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Effects of different schemes of hallux valgus osteotomy on the stress based on computer digital simulation

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Abstract

This study explored how the position and lateral displacement in Chevron osteotomy affect stress on the metatarsophalangeal joint. Using CT images from a patient with moderate hallux valgus, a 3D model was simulated under a standing load. Ansys software analyzed biomechanical properties after six Chevron osteotomy interventions. Results indicated reduced peak stress on the first metatarsal bone with distal 1/5 osteotomy and 2-4mm lateral displacement. Stress increased with distal 2/5 osteotomy. Lateral movement decreased peak stress on the first metatarsophalangeal joint, with 0.48MPa and 0.61MPa stress at distal 4mm osteotomy. Distal 1/5 osteotomy at 5 sites with 4mm lateral displacement was optimal for moderate hallux valgus. Osteotomy position did not affect the first metatarsal bone stress distribution. Distal 1/5 osteotomy provided better stability and reduced stress between the first metatarsophalangeal joints compared to distal 2/5 osteotomy, which distributed stress on both sides of the osteotomy plane, hindering healing.

Keywords: Hallux valgus, chevron osteotomy, first metatarsophalangeal joint, finite element analysis

1. Introduction

Hallux valgus is the first metatarsophalangeal joint deformity [1, 2], often ac-companied by foot pain or severe dysfunction [3]. The disease occurs in 30% of adults and is characterized by medial osseous process, pronation of the big toe, and secondary metatarsophalangeal joint dislocation [4]. Hallux valgus angle (HVA) and intermetatarsal angle (IMA) are usually used to evaluate the degree of hallux valgus [5]. Hallux valgus can cause serious health problems and affect an individual's ability to participate in sports activities [6].

Chevron osteotomy is a distal osteotomy for mild to moderate hallux valgus deformity [7]. In this operation, a V-shaped incision was formed in the head or neck of the distal metatarsal, and the distal fragment was laterally displaced. So far, Chevron osteotomy and its modified operation are the most commonly used surgical methods for the treatment of hallux valgus. How to achieve satisfactory surgical results, reduce pain, and prevent complications is a problem worthy of doctors' consideration [8].

The finite element method is a computer simulation technology that has been widely used in engineering, mechanics, biomechanics, and other fields. In biomechanics, the finite element method has been used to study the behavior of the foot and ankle, including the effect of load on bone and soft tissue. In this study, a series of finite element models with different osteotomy positions and lateral displacement during Chevron osteotomy were established to simulate the stress distribution of metatarsal bone when standing at rest, and to explore the biomechanical properties of hallux valgus foot and the effect of operation on its biomechanics. The evaluation of the curative effect of clinical orthopedic surgery is mainly based on the improvement of clinical symptoms, while mechanical analysis is ignored. From the point of view of biomechanical mechanism, this study studied the influence of osteotomy position and lateral displacement of Chevron osteotomy on the stress of metatarsophalangeal joint, and tried to clarify the stress mechanism of different modified Chevron osteotomy on the first metatarsophalangeal joint [9]. According to the results of this study, optimize the operation plan and improve the success rate of operation and the postoperative rehabilitation effect. In order to improve the relevant theoretical research of the osteotomy, and provide a theoretical basis for a series of clinical evaluation criteria, rehabilitation strategies, or reconstruction techniques [10].

2. Materials and methods

2.1 Model building

According to a patient with moderate hallux valgus (her HVA and IMA were 26.74 °and 14.09 °respectively), the right foot was scanned by CT at an interval of 0.5mm, and the standing state of the right foot was simulated. Mimics16.0 (Materialise, Leuven, Belgium) is used to segment the 2D image to get the 3D model of bone and tissue, and Geomagic Studio 2013 (Geomagic, Inc., Research Triangle Park, NC, United States) is used to smooth the surface of the model. Each surface component is then imported into SolidWorks 2020 (SolidWorks Corporation, Waltham, MA, USA) to form a solid part. The purpose of this study was to explore the stress distribution of the first metatarsophalangeal joint when standing with different osteotomy methods of Chevron osteotomy. Different osteotomy positions were simulated at distal metatarsal1/5 and 2/5, respectively. After osteotomy, the distal metatarsal head was pushed laterally to 2mm, 4mm, and 6mm, and the osteotomy angle of each model was 90° [11]. After the operation simulation was carried out using Solidworks software. Import the model into the software Ansys Workbench 19.2 (ANSYS, Inc., Canonsburg, PA, USA) to establish ligaments, divide meshes, and perform finite element analysis [12].

Chevron osteotomy is simulated in SolidWorks. Chevron osteotomy first removes the medial osseous process of the metatarsal head, and then forms a V-shaped incision in the head or neck of the distal metatarsal bone. At the same time, the distal metatarsal bone is laterally displaced, and the proximal excess metatarsal bone is removed after displacement [13]. In SolidWorks, the steps of simulating Chevron osteotomy are as shown in Figure 1.

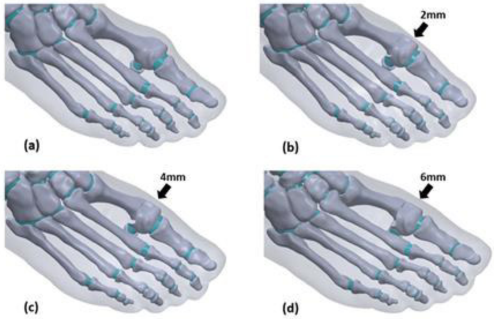

Figure 1. The cartilage constructed in Solidworks, and the methods used to simulate different operations and the final solid model

2.2 Boundary and loadings

In this study, the stress on both feet of patients with hallux valgus was simulated when standing in balance, and the finite element method was used to analyze the standing balance of the right foot. In the study, only the neutral state under the condition of equilibrium standing is considered for static analysis. The upper surface of the soft tissue wrapped outside the bone, the distal tibia and the distal fibula were fixed, and the degrees of freedom in 6 directions were constrained. In this study, the balance standing mass of the subjects was 50kg. In previous finite element studies, most studies simulated quiet standing by applying 50% body weight to the ankle joint, considering muscle strength, and applying 25% body weight to the Achilles tendon. Therefore, the tension of 125N is applied vertically at the attachment point of the Achilles tendon, the ground support is simulated by elastic material, and is only allowed to move freely in the vertical direction, and the vertical ground reaction force of half-body weight is applied to the lower surface of the plate, 250N. Except for soft tissue, all materials are regarded as isotropic linear elastic materials, and the material properties of each part are derived from the literature [14].

3. Results

3.1 Stress distribution of the metatarsal bone

The stress distribution of the 7 model metatarsals is shown in Figure 2. M1-M5 represent the first to the fifth metatarsal, respectively. The results showed that for the foot with and without osteotomy, the stress distribution of the second metatarsal bone was the most concentrated, and the maximum stress was concentrated on the second metatarsal bone. Compared with the postoperative foot, the stress of the second metatarsal bone of the foot without osteotomy was more concentrated. With the increase of lateral displacement distance, the stress distribution should not obviously change, and there is still the maximum stress concentration in the second metatarsal. It is worth noting that when the position of osteotomy is changed from distal 1/5 to 2/5, the stress distribution does not change. for the first metatarsal, the stress is mainly distributed in the middle and lower edge of the metatarsal bone. When the osteotomy position is distal 2/5, the stress of the first metatarsal bone is mainly distributed at both ends of the osteotomy plane, as shown in Figure 2.

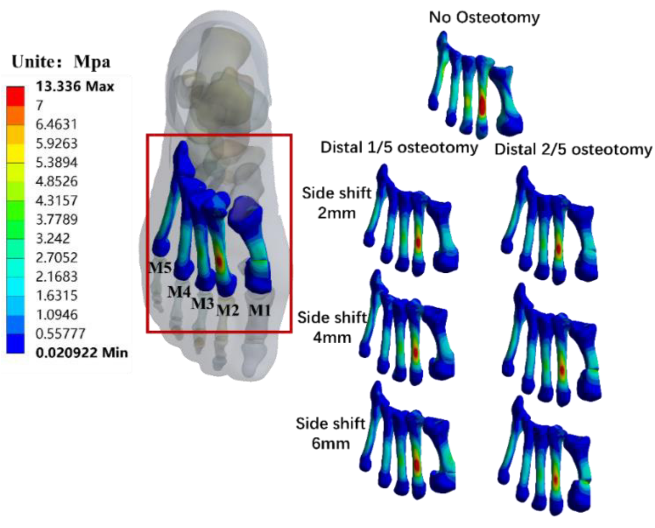

Figure 2. Stress distribution of the first to fifth metatarsal bones under different osteotomy methods

3.2 Stress distribution of the metatarsophalangeal joint

Figure 3 shows the maximum stress of the first metatarsophalangeal articular cartilage without osteotomy and with different osteotomy methods. It can be seen from the figure that the stress of articular cartilage is reduced under lateral 4mm osteotomy, especially at the distal 1/5 osteotomy position, compared with the articular cartilage without osteotomy, the stress is reduced by 28.6%. In the case of lateral 2mm and lateral 6mm, the stress of articular cartilage increased. The stress of articular cartilage in distal osteotomy was higher than that in the distal osteotomy.

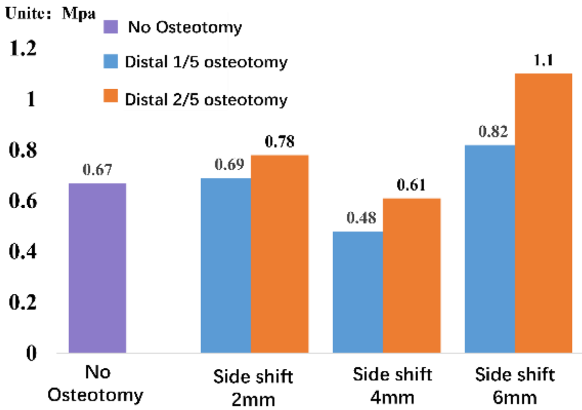

Figure 3. Stress value of the first metatarsophalangeal joint cartilage

4. Discussion

Finite element analysis showed that the maximum stress of the first metatarsal bone changed obviously with the change of the position of osteotomy. When osteotomy was performed at distal 1/5, both lateral 2mm and lateral 4mm could reduce the maximum stress of the first metatarsal bone. The stress of the first metatarsal bone was higher than that of the unosteotomized metatarsal bone with other osteotomy methods, but the stress of the first metatarsal bone increased significantly, and the stability decreased when the osteotomy was performed at the distal 2/5 site. Chevron osteotomy is distal osteotomy, the incision is V-shaped, and the mechanical behavior of this shape prevents slippage; however, the V-shaped vertex of the osteotomy as a fulcrum is easy to lead to varus deformation and gap formation, on the other hand, compared with other osteotomy, because the stress is distributed along the surface of the single-plane osteotomy, sliding rather than gap formation occurs. Therefore, Chevron osteotomy is more anti-sliding, but it is also disadvantageous in the formation of a gap [15], and needs some stability to reduce the formation of the gap. The osteotomy line is located in the neck of the first metatarsal head and neck. Compared with the metatarsal shaft and base, the distance between the distal end of the osteotomy and the osteotomy line is smaller, the force arm is short, and the osteotomy surface is rough, which is more beneficial to increase its stability [16]. There is no need for internal fixation at the end of osteotomy in order to maintain postoperative recovery [17-19]. The stress at the end of the osteotomy is mainly related to the traction of the soft tissue and the friction of the broken end. From the stress analysis diagram of the first metatarsal bone, we can see that under the distal 2/5 osteotomy, the stress of the first metatarsal bone is mainly distributed at both ends of the osteotomy plane, and the distance between the distal end of the osteotomy and the osteotomy line is long, and the force arm is large, which makes the osteotomy end more unstable in the absence of internal fixation. the dorsal displacement of the osteotomy end occurs in the standing state, which is not conducive to promoting the healing of the broken end.

5. Conclusion

The position of osteotomy did not affect the stress distribution of the first metatarsal bone, and the osteotomy at distal 1/5 had better stability than that at distal 2/5, and could better reduce the stress between the first metatarsophalangeal joint. When osteotomy is performed at distal 2/5, the stress is distributed on both sides of the osteotomy plane, which is not conducive to promoting the healing of the broken end. Distal osteotomy and lateral 4mm is the most suitable for patients with moderate hallux valgus with an HVA of 25.6° and an IMA of 14.1°.

6. References

[1] J. Ying, Y. Xu, B. István, and F. Ren. (2021). “Adjusted Indirect and Mixed Comparisons of Conservative Treatments for Hallux Valgus: A Systematic Review and Network Meta-Analysis,” Int J Environ Res Public Health, vol. 18, no. 7.

[2] K. W. Young, H. S. Lee, and K. C. Park. (2019). “Outcome of Second-Ray Pathologies Following Weil Osteotomy in Patients Treated for Hallux Valgus,” Foot Ankle Spec, vol. 12, no. 5, pp. 452-457.

[3] T. L. Lewis, R. Ray, and D. J. Gordon. (2022). “Time to maximum clinical improvement following minimally invasive chevron and Akin osteotomies (MICA) in hallux valgus surgery,” Foot Ankle Surg, vol. 28, no. 7, pp. 928-934.

[4] M. F. Kasparek, E. Benca, L. Hirtler, M. Willegger, F. Boettner, S. Zandieh, J. Holinka, R. Windhager, and R. Schuh. (2022). “Biomechanical evaluation of the proximal chevron osteotomy in comparison to the Lapidus arthrodesis for the correction of hallux valgus deformities,” Int Orthop, vol. 46, no. 10, pp. 2257-2264.

[5] S. Zhang, X. Wang, T. Chen, C. Wang, and J. Wang. (2022). “Outcomes of modified chevron osteotomy for hallux valgus,” Foot Ankle Surg, vol. 28, no. 4, pp. 514-517.

[6] D. W. Austin, and E. O. Leventen. (1981). “A new osteotomy for hallux valgus: a horizontally directed "V" displacement osteotomy of the metatarsal head for hallux valgus and primus varus,” Clin Orthop Relat Res, no. 157, pp. 25-30.

[7] A. Scarton, A. Guiotto, T. Malaquias, F. Spolaor, G. Sinigaglia, C. Cobelli, I. Jonkers, and Z. Sawacha. (2018) “A methodological framework for detecting ulcers' risk in diabetic foot subjects by combining gait analysis, a new musculoskeletal foot model and a foot finite element model,” Gait Posture, vol. 60, pp. 279-285.

[8] Y. Peng, W. Niu, D. W. Wong, Y. Wang, T. L. Chen, G. Zhang, Q. Tan, and M. Zhang. (2021).“Biomechanical comparison among five mid/hindfoot arthrodeses procedures in treating flatfoot using a musculoskeletal multibody driven finite element model,” Comput Methods Programs Biomed, vol. 211, pp. 106408.

[9] H. H. Buddhadev, and C. E. Barbee. (2020). “Redistribution of joint moments and work in older women with and without hallux valgus at two walking speeds,” Gait Posture, vol. 77, pp. 112-117.

[10] C. Matzaroglou, P. Bougas, E. Panagiotopoulos, A. Saridis, M. Karanikolas, and D. Kouzoudis. (2010). “Ninety-degree chevron osteotomy for correction of hallux valgus deformity: clinical data and finite element analysis,” Open Orthop J, vol. 4, pp. 152-6.

[11] [Y. Zhang, J. Awrejcewicz, O. Szymanowska, S. Shen, X. Zhao, J. S. Baker, and Y. Gu. (2018). “Effects of severe hallux valgus on metatarsal stress and the metatarsophalangeal

loading during balanced standing: A finite element analysis," Comput Biol Med, vol. 97, pp. 1-7.

[12] T. Kimura, M. Kubota, N. Suzuki, A. Hattori, and K. Marumo. (2018). "Comparison of Intercuneiform 1-2 Joint Mobility Between Hallux Valgus and Normal Feet Using Weightbearing Computed Tomography and 3-Dimensional Analysis," Foot Ankle Int, vol. 39, no. 3, pp. 355-360.

[13] L. Wu. (2007)."Nonlinear finite element analysis for musculoskeletal biomechanics of medial and lateral plantar longitudinal arch of Virtual Chinese Human after plantar ligamentous structure failures," Clinical Biomechanics, vol. 22, no. 2, pp. 221-229.

[14] J. T.-M. Cheung, M. Zhang, A. K.-L. Leung, and Y.-B. Fan. (2005)."Three-dimensional finite element analysis of the foot during standing—a material sensitivity study," Journal of biomechanics, vol. 38, no. 5, pp. 1045-1054.

[15] R.G. Nielsen.; Rathleff, M.S.; Simonsen, O.H.; Langberg, H. (2009). "Determination of normal values for navicular drop during walking: a new model correcting for foot length and gender," Journal of foot and ankle research, 2, 1-7.

[16] S. Nakamura, R. D. Crowninshield, and R. R. Cooper. (1981). "An analysis of soft tissue loading in the foot--a preliminary report," Bull Prosthet Res, vol. 10-35, pp. 27-34, Spring.

[17] Zhang, L., Zhang, Q., Zhang, Y., Arthur, M., Teo, E. C., Bíró, I., & Gu, Y. (2022). The effect of concave-side intertransverse ligament laxity on the stress of AIS lumbar spine based on finite element method. Bioengineering, 9(12), 724.

[18] Ji, Y., Zhang, Q., Song, Y., Hu, Q., Fekete, G., Baker, J. S., & Gu, Y. (2022). Biomechanical characteristics of 2 different posterior fixation methods of bilateral pedicle screws: A finite element analysis. Medicine, 101(36), e30419.

[19] Zhang, Q., Sun, D., Wang, M., Tafferner-Gulyás, V., Chen, H., Bíró, I., & Gu, Y. (2024). Effect of Plantar Fascia Stiffness on Plantar Windlass Mechanism and Arch: Finite Element Method and Dual Fluoroscopic Imaging System Verification. Medical Engineering & Physics, 104259.