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Numerical Simulation and Analysis of Additively Manufactured TC4 Titanium Alloy Implants

Hongyi Zhang [1]
[1] School of Materials and Chemistry, University of Shanghai for Science and Technology, Shanghai 200093, China

Abstract

Three-dimensional (3D) printing has important potential in personalized orthopedic implants, especially for the diagnosis and treatment planning of complex fractures. In this study, a three-dimensional scapular model was reconstructed from CT data, and its mechanical performance was evaluated through lightweight design and finite element analysis. Ti-6Al-4V titanium alloy was selected as the implant material, and static analysis was conducted under loads of 40, 50, and 60 kgf/cm². Stress, strain, and displacement distributions were compared. The results showed that the lightweight model had good structural stability under all loading conditions, with small displacement and acceptable stress and strain values within the material limits. These findings indicate that the combination of 3D printing, reverse modeling, lightweight design, and finite element analysis can provide useful support for the design and clinical application of personalized scapular implants.

Keywords: *Additive manufacturing;Ti-6Al-4V; Scapular fracture; Personalized treatment; implantation*

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I. INTRODUCTION

Three-dimensional (3D) printing, also known as additive manufacturing, is a novel fabrication technology based on the layer-by-layer deposition of materials, through which three-dimensional virtual data are ultimately transformed into physical objects[1]. As an interdisciplinary manufacturing approach, 3D printing has been integrated with a wide range of engineering technologies, including additive manufacturing, mechanical engineering, Geomagic, Mimics Research, and reverse engineering. Owing to its high technological content, this technique has enabled the rapid conversion of digital 3D models into physical entities with specific structural and functional characteristics or practical industrial applications, thereby providing an efficient means for translating innovative concepts and designs into reality[2]. In the medical field, 3D printing has made it possible to fabricate implantable artificial organs and bone substitutes rapidly and accurately. With the aid of three-dimensional anatomical data, clinicians have been able to make more intuitive preliminary assessments of a patient's condition[3][4]. In addition, artificial bones have been produced by 3D printing using implantable materials such as titanium alloys (e.g., Ti-5Al-2.5Sn) and commercially pure titanium. These printed bone substitutes can be designed with lightweight architectures and microporous structures. Because of its convenience and versatility, 3D printing has brought substantial advances to the medical field and has expanded rapidly in the markets of developed countries[5][6].

At present, the clinical application of 3D printing in medicine has been focused primarily on hard tissues, such as the femur, pelvis, hip, articular bone, and teeth. In contrast, the printing of more complex artificial tissues, including organs and blood vessels, has remained at the stage of continuous exploration and development. With the accelerating aging of the population in China and the growing pursuit of a higher quality of life, the medical industry has faced increasing demands and higher expectations. Considerable progress has been achieved in the application of 3D printing to orthopedic treatment; however, substantial room for further improvement still remains. Although China has entered the global competition in 3D-printing research and development, a significant technological gap compared with developed countries has still existed.

Scapular fractures are relatively uncommon compared with fractures at other anatomical sites, accounting for approximately 3%–5% of all shoulder fractures and about 1% of all fractures throughout the body[7][8]. Among scapular fractures, fractures of the scapular body have accounted for nearly 50%. Most scapular fractures have been caused by high-energy external trauma. In recent years, with the rapid development of various industries, the overall incidence of such injuries has increased year by year. Scapular fractures are often part of multiple-trauma injuries and may be accompanied by various complications. For mild scapular fractures, nonoperative treatment has generally been adopted[9]. With external support of the affected limb and appropriate shoulder rehabilitation exercises, satisfactory functional recovery of the scapula can usually be achieved. However, for unstable fractures or those with obvious displacement, surgical intervention has been required to obtain better long-term outcomes. Once surgery has been delayed because of the inaccurate diagnosis of comminuted scapular fractures, severe impairment of upper-limb activity and shoulder motion may result. Therefore, timely and appropriate postoperative management has been considered the key to preventing functional limitation after scapular fracture. In recent years, increasing attention has been paid to reducing long-term complications such as chronic pain and functional impairment[10]. Nevertheless, in the surgical treatment of comminuted scapular fractures, several challenges have remained, including limited exposure of the fracture site, a heavy operative workload for surgeons, and difficulty in achieving precise reduction and stable fixation of fragmented bone[11]. With the continuous development of 3D-printing technology, physical fracture models produced by 3D printing have enabled orthopedic surgeons to observe scapular injury details more intuitively, formulate more appropriate surgical plans, reduce operative difficulty, achieve more accurate fracture reduction, and ultimately improve surgical outcomes[12][13].

II. RESULT AND DISCUSSION

Most regions of the scapula are covered by different types of soft tissue, and abundant blood vessels are distributed over its anterior surface, posterior surface, and margins[14],[15],[16]. The scapula is surrounded by the musculature of both the upper and lower regions, which provides structural stability and mechanical protection. As a result, most scapular fractures with minimal displacement or inconspicuous dislocation have shown good self-healing potential. However, for comminuted scapular fractures, nonoperative treatment has generally yielded limited therapeutic benefit and has easily led to shoulder dysfunction and persistent long-term pain[17].

In orthopedic trauma care, fracture diagnosis has often relied heavily on clinical experience, and decisions made during surgery have likewise depended to a considerable extent on the surgeon's judgment and expertise[18][19]. Comminuted scapular fractures have presented substantial challenges in both diagnosis and treatment[20]. First, conventional CT images have typically been displayed in a two-dimensional format, and overlap among fracture fragments has frequently interfered with image interpretation. Although three-dimensional CT reconstruction has made it possible to reconstruct a stereoscopic image of the scapula and has facilitated better observation of fracture morphology, the images viewed on a computer screen or during surgery have still been restricted by viewing angle, making some anatomical regions difficult to visualize completely. Consequently, accurate clinical judgment has remained difficult, which has increased the complexity of diagnosis. Therefore, the reverse construction of a comminuted scapular fracture model based on CT data, combined with lightweight structural design, has provided a more effective basis for diagnosis and treatment planning.

Finite element analysis was required for the reconstructed model. Before analysis, the three-dimensional model needed to be imported into the software for meshing and converted into .stp format. First, the meshed scapular model in .stp format, which had undergone surface fitting and mesh generation, was imported into SolidWorks. Next, the SolidWorks Simulation plug-in was activated to perform the mechanical analysis. Before each scapular simulation, the meshed three-dimensional scapular model had to be imported before the subsequent analysis could be carried out, as shown in Figure 1.

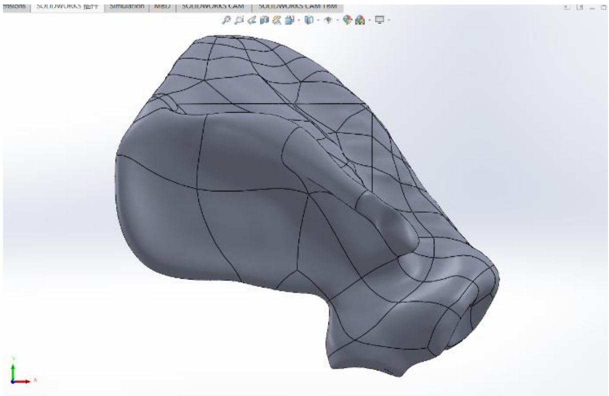

Figure 1 Finite Element Mesh Generation of the Model

After model construction and mesh generation had been completed, boundary conditions and external loads were further applied to simulate the actual loading conditions. First, the Fixture Advisor was selected in the software interface, and the Fixed Geometry option was chosen. The surfaces requiring constraint were then selected in the model, and the settings were confirmed after verification, as shown in Figure 2. The main purpose of this step was to impose displacement constraints on the model and restrict the degrees of freedom in the fixed region, thereby ensuring that the structural boundary conditions used in the subsequent calculations were consistent with the actual service conditions.

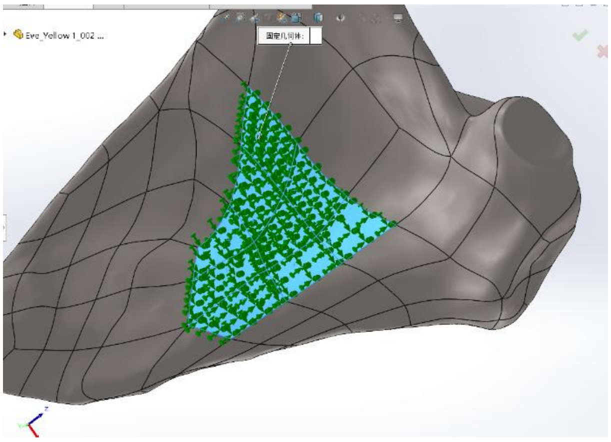

Figure 2 Selection of the Fixed Surface of the Model

Subsequently, the External Loads Advisor was selected, and Force was chosen as the loading type. The actual loading surface of the model was then defined as the load application region, and three loading values, namely 40, 50, and 60 kgf/cm², were applied separately. After the input had been completed, the settings were confirmed, as shown in Figure 3. By applying external loads of different magnitudes, the response characteristics of the material or structure under various loading conditions could be simulated, thus providing a basis for the subsequent analysis of its mechanical behavior.

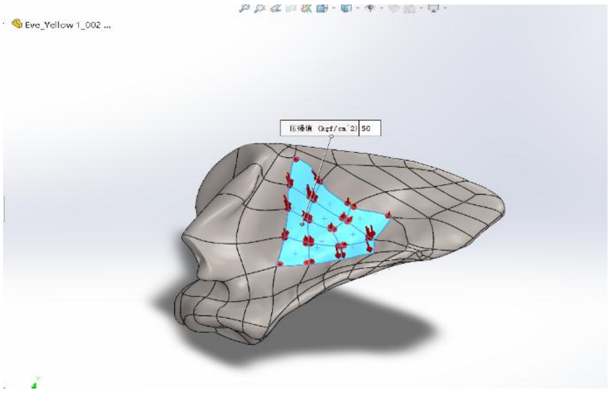

Figure 3 Selection of the Loaded Surface of the Model

After the boundary constraints and loading conditions had been defined, the **Run** command was executed, and the program automatically completed the numerical solution. Once the calculation had finished, the simulation results under different loading conditions were compared and analyzed. To more intuitively illustrate the response behavior of the model during loading, particular attention was given to displacement variation, stress distribution, and strain characteristics. Through the above analysis, the deformation trend and differences in mechanical performance of the model under different loading levels could be further revealed, thereby providing a reference for subsequent structural optimization and performance evaluation.

Static stress analysis of the scapular model was conducted using the stress analysis module, and the mechanical performance of the unoptimized model was evaluated by comparing the maximum stress values. Ti-6Al-4V titanium alloy was used as the material, with a yield strength of 8.27×10^{8} N/m². Under the different loading conditions examined, the maximum displacement was only 1.593×10^{-6} mm, which was well below the allowable deformation range for implant applications. As summarized in Table 1, the calculated stress and strain values were both within the permissible limits of the material, indicating that the model satisfied the basic mechanical requirements prior to optimization.

Table 1 Static Stress Analysis Results of Ti-6Al-4V

	Stress (N/m²)	**Maximum Displacement (mm)**	**Strain**
40kg	3.891×10^{-6}-1.781×10^{3}	1.62×10^{-6}	2.969×10^{-17}-1.156×10^{-8}
50kg	4.580×10^{-6}-2.226×10^{3}	1.327×10^{-6}	3.557×10^{-17}-1.445×10^{-8}
60kg	5.448×10^{-6}-2.672×10^{3}	1.593×10^{-6}	4.231×10^{-17}-1.734×10^{-8}

III. CONCLUSION

The mechanical analysis results indicated that titanium alloy exhibited superior overall performance compared with commercially pure titanium. Under an applied load of 60 kg (the maximum external load considered in this study), the titanium alloy showed lower stress, strain, and displacement levels, while also possessing higher intrinsic strength. For the three loading conditions corresponding to each material, the maximum displacement at the loaded region showed a progressively decreasing trend. Moreover, no deformation of the scapular model was observed under the actual proportional conditions, further demonstrating that the lightweight structure was able to satisfy the requirements for implantation.

Compared with conventionally manufactured implants, 3D-printed implants offered clear advantages in terms of structural design, mechanical performance, and material utilization. Specifically, 3D printing made it possible to fabricate implantable structures with reduced material consumption, while the titanium alloy exhibited relatively small stress and displacement responses. In addition, titanium alloy showed excellent biocompatibility. Therefore, titanium alloy was considered an appropriate material for prosthetic implantation, capable of achieving favorable therapeutic outcomes and consistent with the original design objective of this study.

REFERENCES

[1]. J.L. Amaya-Rivas, B.S. Perero, C.G. Helguero, J.L. Hurel, J.M. Peralta, F.A. Flores, J.D. Alvarado, Future trends of additive manufacturing in medical applications: An overview, Heliyon 10(5) (2024) e26641. DOI: 10.1016/j.heliyon.2024.e26641

[2]. .M. Żukowska, M.A. Rad, F. Górski, Additive Manufacturing of 3D Anatomical Models-Review of Processes, Materials and Applications, Materials (Basel) 16(2) (2023) 880. DOI: 10.3390/ma16020880

[3]. A. Palmquist, M. Jolic, E. Hryha, F.A. Shah, Complex geometry and integrated macro-porosity: Clinical applications of electron beam melting to fabricate bespoke bone-anchored implants, Acta Biomater. 156 (2023) 125-145. DOI: 10.1016/j.actbio.2022.06.002

[4]. E. Marin, A. Lanzutti, Biomedical Applications of Titanium Alloys: A Comprehensive Review, Materials 17(1) (2024) 114. DOI: 10.3390/ma17010114

[5]. G. Huang, Y. Zhao, D. Chen, L. Wei, Z. Hu, J. Li, X. Zhou, B. Yang, Z. Chen, Applications, advancements, and challenges of 3D bioprinting in organ transplantation, Biomater. Sci. 12(6) (2024) 1425-1448. DOI: 10.1039/d3bm01934a

[6]. V. Schmidt, S. Mukka, C. Bergdahl, C. Ekholm, A. Bruggemann, O. Wolf, Epidemiology, treatment, and mortality of 3973 scapula fractures from the Swedish fracture register, J. Shoulder Elbow Surg. 34(1) (2025) e47-e56. DOI: 10.1016/j.jse.2024.03.024

[7]. M. Cantore, D. Manni, V. Candela, J. Preziosi Standoli, A. Are, S. Gumina, Epidemiology and classification of scapular fractures: a detailed survey on a large sample of patients, JSES Int. 9(4) (2025) 1069-1075. DOI: 10.1016/j.jseint.2025.04.012

[8]. M. Daher, S. Abi Farraj, B. El Hassan, Management of Extra-articular Scapular Fractures: A Narrative Review and Proposal of a Treatment Algorithm, Clin. Orthop. Surg. 15(5) (2023) 695-703. DOI: 10.4055/cios23031

[9]. H.C. Sernandez, J.T. Riehl, J. Fogel, Sling and forget it? A systematic review of operative versus nonoperative outcomes for scapula fractures, J. Shoulder Elbow Surg. 33(12) (2024) 2743-2754. DOI: 10.1016/j.jse.2024.05.042

[10]. D. Dreizin, K. Champ, M.P. Dattwyler, A.D. Garzan, T. Edmond, CT of Acute Shoulder Girdle Fractures in Adults: Biomechanics, Classification, and Management, Radiographics 46(1) (2026) e250025. DOI: 10.1148/rg.250025

[11]. P.A. Cole, L.K. Schroder, I.S. Brahme, C.N. Thomas, L. Kuhn, E. Zaehringer, A. Petersik, Three-Dimensional Mapping of Scapular Body, Neck, and Glenoid Fractures, J. Orthop. Trauma 38(2) (2024) e48-e54. DOI: 10.1097/BOT.0000000000002734

[12]. O. O'Connor, R. Patel, A. Thahir, J. Sy, E. Jou, The use of Three-Dimensional Printing in Orthopaedics: a Systematic Review and Meta-analysis, Arch. Bone Jt. Surg. 12(7) (2024) 441-456. DOI: 10.22038/ABJS.2024.74117.3465

[13]. S. Cattaneo, M. Domenicucci, C. Galante, E. Biancardi, A. Casiraghi, G. Milano, Use of patient-specific guides and 3D model in scapula osteotomy for symptomatic malunion, 3D Print. Med. 9(1) (2023) 24. DOI: 10.1186/s41205-023-00184-w

[14]. Daher M, Abi Farraj S, El Hassan B. Management of Extra-articular Scapular Fractures: A Narrative Review and Proposal of a Treatment Algorithm. Clinics in Orthopedic Surgery. 2023;15(5):695-703.DOI: https://doi.org/10.4055/cios23031

[15]. Sernandez HC, Riehl JT, Fogel J. Sling and forget it? A systematic review of operative versus nonoperative outcomes for scapula fractures. Journal of Shoulder and Elbow Surgery. 2024;33(12):2743-2754.DOI: https://doi.org/10.1016/j.jse.2024.05.042

[16]. Schmidt V, Mukka S, Bergdahl C, Ekholm C, Brüggemann A, Wolf O. Epidemiology, treatment, and mortality of 3973 scapula fractures from the Swedish fracture register. Journal of Shoulder and Elbow Surgery. 2025;34(1):e47-e56.DOI: https://doi.org/10.1016/j.jse.2024.03.024

[17]. Dreizin D, Champ K, Sanders TG, et al. CT of Acute Shoulder Girdle Fractures in Adults: Biomechanics, Classification, and Management. RadioGraphics. 2026;46(1).DOI: https://doi.org/10.1148/rg.250025

[18]. Cole PA, Gauger EM, Schroder LK, et al. Three-Dimensional Mapping of Scapular Body, Neck, and Glenoid Fractures. Journal of Orthopaedic Trauma. 2024;38(1):e18-e24.

[19]. Cattaneo S, Domenicucci M, Galante C, Biancardi E, Casiraghi A, Milano G. Use of patient-specific guides and 3D model in scapula osteotomy for symptomatic malunion. 3D Printing in Medicine. 2023;9(1):24.DOI: https://doi.org/10.1186/s41205-023-00184-w

[20]. O'Connor O, Patel R, Thahir A, Sy J, Jou E. The use of Three-Dimensional Printing in Orthopaedics: a Systematic Review and Meta-analysis. Archives of Bone and Joint Surgery. 2024;12(7):441-456.DOI: https://doi.org/10.22038/ABJS.2024.74117.3465