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Original Article

Cannulated compressive screw compared with cortical screw for fixation of simple first tarsometatarsal joint fracture-dislocation: a finite element analysis

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Abstract: *Objective:* Nowadays, various kinds of screws can be used in orthopedic surgeries; however, in the fixation tarsometatarsal joint injury, which screw should always be used is widely controversial. The aim of this study was to explore the biomechanical characteristics between the cannulated screw and cortical screw for the fixation of simple first tarsometatarsal joint fracture-dislocation. *Methods:* The finite element analysis was used and after the establishment of the finite element model of simple first tarsometatarsal joint fracture-dislocation, two simulations were designed. In one model, the AO 4.5 mm-cannulated compressive screw was simulated in the fixation of the fracture-dislocation. In the other model, the fracture-dislocation was fixed with the AO 3.5 mm-cortical screw. The two finite element models were simulated under the same loading and the displacement of the first tarsometatarsal articular surface and the stress distribution in screws of the two models were calculated respectively. *Results:* The maximum principal stress focused on the lower leg in both the models under the same loading. In the model of cannulated compressive screw fixation, the minimum displacement of the articular surface was 0.4834 mm, while it was 0.496 mm in the model of cortical screw fixation. The maximum principal stress in the cannulated compressive screw and cortical screw were 4.124×10^2 MPa and 6.075×10^2 MPa respectively, which were mainly concentrated in the middle of screws, especially in the side of the first metatarsal. *Conclusion:* Both the cannulated compressive screw and cortical screw are suitable for fixing simple first tarsometatarsal joint fracture-dislocation. However, compared with the cortical screw, the cannulated compressive screw has more obvious advantages. Therefore, using the cannulated compressive screw to fix the simple first tarsometatarsal joint fracture-dislocation is recommended.

Keywords: Cannulated compressive screw, cortical screw, tarsometatarsal joint, fracture-dislocation, finite element analysis

Introduction

The first tarsometatarsal joint plays an important role in the foot, which has important significance in the maintenance of foot arch and load transfer. Therefore, the first tarsometatarsal joint injury should be treated actively to recover the alignment of the midfoot and to ensure the load transfer from forefoot to the midfoot [1]. The screw might be the first choice to fix the first tarsometatarsal joint injury. However, there are many kinds of screws and which kind is the most suitable implant is still controversial, for improper implant may cause the changes of the local biomechanical environment of the feet, leading to the complications such as implant breakage, loss of reduction and malunion easily [2]. Therefore, it is necessary to study the biomechanical characteristics of different screws.

Due to the irregular anatomical structure of the first tarsometatarsal joint in midfoot, it is quite difficult to carry out the biomechanical research on the corpse specimens [3]. Therefore, in this study, a three dimensional (3D) finite element model of simple first tarsometatarsal joint fracture-dislocation was established and two kinds of implants, which were the AO 4.5 mm-cannulated compressive screw and the AO-3.5 mm cortical screw were simulated. The aim of this study was to analyze the displacement of the articular surface and the stress distribution in

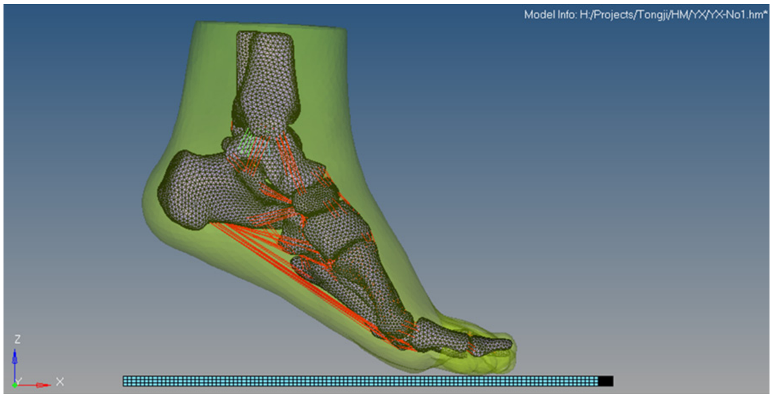

Figure 1. The three dimensional finite element of foot. The three dimensional finite element of foot with ligaments and plantar fascia was established and the ankle was fixed at 30° of plantar flexion to simulate the position of the tarsometatarsal joint injury.

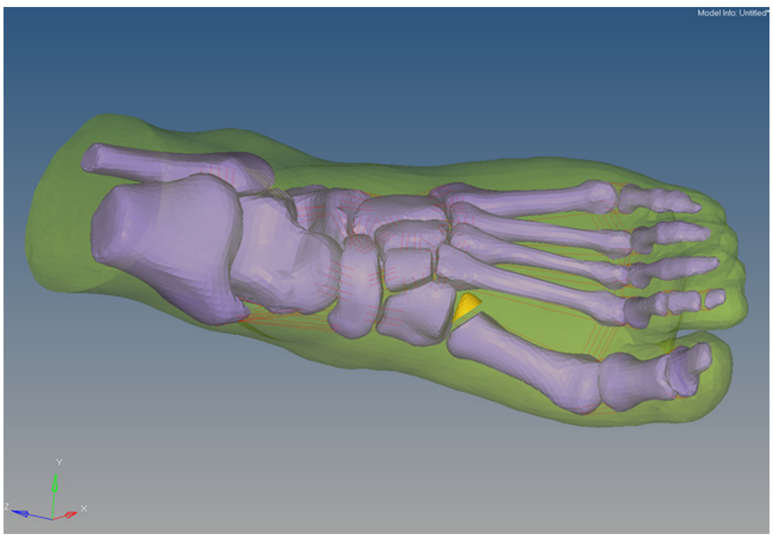

Figure 2. The simple first tarsometatarsal joint intra-articular fracture model. It was established by cutting off the dorsal and plantar ligaments between the medial cuneiform and the first metatarsal and osteotomy along the articular surface of the first tarsometatarsal joint.

the screws to provide experimental evidence for the choice of screws for the first tarsometatarsal joint injury.

Materials and methods

General data

A 35 year-old healthy male Chinese volunteer (height 170 cm and weight 70 kg) was recruited. The appearance and X-ray examination showed there was no deformity and damage in the foot. The volunteer signed the informed consent of the potential radiation hazard and the experiment was approved by the Ethics Committee of Ningbo NO.2 Hospital.

Equipment and software

In this study, the following equipment and software were used: (1) The 4D dual source CT (Siemens Ltd, German); (2) Mimics 12.0 (Materialise Ltd, Belgium); (3) Geomagic Studio (Rainrrop Ltd, USA); (4) SolidWorks 2010 (Dassault Systemes Ltd, USA); (5) ANSYS 13.0 (ANSYS Ltd, USA).

Experimental method

Data collection: The 4D dual source CT was used to scan the volunteer from lower segment of the leg to the whole foot in neutral position. The slice thickness was 1 mm and the scan speed is 0.4 s/ring. The original CT image data of 512×512 matrix was obtained (Dicom format).

Establishment of 3D model: The original data was loaded in the software of Mimics 12.0 to obtain a three-dimensional model of the foot. After the optimization of the model, it was loaded to the software of Ansys 13.0 and a three dimensional finite element of foot with 66540 nodes and 349475 units could be obtained. The materials in the model were simplified as homogeneous elastic materials. The thickness of the cortical bone was set in 2 mm. The ligaments and plantar fascia were established by 2 node TRUSS unit (**Figure 1**). The model of the foot was then loaded into the Solidworks 2010 to simulate cutting off the dorsal and plantar ligaments between the medial cuneiform and the first metatarsal and osteotomy along the articular surface of the first tarsometatarsal joint to result in the simple first tarsometatarsal joint intra-articular fracture model [4] (**Figure 2**). In order to reflect the stress distribution of the two screws better,

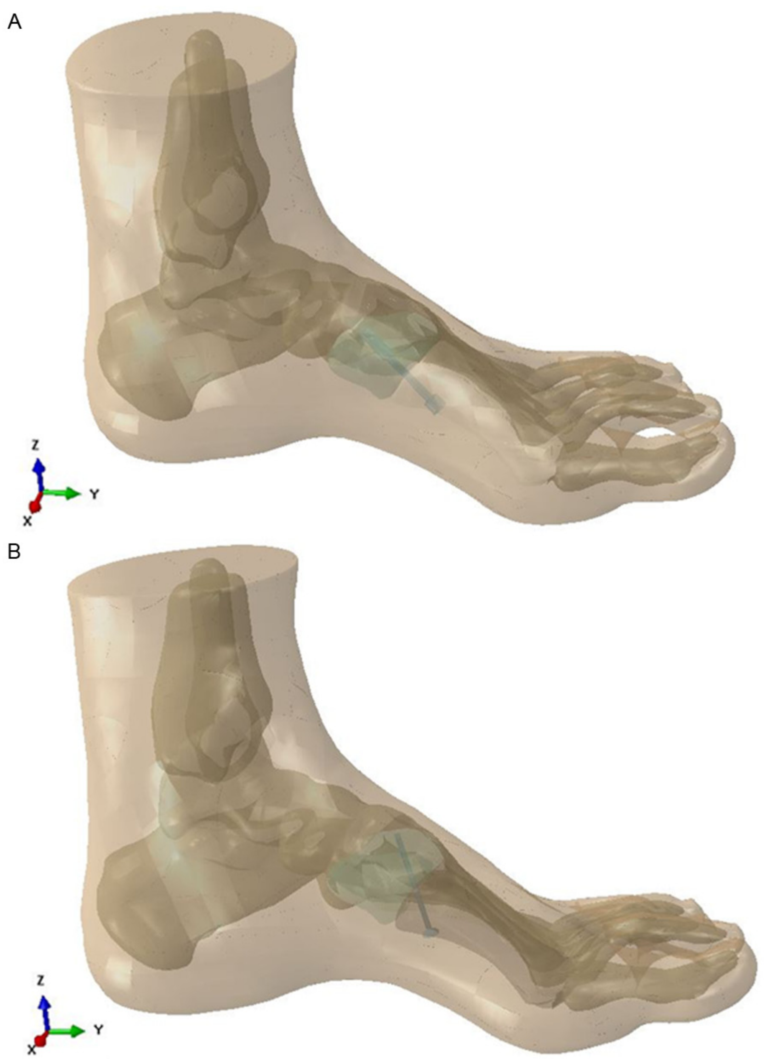

Figure 3. Two implant models were established. A. The AO 4.5 mm-cannulated compressive screw was fixed trans-articular from the base to the first metatarsal to the media cuneiform, which was perpendicular to the fracture line. B. The AO 3.5 mm-cortical screw was also fixed trans-articular from the base to the first metatarsal to the media cuneiform, which was perpendicular to the fracture line.

Table 1. Elastic constants of the different materials

Materials	Modulus of elasticity (MPa)	Poisson ratio
Cortical bone	7300	0.3
Cancellous bone	100	0.3
Titanium screw	110000	0.28
Fracture line	5	0.4
Ligaments and plantar fascia	500	0.3

the fracture line was replaced by the soft material.

The geometric parameters of the screws were loaded into the Solidworks 2010 and two implant models were established according to the experiment. The AO 4.5 mm-cannulated compressive screw was fixed trans-articular from the base to the first metatarsal to the media cuneiform, which was perpendicular to the fracture line. The AO 3.5 mm-cortical screw was also fixed trans-articular from the base to the first metatarsal to the media cuneiform, which was perpendicular to the fracture line (**Figure 3**). The elastic constants of the different materials were set as shown in **Table 1** [5].

Loading of the external force: According to the mechanism of tarsometatarsal joint injury, in this study, the ankle was fixed at 30° of plantar flexion (**Figure 1**). We set the lowest contact point of the tibia and fibula and the head of the first metatarsal with the ground as the constraint point. The loading was 700 N in accordance with the body weight and direction was set from the lower leg perpendicular to the ground, while the reverse direction was set in the head of the first metatarsal. The tensile force caused by the traction of the muscles and ligaments around the joint could be offset according to the principle of the synthesis and decomposition of the force [5].

Results

Displacement of the articular surface

After the loading of 700 N, both of the screws provided the firm fixation to the models without breakage of the screws and destroy of the models. However, the articular surface still had a tendency of dorsal dislocation in both models. The maximum displacement in the model of

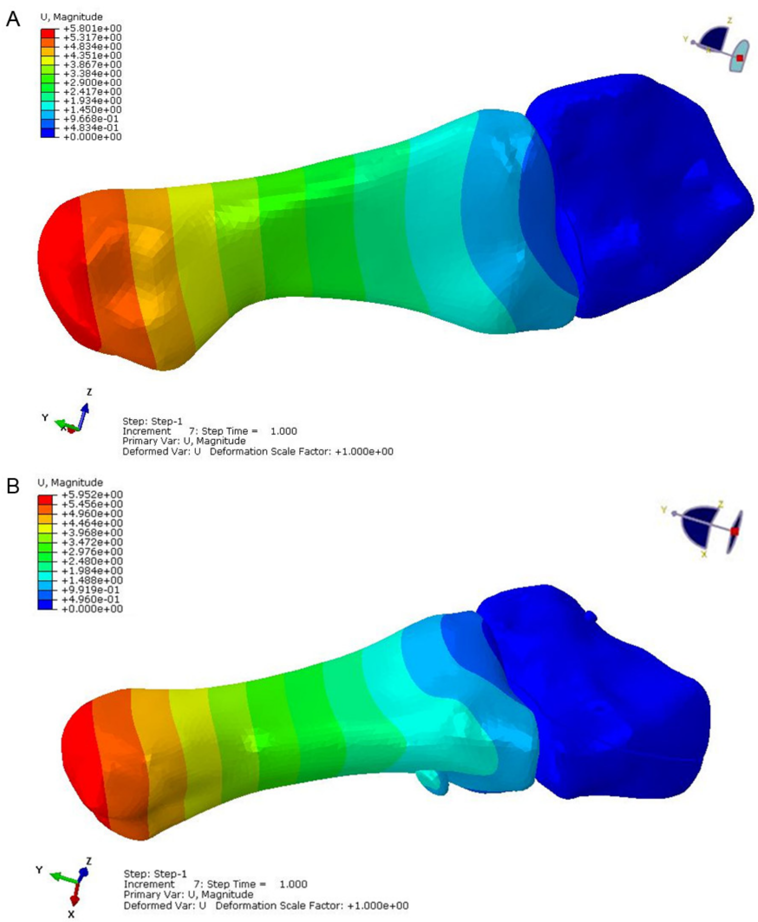

Figure 4. The displacement of the articular surface. A. The maximum displacement in the model of cannulated compressive screw fixation was 5.801 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.4834 mm, which appeared in the first tarsometatarsal articular surface. B. The maximum displacement in the model of cortical screw fixation was 5.952 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.496 mm, which appeared in the first tarsometatarsal articular surface.

cannulated compressive screw fixation was 5.801 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.4834 mm, which appeared in the first tarsometatarsal articular surface. The maximum displacement in the model of cortical screw fixation was 5.952 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.496 mm, which appeared in the first tarsometatarsal articular surface (**Figure 4**).

Stress distribution in the implants

After the loading of 700 N, it showed a concentrated distribution of the stress both in the cannulated compressive screw and cortical screw. The maximum stress in the cannulated compressive screw was 4.124×10^2 MPa, which was mainly concentrated in the middle of the screw but it supported equal stress both the in the sides of the first metatarsal and medial cuneiform. However, the maximum stress in the cortical screw was 6.075×10^2 MPa, which was also mainly concentrated in middle of the screw, especially in the side of the first metatarsal, which supported more stress than that in the side of medial cuneiform (**Figure 5**).

Discussion

Due to the irregular anatomical structure of the first tarsometatarsal joint in midfoot, it is quite difficult to do the biomechanical research on the corpse specimens. Furthermore, the simulation of simple fracture-dislocation in the first tarsometatarsal joint cannot always be uniform, which will also affect the results [3]. Therefore, the finite element analysis (FEA) is always used for the biomechanical research with its special advantage of high accuracy simulation of complex shapes and material properties [6, 7]. In the study, the original data from CT scan of the foot was loaded in Mimics12.0 to obtain the initial 3D model of the foot, and then the Solidworks 2010 could be used to cleave the model according to the Myerson classification type B1 to achieve the model of simple first tarsometatarsal joint fracture-dislocation. The Ansys 13.0 can be used to simulate the operations and assign the physical properties to the implants. After loading, the calculation could be carried on to work out the displacement of the articular surface, the stress distribution in the implants. However, as the limitation of the finite element analysis, the mechanical properties of materials are defined as continuous and homoge-

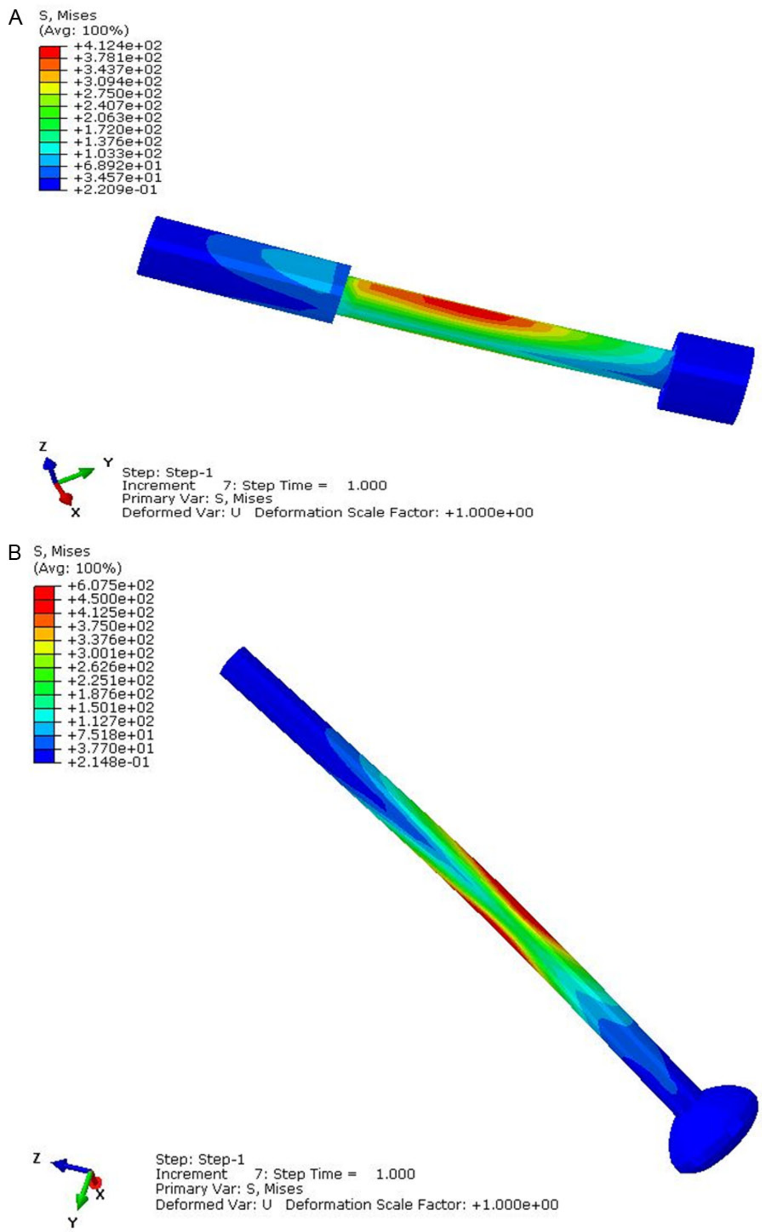

Figure 5. The stress distribution in the implants. A. The maximum stress in the cannulated compressive screw was 4.124×10^2 MPa, which was mainly concentrated in the middle of the screw but it supported equal stress both the in the sides of the first metatarsal and medial cuneiform. B. The maximum stress in the cortical screw was 6.075×10^2 MPa, which was also mainly concentrated in middle of the screw, especially in the side of the first metatarsal, which supported more stress than that in the side of medial cuneiform.

neous, isotropic, this assumption is slightly different from the real situation of the first tarsometatarsal joint in midfoot itself [8, 9].

According to the mechanism of tarsometatarsal joint injury, the model was axially loaded in 30° plantar flexion of the ankle rather than neutral position with the maximum load of 700 N (body weight of the volunteer). In order to reflect the displacement of the articular surface and the stress distribution of the implants more veritably, the fracture line and articular surface was replaced and bonded by the soft material with the Modulus of elasticity 5 MPa and Poisson ratio 0.4 and the titanium screws with the Modulus of elasticity 110 Gpa and Poisson ratio 0.28. After loading, the results showed that the displacements of the articular surface of two models were less than 2 mm, which meant that both of the implants could provide firm fixation [10]. However, the articular surface still had a tendency of dorsal dislocation in both models. In the model of cannulated compressive screw fixation, the minimum displacement of the articular surface was 0.4834 mm, while in the model of cortical screw fixation, the minimum displacement was 0.496 mm. The results revealed that the firm fixation by cannulated compressive screw or cortical screw could restore the normal anatomy and slight mobility of the first tarsometatarsal joint. According to the FEA, the maximum displacements were located in the head of the first metatarsal in both models. Therefore, when the first tarsometatarsal joint is injured, it is advisable to stop the weight bearing of the foot whether or not the implants are fixed. Otherwise, it may cause the instability of the first ray, leading to complications such as the metatarsalgia, plantar fasciitis and pressure ulcer and so on [11].

As for the stress distribution in the implants, after the loading of 700 N, it showed a concentrated distribution of the stress both in the cannulated compressive screw and cortical screw. Furthermore, it manifested that the implants could act a certain of stress shielding effect, which was beneficial to the early healing of the fracture and early functional exercise without weight bearing [12]. In this study, the maximum stress in the cannulated compressive screw and cortical screw were 4.124×10^2 MPa and 6.075×10^2 MPa respectively, which were mainly concentrated in middle of the screw, especially in the side of the first metatarsal. In this study, the value of the stress was obviously larger in the cortical screw than the cannulated compressive screw and accordingly, the cortical screw could provide more obviously a stress shielding effect. Certain stress shielding effects may be beneficial to the fracture, but it was dangerous if the stress shielding effect was too obvious, because it would result in the breakage of the implant and the nounion of the fracture [13]. Therefore, the patient should be careful of the weight bearing of the foot when there is an implant in the first tarsometatarsal joint. It is advisable to remove the screw if the patient wants to walk or run after the healing of the first tarsometatarsal joint injury. During the period of the removal of implant, the surgeons should pay more attention to the middle of the screws that the stress is more concentrated. Sometimes, the screws might have broken since the initial time of the patient to walk [14].

In the first tarsometatarsal joint injury, the main factor that affected the prognosis is the congruity of the articular surface. Therefore, how to fix it firmly in the first tarsometatarsal joint is good question in clinical practices. There are many kinds of implants which can be used in the fixation of the tarsometatarsal joint and cannulated screw alone or plate with screws is the first choice [14]. Occasionally, in some tarsometatarsal joint fracture-dislocation cases, the plate will eventually lead to the irritation of soft tissue and necrosis of the skin. Therefore, the screw can be substituted for plate. However, which screw should be used? In this study, we tested the cannulated compressive screw and cortical screw. The results showed both of the screws were suitable for fixing simple first tarsometatarsal joint fracture-dislocation. However, the cannulated compressive screw used in the study showed less displacement and also a suitable stress shielding effect [15]. Compared with the cortical screw in this study, it had more obvious advantages in fixing simple fracture-dislocation. Furthermore, the cannulated compressive screw will lead less iatrogenic traumatic arthritis than the cortical screw because the cannulated design will make the area of the necrosis in the articular surface smaller [16].

In conclusion, in this finite element analysis we found that both the cannulated compressive screw and cortical screw are suitable for fixing simple first tarsometatarsal joint fracture-dislocation. However, compared with the cortical screw, the cannulated compressive screw had more obvious advantages in biomechanics. Therefore, it is recommended to use the cannulated compressive screw to fix simple first tarsometatarsal joint fracture-dislocation.

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Disclosure of conflict of interest

None.

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References

[1] Arastu MH and Buckley RE. Tarsometatarsal joint complex and midtarsal injuries. Acta Chir Orthop Traumatol Cech 2012; 79: 21-30.

[2] Russell NA, Regazzola G, Aiyer A, Nomura T, Pelletier MH, Myerson M and Walsh WR. Evaluation of Nitinol Staples for the Lapidus arthrodesis in a reproducible biomechanical model. Front Surg 2015; 2: 65.

[3] Smith BR, Begeman PC, Leland R, Meehan R, Levine RS, Yang KH and King AI. A mechanism of injury to the forefoot in car crashes. Traffic Inj Prev 2005; 6: 156-169.

[4] Panchbhavi VK, Andersen CR, Vallurupalli S and Yang J. A minimally disruptive model and three-dimensional evaluation of Lisfranc joint diastasis. J Bone Joint Surg Am 2008; 90: 2707-2713.

[5] Pang QJ, Yu X and Guo ZH. The sustentaculum tali screw fixation for the treatment of Sanders

type II calcaneal fracture: A finite element analysis. Pak J Med Sci 2014; 30: 1099-1103.

[6] Golovakha ML, Orljanski W, Benedetto KP, Panchenko S, Buchler P, Henle P and Aghayev E. Comparison of theoretical fixation stability of three devices employed in medial opening wedge high tibial osteotomy: a finite element analysis. BMC Musculoskelet Disord 2014; 15: 230.

[7] Abdul-Kadir MR, Hansen U, Klabunde R, Lucas D and Amis A. Finite element modelling of primary hip stem stability: the effect of interference fit. J Biomech 2008; 41: 587-594.

[8] Gefen A, Megido-Ravid M, Itzchak Y and Arcan M. Biomechanical analysis of the three-dimensional foot structure during gait: a basic tool for clinical applications. J Biomech Eng 2000; 122: 630-639.

[9] Zhang BC, Liu HB, Cai XH, Wang ZH, Xu F, Kang H, Ding R and Luo XQ. Biomechanical comparison of a novel transoral atlantoaxial anchored cage with established fixation technique-a finite element analysis. BMC Musculoskelet Disord 2015; 16: 261.

[10] Kitsukawa K, Hirano T, Niki H, Tachizawa N, Nakajima Y and Hirata K. MR imaging evaluation of the lisfranc ligament in cadaveric feet and patients with acute to chronic lisfranc injury. Foot Ankle Int 2015; 36: 1483-1492.

[11] Dietze A, Bahlke U, Martin H and Mittlmeier T. First ray instability in hallux valgus deformity: a radiokinematic and pedobarographic analysis. Foot Ankle Int 2013; 34: 124-130.

[12] Caparros C, Ortiz-Hernandez M, Molmeneu M, Punset M, Calero JA, Aparicio C, Fernandez-Fairen M, Perez R and Gil FJ. Bioactive macroporous titanium implants highly interconnected. J Mater Sci Mater Med 2016; 27: 151.

[13] Costa FW, Bezerra MF, Ribeiro TR, Pouchain EC, Saboia Vde P and Soares EC. Biomechanical analysis of titanium plate systems in mandibular condyle fractures: a systematized literature review. Acta Cir Bras 2012; 27: 424-429.

[14] Yu X, Pang QJ and Yang CC. Functional outcome of tarsometatarsal joint fracture dislocation managed according to Myerson classification. Pak J Med Sci 2014; 30: 773-777.

[15] Peterson KS, McAlister JE, Hyer CF and Thompson J. Symptomatic hardware removal after first tarsometatarsal arthrodesis. J Foot Ankle Surg 2016; 55: 55-59.

[16] Lawrence BR, Theun E. A retrospective review of the primus first MTP joint double-stemmed silicone implant. Foot Ankle Spec 2013; 25: 94-100.