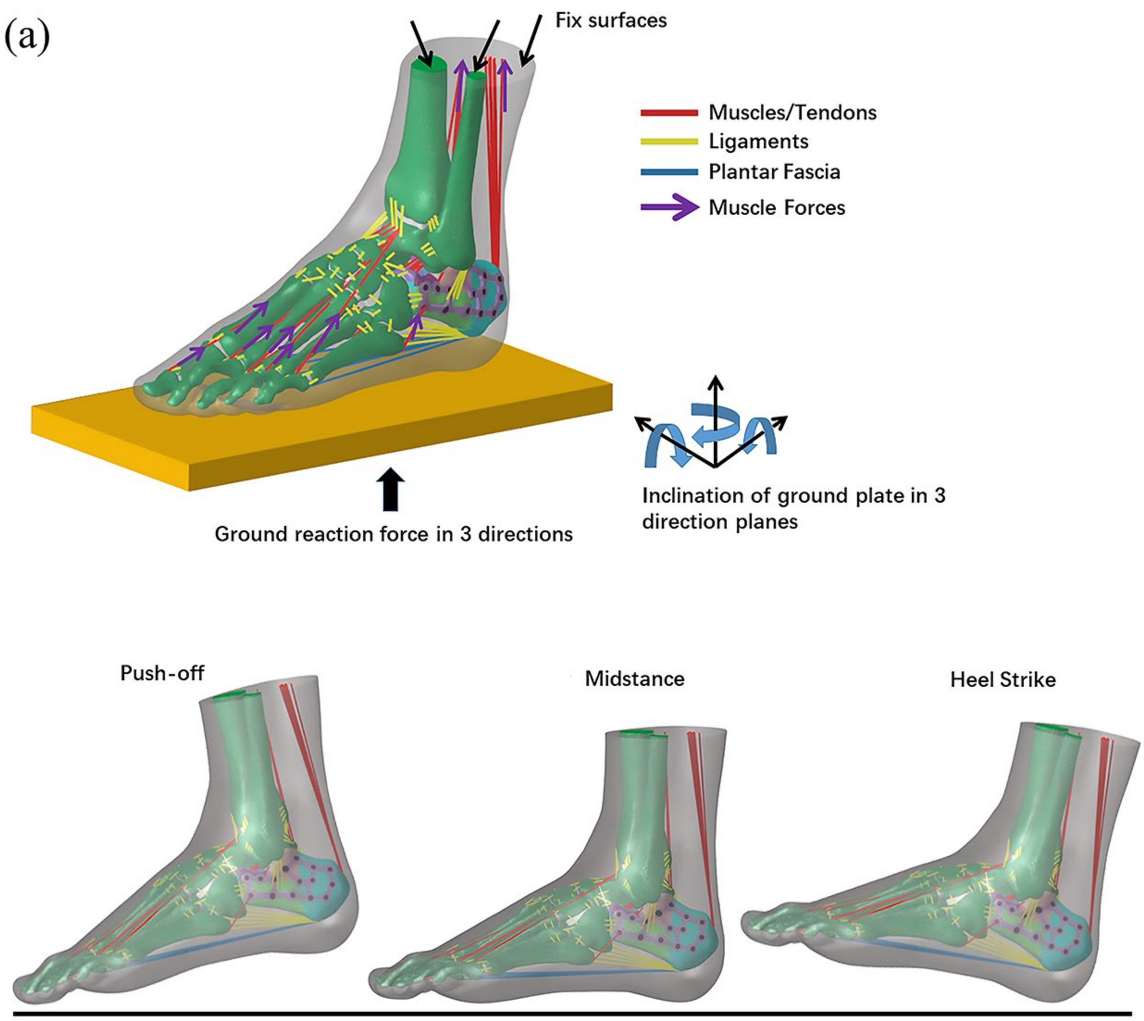

Fig.1. Model geometry and loading/boundary conditions for the finite element analyses and the illustration of the simulation of walking gait.

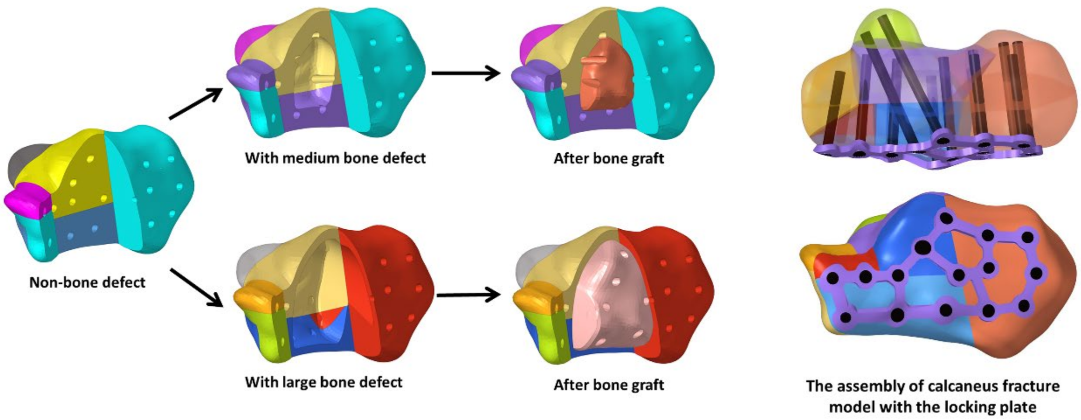

Fig.2. Calcaneus under five conditions: non-bone defect, moderate bone defect, severe bone defect, moderate bone defect with bone graft, severe bone defect with bone graft, and the assembled position of the implants-fixed bone block.

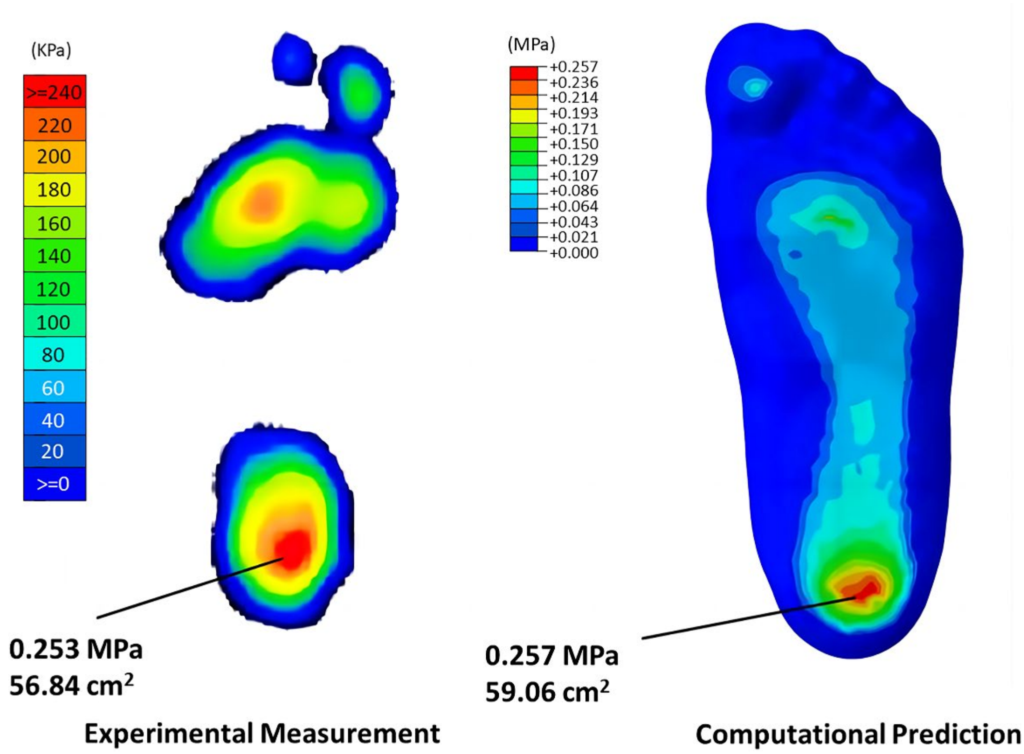

Fig.3. Comparison of the plantar pressure between experimental measurem and computational prediction.

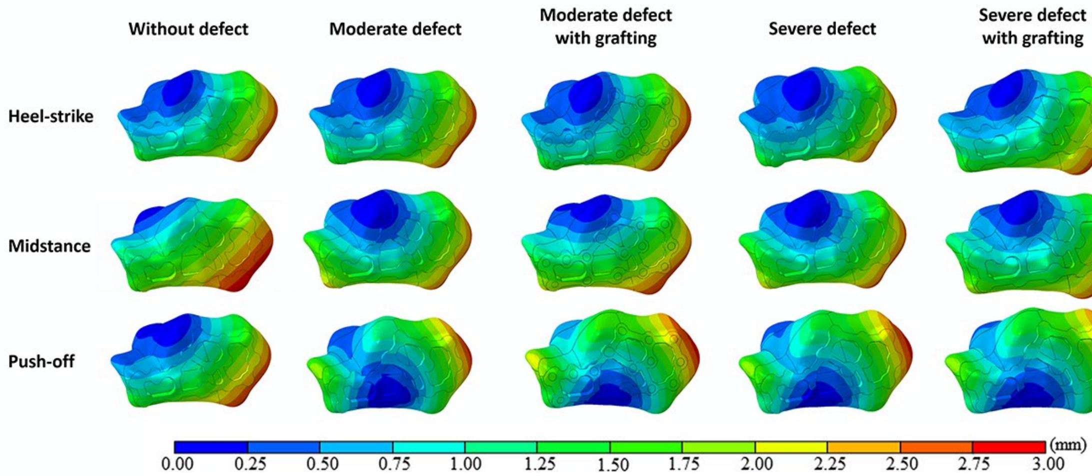

Fig.4. Resultant displacement (mm) of the calcaneus and implant under different conditions, respectively.

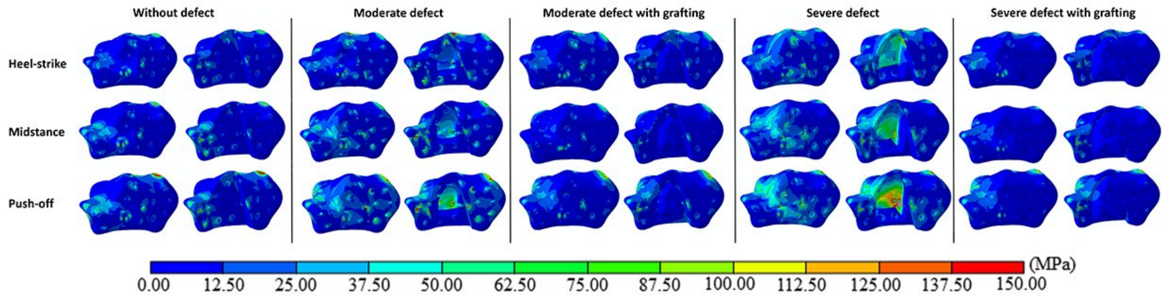

Fig.5. von Mises stress (in MPa) of inside and outside calcaneus under different conditions, respectively.