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Biomechanical evaluation of different hallux valgus treatment with plate fixations using single first metatarsal bone model and musculoskeletal lower extremity model

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Abstract

A numerical approach is one of feasible ways to discover the biomechanics of hallux valgus deformity with various osteotomy and fixation strategies. In the present study, two types of finite element models for analyzing the biomechanical performances of hallux valgus treatment with plate fixations were developed including the single first metatarsal bone model and the musculoskeletal lower extremity model. There are four types of plate fixations that were used to correct the deformity of hallux valgus. The strengths and limitations of both the single first metatarsal bone model and the musculoskeletal lower extremity model were evaluated and discussed. The results revealed that the single metatarsal bone models can be used to quickly predict the biomechanical performances of different hallux valgus treatments. Additionally, the musculoskeletal lower extremity models can be used to predict the biomechanical performances of different hallux valgus treatments under a physiological loading. The plate fixations with the insertion of all locking screws revealed better osteotomy fixation stability and lower risk of the implant failure compared to the other fixations. Additionally, the plate fixations with the insertion of six bone screws had lower risk of the metatarsal bone failure compared to the plate fixations with the insertion of four bone screws. The six holes plate with the insertion of six locking screws was the best treatment among the four treatment strategies. The numerical models and simulation techniques developed in the present study can provide useful information for understanding the biomechanics of hallux valgus treatments.

Keywords: Hallux valgus, Fixation stability, Implant failure, Bone failure, Finite element analysis, Lower extremity

1. Introduction

A hallux valgus is a deformity of the first metatarsophalangeal joint of human great toe (Malagelada et al., 2019). It can become painful and lead to other symptoms involving swelling, redness or soreness around the big toe joint (Lucattelli et al., 2020). Osteotomy and fixation are a good method for correcting a hallux valgus if the first metatarsophalangeal joint has no or little arthritis (Acar et al., 2018). There are several osteotomy and fixation methods to be applied for the treatment of hallux valgus deformity in clinical practice (Atkinson et al., 2019; Klauser, 2019). However, it is quite difficult to accurately control the variations in bone anatomy, bone density, osteotomy site, and fixation method (Arand et al., 2018; Lee et al., 2017). Fortunately, a computational approach, which uses finite element method, is one of possible ways to accurately control all the variations (Shih et al., 2020; Yan et al., 2020). Past studies had investigated the biomechanics of hallux valgus deformity using finite element analysis. Wong et al. (Wong et al., 2020) developed computational foot model from a mild hallux valgus participant and conducted a gait analysis to derive the simulation of walking. The effect of generalized ligament laxity on the stress pattern of the first ray had been studied. Zhang et al.

(Zhang et al., 2018) had investigated the effects of severe hallux valgus on metatarsal stress and the metatarsophalangeal loading during balanced standing using finite element method. Matzaroglou et al. (Matzaroglou et al., 2010) analyzed both sixty-degree Chevron osteotomy and ninety-degree Chevron osteotomy for correction of hallux valgus deformity using finite element method. Those studies had carefully investigated the biomechanics of hallux valgus deformity using either a single first metatarsal bone model or a complete musculoskeletal foot model. However, the difference between a simplified model and a complete model on the biomechanics of hallux valgus deformity is needed to be discovered. Thus, the purpose of the present study was to evaluate the biomechanical performances of the deformity of the first metatarsophalangeal joint with a distal osteotomy and various plate fixations using both a single first metatarsal bone model and a complete musculoskeletal foot model.

2. Materials and Methods

2.1 Single first metatarsal bone model

A single first metatarsal bone model was constructed based on a commercial skeleton model (Zygote Solid Skeleton Model-2nd Generation, Zygote Media Group, Inc., UT, USA). This skeleton model was developed from computed tomography scans of a 50th percentile male. The first metatarsal bone model was divided into cortical bone and cancellous bone by using a three-dimensional sculpting design software Geomagic Freeform (3D Systems, SC, USA). Then, the surface bone model was transferred into a reverse engineering software Geomagic Wrap (3D Systems, SC, USA) to construct the solid bone model. Finally, the solid bone model was transferred into a computer aided design software SolidWorks (SolidWorks Corporation, Concord, MA, USA) for further three-dimensional modelling.

To prepare the hallux valgus treatment models, there are two steps to develop the hallux valgus treatment models. The first step was to cut the first metatarsal bone to correct the deformity. In this study, the distal osteotomy was used in all the fixation strategies. The second step was to fix the osteotomy. In this study, titanium plates were used to securely fix the osteotomy until bone healing occurs. Four types of the plate fixations were analyzed and discussed including a four holes plate with four locking screws (4H4LS), a six holes plate with four locking screws (6H4LS), a six holes plate with four locking screws and two dynamic screws (6H4LS2DS), and a six holes plate with six locking screws (6H6LS). The geometry and dimension of the plates and screws were referred to a commercial plate design DARCO (Wright Medical Technology, Inc., Memphis, TN, USA). All the plates and screws were constructed and modified by using a computer aided design software SolidWorks (Fig. 1).

Fig. 1 The solid models of the single first metatarsal bone with various plate fixations.

2.2 Musculoskeletal lower extremity model

A musculoskeletal lower extremity model was developed using the same modelling technique of the single first metatarsal bone model. The lower extremity skeleton model consisted of tibia, fibula, talus, calcaneus, navicular, lateral cuneiform, middle cuneiform, medial cuneiform, cuboid, metatarsal bone, proximal phalanx, middle phalanx, and distal phalanx. All the bone parts of the lower extremity model were assembled by using SolidWorks. The assembly model of

the lower extremity was transferred into SolidWorks for further modelling. To prepare the hallux valgus treatment models, the similar modeling steps developed from the single first metatarsal bone models were used in the musculoskeletal lower extremity model (Fig. 2). To simulate the effects of foot ligaments, the following ligaments were considered in the present study including posterior tibiofibular ligament, anterior tibiofibular ligament, tibiocalcaneal ligament, tibionavicular ligament, plantar calcaneonavicular ligament, long plantar ligament, fibularis longus ligament, plantar metatarsal ligament, deep transverse metatarsal ligament, anterior tibiofibular ligament, posterior talofibular ligament, calcaneofibular ligament, superior fibular retinaculum, dorsal tarsometatarsal ligament, metatarsophalangeal joint capsules, and phalangeal ligament. The detailed modeling technique of the foot ligaments would be described in the section of finite element analysis.

Fig. 2 The solid models of the musculoskeletal lower extremity with various plate fixations.

2.3 Finite element analysis

Three-dimensional finite element models of the single first metatarsal bone and musculoskeletal lower extremity were created by using ANSYS Workbench (ANSYS, Inc., Canonsburg, PA, USA). The solid models of the single first metatarsal bone and musculoskeletal lower extremity were imported into ANSYS Workbench via Parasolid format. The fixation plates were made of titanium alloy, and they were simulated by using a linear elastic isotropic material. All the bone parts were divided into cortical bone and cancellous bone, and they were also simulated by using a linear elastic isotropic material. The foot ligaments were simulated by using tension-only spring elements (Fig. 3). The material properties of the finite element models were listed in Table 1. Due to the irregular geometries of the fixation plates and bones, the solid models were free-meshed by using 20-node solid elements of SOLID 186. A convergence analysis was conducted to ensure the numerical accuracy of the finite element models by changing element sizes. For the interface condition, a frictionless contact was assumed between the osteotomy surfaces. A bonded interface was assumed between the first metatarsal bone and the screws to simulate the screw threads fastening on the bone. Additionally, the interfaces between the locking screws and the threaded plate holes were assumed to be bonded. The dynamic screws have no locking head design. Thus, the interfaces between the dynamic screws and the plate holes were assumed to be a frictionless contact. For the loading and boundary conditions of the single first metatarsal bone, a force of 31 N was applied in the distal end of the first metatarsal bone, and the proximal end of the first metatarsal bone was fully constrained. These loading and boundary conditions were referred to past studies that developed a dorsally-directed cantilever bending test (Hofstaetter et al., 2008; Trnka et al., 2000). For the loading and boundary conditions of the musculoskeletal lower extremity, a ground reaction force of 350 N and an Achilles tendon force of 175 N were considered in the present study (Wong et al., 2015). Additionally, the proximal end of the tibia was fully constrained (Fig. 4). These loading and boundary conditions simulated a double-legged stance condition. The solution was done by an iterative solver with a time step size of 0.01. The time at the end of step was 1, and the maximum and minimum time step sizes were 0.1 and 0.001 respectively.

Fig. 3 The foot ligaments and external geometry of the musculoskeletal lower extremity models.

Table 1 The material properties of the finite element models.

Materials	Young's modulus (MPa)	Poisson's ratio	Stiffness (N/mm)
Plate (Titanium alloy)	114,000	0.34	-
Screws (Titanium alloy)	114,000	0.34	-
Cortical bone	10,000	0.34	-
Cancellous bone	100	0.30	-
Articular cartilage	3.4	0.40	-
Soft tissue	1.15	0.49	-
Posterior tibiofibular ligament	-	-	257.8
Anterior tibiofibular ligament	-	-	115.9
Tibiocalcaneal ligament	-	-	109.5
Tibionavicular ligament	-	-	14.5
Plantar calcaneonavicular ligament	-	-	65.7
Long plantar ligament	-	-	28.1
Fibularis longus ligament	-	-	67.2
Plantar metatarsal ligament	-	-	15.7
Deep transverse metatarsal ligament	-	-	78.0
Anterior tibiofibular ligament	-	-	47.3
Posterior talofibular ligament	-	-	25.5
Calcaneofibular ligament	-	-	24.9
Superior fibular retinaculum	-	-	25.6
Dorsal tarsometatarsal ligament	-	-	115.2
Metatarsophalangeal joint capsules	-	-	136.5
Phalangeal ligament	-	-	169.1

Fig. 4 Loading and boundary conditions: (A) first metatarsal bone models and (B) musculoskeletal lower extremity models.

2.4 Predicted biomechanical performances

The biomechanical performances of different hallux valgus treatment were predicted including the osteotomy fixation stability, the implant failure risk, and the metatarsal bone failure risk. The maximum deformation of the first metatarsal bone was calculated to evaluate the osteotomy fixation stability. The smaller maximum deformation of the first metatarsal bone represented the better osteotomy fixation stability. The maximum stress of the fixation implants was calculated to evaluate the failure risk of the fixation implants. The lower maximum stress of the fixation implants represented the lower risk of the implant failure. The maximum stress of the metatarsal bone was calculated to evaluate the failure risk of the metatarsal bone. The lower maximum stress of the metatarsal bone represented the lower risk of the bone breakage.

3. Results

3.1 Numerical convergence

Finite element method is one of methods to provide an approximated solution. This approximated solution was significantly affected by the mesh quality of finite element model. In the present study, the element size from 5 mm to 1 mm was assigned to the first metatarsal bone, and the element size from 1.0 mm to 0.5 mm was assigned to the fixation plates. The convergence results of the output performances in terms of different element size for the single metatarsal bone models were shown in Fig. 5. The variation due to different element size was less than 5% for the maximum deformation of the first metatarsal bone. Additionally, the variations due to different element size for both the maximum stress of the fixation implants and the maximum stress of the metatarsal bone were 7% and 6% respectively. After the convergence analysis, the element size of 1.0mm was determined for the first metatarsal bone, and the element size of 0.5mm was determined for the fixation implants.

3.2 Osteotomy fixation stability

The displacement distributions of the single metatarsal bone models were similar to that of the musculoskeletal lower extremity models. Thus, the displacement distributions obtained from the single metatarsal bone models were selected and shown in Fig. 6. The maximum displacement of the first metatarsal bone occurred at the distal end of the bone. A discontinuous deformation was found at the interface of the osteotomy site for all the plate fixations. The maximum deformation of the first metatarsal bone for both the single first metatarsal bone models and the musculoskeletal lower extremity models was obtained (Fig. 7). In the result of the single first metatarsal bone models, the maximum displacement of the 4H4LS and 6H6LS had revealed the relatively lower maximum deformation of the bone than the 6H4LS and 6H4LS2DS. The 6H4LS has two dynamic screw holes, and these dynamic screw holes significantly increased the maximum deformation of the bone. Thus, the hallux valgus deformity with the fixation of the 6H4LS deteriorated the

osteotomy fixation stability. In the result of the musculoskeletal lower extremity models, the maximum deformation of the bone had small difference between various plate fixations. The 6H6LS had revealed better osteotomy fixation stability than the other plate fixations.

Fig. 5 The result of the convergence analysis.

Fig. 6 The displacement distribution of the first metatarsal bone and the fixation plate.

Fig. 7 The result of the osteotomy fixation stability.

3.3 Implant failure risk

The stress distributions of the fixation implants obtained from the single metatarsal bone models were also similar to that of the musculoskeletal lower extremity models. Thus, the stress distributions of the implants obtained from the single metatarsal bone models were selected and shown in Fig. 8. The maximum implant stress of the 4H4LS occurred at the central region of the plate. Additionally, the maximum implant stress occurred at the central region of the plate near the screw hole for the 6H4LS, 6H4LS2DS, and 6H6LS. The maximum stress of the fixation implants for both the single first metatarsal bone models and the musculoskeletal lower extremity models was obtained (Fig. 9). In the result of the single first metatarsal bone models, both the 4H4LS and 6H6LS revealed the lower implant stress than the other plate fixations. The 6H4LS which had two dynamic screw holes without the insertion of the dynamic screws revealed the highest implant stress than the others. It was reasonable that the 6H4LS2DS could reduce the implant stress due to the additional insertion of two dynamic screws. Thus, both the 4H4LS and 6H6LS had lower risk of the implant failure than the other plate fixations. In the result of the musculoskeletal lower extremity models, all the plate fixations had lower implant stress as compared with the result of the single first metatarsal bone models. Both the 4H4LS and 6H6LS revealed lower implant stress than the other plate fixations. These two plate fixations had lower risk of the implant failure.

Fig. 8 The stress distribution of the fixation implants.

Fig. 9 The result of the maximum implant stress.

3.4 Metatarsal bone failure risk

The stress distributions of the first metatarsal bones obtained from the single metatarsal bone models were shown in Fig. 10. The maximum stress of the first metatarsal bone occurred at the proximal screw hole for the 4H4LS, 6H4LS, and 6H4LS2DS and at the distal screw hole for the 6H6LS. The maximum stress of the first metatarsal bones for both the single first metatarsal bone models and the musculoskeletal lower extremity models was obtained (Fig. 11). In the result of the single first metatarsal bone models, both the 6H4LS2DS and 6H6LS showed the relatively lower bone stress than the other plate fixations. The 6H4LS had highest bone stress as compared with the other plate fixations. Thus, both the 6H4LS2DS and 6H6LS had lower risk of the metatarsal bone failure than the 4H4LS and 6H4LS. In the result of the musculoskeletal lower extremity models, all the plate fixations had lower metatarsal bone stress as compared with the result of the single first metatarsal bone models. Both the 6H4LS2DS and 6H6LS showed lower metatarsal bone stress than the 4H4LS and 6H4LS. Thus, both the 6H4LS2DS and 6H6LS had lower risk of the metatarsal bone failure.

Fig. 10 The stress distribution of the first metatarsal bone.

Fig. 11 The result of the maximum metatarsal bone stress.

4. Discussions

A single bone model, which is extracted from a musculoskeletal system model, has neglected the effects of the adjacent bones and muscles. The effective loading and boundary conditions are normally applied to simulate the effects of the adjacent bones and muscles. This kind of simplified method had been used to evaluate the biomechanics of human bones such as femur (Dhanopia & Bhargava, 2017), tibia (Abdul Wahab et al., 2020), humerus (Jabran et al., 2019), rib (Yates et al., 2021), and vertebra (Rayudu et al., 2021). Those finite element models could significantly reduce the modelling steps and computational time as compared to a musculoskeletal system model. Although this simplified method could improve the computational efficiency, the ideal loading and boundary conditions might not realistically simulate an actual condition (Chang et al., 2019; Parashar & Sharma, 2016). Thus, it should carefully consider these sensitive loading and boundary conditions. Compared to a single bone model, a musculoskeletal system model has considered the effects of the adjacent bones and muscles. Although this method is time consuming and requires a lot of modeling steps, the musculoskeletal system model can naturally generate the realistic loading and boundary conditions (Li et al., 2019). It implied that the musculoskeletal system model can more accurately discover the biomechanics of human musculoskeletal system.

Three types of the biomechanical performances were obtained to investigate the biomechanics of hallux valgus treatment using the single first metatarsal bone models and musculoskeletal lower extremity models in the present study. Compared to the musculoskeletal lower extremity models, the biomechanical performances of the various plate fixations obtained by the single first metatarsal bone models had significant changes. It meant that it is easy to evaluate the good or bad hallux valgus treatments. Although the musculoskeletal lower extremity models revealed minor changes on various plate fixations, they still can evaluate the good or bad hallux valgus treatments. The single first metatarsal bone models were a simple and quick method to analyze the hallux valgus deformity, but their results might be used for relative comparison between the plate fixations. The musculoskeletal lower extremity models were a more accurate method than the single first metatarsal bone models. However, they require more modeling steps and take a long time to get the answers. Both the single first metatarsal bone models and musculoskeletal lower extremity models had revealed different strengths and limitations. Fortunately, both modeling methods can provide similar prediction to evaluate various hallux valgus treatments.

A fixation stability had been proposed by previous studies to evaluate the fixation stability of bone fracture (Ouyang et al., 2017) or bone osteotomy (Radtko et al., 2020). In the present study, the maximum deformation of the first metatarsal bone was also used to evaluate the osteotomy fixation stability of different hallux valgus fixation strategies. The result indicated that the 6H6LS had better fixation stability than the 6H4LS. This finding can be verified by a previous study that concluded that an locking compression plate with a large number of locking screws can enhance fixation stability (Lee et al., 2014). Another finding was that the 6H6LS had better fixation stability than the 6H4LS2DS. This indicated

that a locking plate could provide better fixation stability than a non-locking plate in hallux valgus deformity. In fact, the similar finding was found by a previous research that concluded that the locking miniplates have advantage of greater stability over non-locking plates in mandibular fractures (Yadav et al., 2018). The fixation stability of all the plate fixations obtained by the single first metatarsal bone models had significantly lower than that of the musculoskeletal lower extremity models. The reason was that a fully constrained condition was applied to the proximal end of the first metatarsal bone model. This rigid constraint limited the deformation of the bone. However, a fully constrained condition was applied to the proximal tibia of the musculoskeletal lower extremity model. The first metatarsal bone of the lower extremity model was fixed by the adjacent bone. Thus, a larger deformation from the musculoskeletal lower extremity model was expected.

Device stress and bone stress had been used to evaluate the failure risk of fixation devices and bones respectively (Antoniatic et al., 2019; Yan et al., 2020). In the present study, the six holes plate with insertion of six locking screws (6H6LS) revealed lower device stress and bone stress than the six holes plate with insertion of four locking screws and two dynamic screws (6H4LS2DS). This finding could be verified by a past study that concluded that locking systems have more advantages than non-locking system because of the less stresses on the bone and on the screws (Muftuoglu et al., 2020). Another interesting point is needed to be pointed out that was the design of the dynamic holes. The 6H4LS has two additional dynamic screw holes as compared to the design of the 4H4LS. These additional dynamic screw holes without the insertion of bone screws could lead to stress concentration effect and result high device stress near the screw holes. However, this plate design was more flexible and its stiffness was closer to bone stiffness. Thus, a reduction on stress shielding phenomenon could be found as a bone plate has additional screw holes without the insertion of bone screws or hollow structure design (Limmahakhun et al., 2017; Liu et al., 2018).

The present study has following limitations that need further research. First, the finite element models developed in this study were based on a commercial skeleton model which was developed from computed tomography scans of a 50th percentile male. Thus, the predicted results couldn't be applied to individual patient. However, the numerical modeling steps and simulation assumptions might be used for further patient-specific finite element modeling. Second, there are a lot of distal osteotomies to be used for the treatment of hallux valgus deformity. The present study had only investigated a simple flat-cut osteotomy. However, the effects of different distal osteotomies on the fixation stability, device stress, and bone stress are unclear and needed further investigation. Finally, there are a lot of osteotomy fixation strategies for hallux valgus deformity such as plate fixation, screw fixation, and Kirschner wire fixation. The present study had only investigated the effects of plate fixation on the biomechanics of hallux valgus deformity. The strengths and limitations of various types of osteotomy fixation strategies are needed to be further investigated.

5. Conclusion

The biomechanics of hallux valgus deformity treated with the distal osteotomy and plate fixations could be discovered by both the single first metatarsal bone models and the musculoskeletal lower extremity models. The single metatarsal bone models can be used to quickly predict the biomechanical performances of different hallux valgus treatments. The musculoskeletal lower extremity models can be used to predict the biomechanical performances of different hallux valgus treatments under a physiological loading. The single first metatarsal bone models, which had less simulation modeling steps and computational time, could provide the similar outcomes obtained by the musculoskeletal lower extremity models. The six holes plate with the insertion of six locking screws was the best treatment among the four treatment strategies. The hallux valgus treatment models and computational techniques developed in this study can provide useful information for understanding the biomechanics of hallux valgus.

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References

Abdul Wahab, A. H., Wui, N. B., Abdul Kadir, M. R., & Ramlee, M. H., Biomechanical evaluation of three different

- configurations of external fixators for treating distal third tibia fracture: Finite element analysis in axial, bending and torsion load, *Computers in Biology and Medicine*, Vol.127, (2020), pp.104062.
- Acar, B., Kose, O., Turan, A., Unal, M., Kati, Y. A., & Guler, F., Comparison of Bioabsorbable Magnesium versus Titanium Screw Fixation for Modified Distal Chevron Osteotomy in Hallux Valgus, *BioMed Research International*, Vol.2018, (2018), pp.1–9.
- Antoniac, I., Stoia, D., Ghiban, B., Tecu, C., Miculescu, F., Vigar, C., & Saceleanu, V., Failure Analysis of a Humeral Shaft Locking Compression Plate—Surface Investigation and Simulation by Finite Element Method, *Materials*, Vol.12, (2019), pp.1128.
- Arand, C., Wagner, D., Richards, R. G., Noser, H., Kamer, L., Sawaguchi, T., & Rommens, P. M., 3D statistical model of the pelvic ring - a CT-based statistical evaluation of anatomical variation, *Journal of Anatomy*, Vol.234, (2018), pp.376–383.
- Atkinson, H. D., Khan, S., Lashgari, Y., & Ziegler, A., Hallux valgus correction utilising a modified short scarf osteotomy with a magnesium biodegradable or titanium compression screws—a comparative study of clinical outcomes, *BMC Musculoskeletal Disorders*, Vol.20, (2019), pp.334.
- Chang, T. K., Hsu, C. C., Yang, M. A., & Sutaji, D., Effects of Fusion Device Designs on Spine Biomechanics: Computational Simulation for Smart Health Care, *IEEE Consumer Electronics Magazine*, Vol.8, (2019), pp.84–89.
- Dhanopia, A., & Bhargava, M., Finite Element Analysis of Human Fractured Femur Bone Implantation with PMMA Thermoplastic Prosthetic Plate, *Procedia Engineering*, Vol.173, (2017), pp.1658–1665.
- Hofstaetter, S. G., Glisson, R. R., Alitz, C. J., Trnka, H. J., & Easley, M. E., Biomechanical comparison of screws and plates for hallux valgus opening-wedge and Ludloff osteotomies, *Clinical Biomechanics*, Vol.23, (2008), pp.101–108.
- Jabran, A., Peach, C., Zou, Z., & Ren, L., Parametric Design Optimisation of Proximal Humerus Plates Based on Finite Element Method, *Annals of Biomedical Engineering*, Vol.47, (2019), pp.601–614.
- Klauser, H., Internal fixation of three-dimensional distal metatarsal I osteotomies in the treatment of hallux valgus deformities using biodegradable magnesium screws in comparison to titanium screws, *Foot and Ankle Surgery*, Vol.25, (2019), pp.398–405.
- Lee, C. H., Hsu, C. C., & Huang, P. Y., Biomechanical study of different fixation techniques for the treatment of sacroiliac joint injuries using finite element analyses and biomechanical tests, *Computers in Biology and Medicine*, Vol.87, (2017), pp.250–257.
- Lee, C. H., Shih, K. S., Hsu, C. C., & Cho, T., Simulation-based particle swarm optimization and mechanical validation of screw position and number for the fixation stability of a femoral locking compression plate, *Medical Engineering & Physics*, Vol.36, (2014), pp.57–64.
- Li, J., Lu, Y., Miller, S., Jin, Z., & Hua, X., Development of a finite element musculoskeletal model with the ability to predict contractions of three-dimensional muscles, *Journal of Biomechanics*, Vol.94, (2019), pp.230–234.
- Limmahakhun, S., Oloyede, A., Sitthiseripratip, K., Xiao, Y., & Yan, C., Stiffness and strength tailoring of cobalt chromium graded cellular structures for stress-shielding reduction, *Materials & Design*, Vol.114, (2017), pp.633–641.
- Liu, F., Zhang, D., Zhang, P., Zhao, M., & Jafar, S., Mechanical Properties of Optimized Diamond Lattice Structure for Bone Scaffolds Fabricated via Selective Laser Melting, *Materials*, Vol.11, (2018), pp.374.
- Lucattelli, G., Catani, O., Sergio, F., Cipollaro, L., & Maffulli, N., Preliminary Experience With a Minimally Invasive Technique for Hallux Valgus Correction With No Fixation, *Foot & Ankle International*, Vol.41, (2020), pp.37–43.
- Malagelada, F., Sahirad, C., Dalmau-Pastor, M., Vega, J., Bhumbra, R., Manzaneres-Céspedes, M. C., & Laffenêtre, O., Minimally invasive surgery for hallux valgus: a systematic review of current surgical techniques, *International Orthopaedics*, Vol.43, (2019), pp.625–637.
- Matzaroglou, C., Bougas, P., Panagiotopoulos, E., Saridis, A., Karanikolas, M., & Kouzoudis, D., Ninety-degree chevron osteotomy for correction of hallux valgus deformity: clinical data and finite element analysis, *The open orthopaedics journal*, Vol.4, (2010), pp.152–156.
- Muftuoglu, G., Bayram, B., & Aydin, P., Comparison of Locking and Non-Locking Reconstruction Plate-Screw System in Lateral Mandibular Defects by Finite Element Analysis, *Journal of Stomatology, Oral and Maxillofacial*

- Surgery, (2020),
- Ouyang, H., Deng, Y., Xie, P., Yang, Y., Jiang, B., Zeng, C., & Huang, W., Biomechanical comparison of conventional and optimised locking plates for the fixation of intraarticular calcaneal fractures: a finite element analysis, *Computer Methods in Biomechanics and Biomedical Engineering*, Vol.20, (2017), pp.1339–1349.
- Parashar, S. K., & Sharma, J. K., A review on application of finite element modelling in bone biomechanics, *Perspectives in Science*, Vol.8, (2016), pp.696–698.
- Radtke, K., Goede, F., Schwarze, M., Paes, P., Ettinger, M., & Welke, B., Fixation Stability and Stiffness of Two Implant Systems for Proximal Femoral Varization Osteotomy, *Applied Sciences*, Vol.10, (2020), pp.5867.
- Rayudu, N. M., Dieckmeyer, M., Löffler, M. T., Noël, P. B., Kirschke, J. S., Baum, T., & Subburaj, K., Predicting Vertebral Bone Strength Using Finite Element Analysis for Opportunistic Osteoporosis Screening in Routine Multidetector Computed Tomography Scans-A Feasibility Study, *Frontiers in endocrinology*, Vol.11, (2021), pp.526332.
- Shih, K. S., Hsu, C. C., & Shih, B. Y., A Biomechanical Study of Various Fixation Strategies for the Treatment of Clavicle Fractures Using Three-Dimensional Upper-Body Musculoskeletal Finite Element Models, *Applied Sciences*, Vol.10, (2020), pp.5651.
- Trnka, H. J., Parks, B. G., Ivanic, G., Chu, I. T., Easley, M. E., Schon, L. C., & Myerson, M. S., Six First Metatarsal Shaft Osteotomies, *Clinical Orthopaedics and Related Research*, Vol.381, (2000), pp.256–265.
- Wong, D. W. C., Wang, Y., Chen, T. L., Yan, F., Peng, Y., Tan, Q., Ni, M., Leung, A. K., & Zhang, M., Finite Element Analysis of Generalized Ligament Laxity on the Deterioration of Hallux Valgus Deformity (Bunion), *Frontiers in bioengineering and biotechnology*, Vol.8, (2020), pp.571192.
- Wong, D. W. C., Wang, Y., Zhang, M., & Leung, A. K. L., Functional restoration and risk of non-union of the first metatarsocuneiform arthrodesis for hallux valgus: A finite element approach, *Journal of Biomechanics*, Vol.48, (2015), pp.3142–3148.
- Yadav, M., Yadav, N., & Kumar, A., Comparison of Conventional 2.0 mm Non-Locking and Locking Miniplates in Management of Fracture Mandible, *International Journal of Dental and Medical Specialty*, Vol.5, (2018), pp.13–17.
- Yan, L., Lim, J. L., Lee, J. W., Tia, C. S. H., O'Neill, G. K., & Chong, D. Y. R., Finite element analysis of bone and implant stresses for customized 3D-printed orthopaedic implants in fracture fixation, *Medical & Biological Engineering & Computing*, Vol.58, (2020), pp.921–931.
- Yates, K. M., Agnew, A. M., Albert, D. L., Kemper, A. R., & Untaroiu, C. D., Subject-specific rib finite element models with material data derived from coupon tests under bending loading, *Journal of the Mechanical Behavior of Biomedical Materials*, Vol.116, (2021), pp.104358.
- Zhang, Y., Awrejcewicz, J., Szymanowska, O., Shen, S., Zhao, X., Baker, J. S., & Gu, Y., Effects of severe hallux valgus on metatarsal stress and the metatarsophalangeal loading during balanced standing: A finite element analysis, *Computers in Biology and Medicine*, Vol.97, (2018), pp.1–7.