3D Printing and Computer-Aided Design for Precision Osteotomy-Aided Modules in Bone Biomechanical Study

Daofeng Wang¹,²†, Lin Han³†, Gaoxiang Xu¹,²†, Wupeng Zhang¹,²,⁴, Hua Li¹,², Cheng Xu¹,², Huanyu Li⁵, Jitian Li⁶*, Hao Zhang¹,²*, Jiantao Li¹,²*

¹Department of Orthopedics, The Fourth Medical Center of Chinese PLA General Hospital, Beijing, China
²National Clinical Research Center for Orthopedics, Sports Medicine and Rehabilitation, Beijing, China
³Department of Orthopaedics, Shanghai Changzheng Hospital, Second Military Medical University, Shanghai, China
⁴Department of Orthopaedics, School of Medicine, Nankai University, Tianjin, China
⁵Department of Pharmacology, School of Pharmacy, China Medical University, Shenyang, Liaoning Province, China
⁶Henan Luoyang Orthopedic Hospital (Henan Provincial Orthopedic Hospital), Henan Institute of Orthopedic and Traumatology, Luoyang, China

†These authors contributed equally to this work

Abstract: Precise and shape-matching osteotomy models are determinants of the experimental homogeneity in the assessment of orthopedic biomechanical properties. At present, however, publications on detailed description of osteotomy in bone biomechanical study are scanty. The purposes of this study were to design a new method of osteotomy-aided module production for bone biomechanical study with the help of three-dimensional (3D) printing and computer-aided design (CAD) and to test the accuracy of osteotomy. Fourteen fourth-generation composite femurs were analyzed. The composite bone was scanned using computed tomography (CT) scanner and loaded in Mimics for reconstruction and, then, imported into 3-Matic software to design intertrochanteric region, distal femur, and rotation control lever models. 3D printer was used to print each component. After assembling Sawbones and osteotomy modules, a horizontal band-saw was used to create fracture models. The volume and mass of intermediate fragments were calculated and analyzed. Satisfactory osteotomies of all composite Sawbones were achieved. The mean volume and mass of intermediate fragments were 21.0 ± 1.5 mm³ and 19.0 ± 1.2 g, respectively. Range of deviation from average of volumes was −1.9 – 2.8 mm³ and most of these deviations fall within the range of −1.4 – 2.1 mm³. Range of deviation from average of mass was −2.0 – 1.6 g and most of these deviations fall within the range of −1.4 – 1.6 g. One-dimensional histogram of deviation from average shows the precise and stable osteotomy performed based on the modules accordingly. A new method of osteotomy-aided module production for bone biomechanical study with the help of 3D printing and CAD was designed and the accuracy of osteotomy was verified. This method is expected to achieve homogeneity and standardization of osteotomy in bone biomechanical study.

Keywords: Osteotomy; 3D printing; Computer-aided design; Bone biomechanics

*Correspondence to: Jitian Li, Henan Luoyang Orthopedic Hospital (Henan Provincial Orthopedic Hospital), Henan Institute of Orthopedic and Traumatology, Luoyang, China; jitianlee@hotmail.com; Hao Zhang, Department of Orthopedics, The Fourth Medical Center of Chinese PLA General Hospital, Beijing, China; zhanghao0103@qq.com; Jiantao Li, National Clinical Research Center for Orthopedics, Sports Medicine and Rehabilitation, Beijing, China; lijiantao618@163.com

Received: May 3, 2022; Accepted: June 4, 2022; Published Online: August 23, 2022

This article belongs to the Special Issue: 3D Printing of Advanced Biomedical Devices


1. Introduction
Bone biomechanical study can provide scientific guidance for mechanical properties and clinical applications of orthopedic implants¹,²,³. Bone biomechanics encompass the simulation of the mechanical loading conditions in clinical practice and the analysis of the structural...
Wang, et al.

stability of bone under different fixation conditions\(^4\). Structure properties of composite Sawbones such as mineral density and elastic modulus approach to the human bone ensure compliance with the requirements of bone mechanical testing\(^6\). Therefore, composite Sawbones and human cadavers have often been used in mechanical trials. Establishment of bone traumatic models according to standard fracture classifications requires precise and shape-matching osteotomy. However, the osteotomy methods vary among different research groups\(^5,8-11\), restricting the homogenization, and universality of different mechanical study to some extent.

To date, few bone biomechanical studies used the osteotomy-aided modules for precise creation of fracture sample. Windolf et al.\(^9\) firstly introduced their osteotomy-aided modules named custom-made saw-guide for unstable 31-B2 fracture models and realized the smooth osteotomy. Rupprecht et al. subsequently utilized this device for biomechanical analysis\(^12\). In addition, another osteotomy module featuring cutting navigation was proposed by Windell et al.\(^8\) in a biomechanical study comparing different implants in periprosthetic femoral fracture. Unfortunately, the study did not evaluate the accuracy of osteotomy. Challenges such as time- and manpower-consuming aspects and high cost in industrial designs and application also limit the experimental use of these device.

Computer-aided design (CAD) technique can precisely establish the three-dimensional (3D) digital bone models, extract local parameters at the site of interest, and design precise osteotomy-aided modules with the help of engineering software\(^13\). 3D printing technique has been recently applied to the domains of regenerative medicine of tissues and organs, surgical decisions-making, personal design of tissue engineering scaffolds materials, and prosthetic or implants in orthopedic\(^14\). Compared with traditional industrial design, 3D printing technique reduces labor and material costs, simplifies workflows, and improves consistency. The advantages of 3D printing applied to medical devices design are numerous, such as high production efficiency, high level of design precision, fine anatomical fitting, and good repeatability\(^15,16\).

Based on above, we believe that the combination of CAD and 3D printing techniques can help establish precise osteotomy-aided modules matching bone morphology and confirm homogenization. Further studies are warranted. Therefore, considering the design of AO/OTA 31 A2.3 intertrochanteric unstable fracture models as an example, the present study aims to design a new method of osteotomy-aided module production for bone biomechanical study with the help of 3D printing coupled with CAD and to test the accuracy of osteotomy.

2. Materials and methods

2.1. Study design

Fourteen fourth-generation composite femurs (Model 3406; Pacific Research Laboratories, Vashon, Washington, USA) were used to simulate osteotomy. Bone materials properties and geometrical parameters were close to fresh-frozen cadaveric femurs (Table 1 and Figure 1)\(^6,17-20\). Computed tomography (CT) scans of one composite Sawbone was performed on a 64-slice CT scanner (Siemens Sensation Open, Erlangen, Germany). Scan slice thickness was 5 mm. Digital Imaging and Communications in Medicine files (DICOM) of the selected CT scans were retrieved and loaded in Mimics software (Version 20.0, Materialise, Belgium). The femur and medullary cavity models were then reconstructed in Mimics. Subsequently, the above 3D reconstructions were imported into 3-Matic (Version 12.0, Materialise, Belgium) in STL formats to design osteotomy models. The osteotomy models were, then, obtained and imported into 3D printer (OBJET EDEN260V, Stratasys Ltd, Rehovot, Israel) to manufacture anatomical osteotomy modules for intertrochanteric fracture. Finally, after assembling the composite Sawbones and osteotomy modules, osteotomy was performed using horizontal band-saw. The study flowchart is shown in Figure 2.

2.2. Computer-aided design (CAD)

2.2.1. Osteotomy models

We used AO/OTA 31 A2.3 intertrochanteric unstable fracture model design as an example. The central axis of femoral shaft was established in 3-Matic, and a plane perpendicular to the placing plane was obtained through the central axis\(^13\). The plane was rotated 20° clockwise with Y-plane as the rotation center, and a set of parallel osteotomy reference planes could be established based on the obtained plane. The plane was rotated 20° clockwise with Y-plane as the rotation center, and a set of parallel osteotomy reference planes could be established based on the obtained plane. The horizontal plane (parallel to the XY plane) was established based on the tip of the greater

Figure 1. Geometrical parameters of Sawbones.
trochanter. The horizontal plane was moved down 1 cm and intersected with the central axis of femoral shaft. The osteotomy plane through intersection was defined as the first osteotomy reference plane. The second osteotomy reference plane was determined by three points: The tip of the greater trochanter, the most prominent intersection on the intersecting lines of the first osteotomy plane, and the trochanter anterior plane, and the tip 1 cm below the lesser trochanter. The second osteotomy reference plane detaches the posteromedial cortex of the proximal femur from the femur (Figure 3).

2.3. Osteotomy modules

2.3.1. Intertrochanteric region

In 3-Matic, a detachable and anatomical structure morphology-matched module was established in proximal femur. A 1.6 mm oscillating saw seam was designed on the module according to the fracture line mentioned above. Subsequently, a positioning device was used to ensure the precision alignment of each component (Figure 4A and 4B).

2.3.2. Distal femur

The tip of the greater trochanter was maintained at 40 cm away from the femur, and the distal femoral condyle was removed. The proximal 30 cm was used for mechanical test, and the distal 10 cm was placed in fixation device equipped with polymer-based denture powder and Kircher wires (Figure 4C and 4D).[21,22]

2.3.3. Rotation control lever modules

The proximal femur rotation control module was designed in 3-Matic. The axis of rotation was perpendicular to the first osteotomy reference plane. A hole was made on the module side to facilitate the insertion of Kirchner wires for head fixation. Six cylindrical channels in proximal femur were dispersedly and symmetrically designed to match six steel nails as rotation control lever (Figure S1 in Supplementary File). Finally, the osteotomy-aided models were created in 3-Matic.

![Table 1. Material properties of Sawbones.](image)

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Longitudinal tensile</th>
<th>Transverse tensile</th>
<th>Compressive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Modulus (GPa)</td>
<td>Strength (MPa)</td>
</tr>
<tr>
<td>(A) Simulated cortical bone (short fiber-filled epoxy)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.64</td>
<td>106</td>
<td>16.0</td>
<td>93</td>
</tr>
<tr>
<td>(B) Simulated cancellous bone (rigid polyurethane foam)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>106</td>
<td>16.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Flowchart of this study.

Figure 3. Osteotomy plane of intertrochanteric fracture designed in 3-Matic. (A) The first osteotomy reference plane. (B) The second osteotomy reference plane.
2.4. 3D printing for solid modules

The intertrochanteric region, distal femur, and rotation control lever modules were imported into 3D printer to manufacture anatomical osteotomy modules for each component (Figure 5).

2.5. Assembly and osteotomy

Fourteen composite Sawbones were used for osteotomy. A senior biomechanical specialist performed osteotomy according to a standard method: Placing guide needle in Sawbones in the intramedullary main nail guides-guided procedure, expanding medullary cavity to appropriate depth, and inserting and subsequently removing intramedullary nail. Then, distal femur osteotomy modules were assembled at the distal femur after removal of distal femoral condyle. The intertrochanteric region osteotomy modules were assembled at the proximal femur and a horizontal band-saw was used to create AO/OTA 31 A2.3 unstable intertrochanteric fracture models (Figure 6).

2.6. Evaluation of osteotomy

The intermediate fragments after osteotomy were collected and the mass was measured using an electronic balance (accuracy: 0.001 g). The volume of fragments was measured according to drainage method with a 50-ml graduated measuring cylinder (accuracy: 0.1 ml) and 500-ml measuring cup.

2.7. Statistical analysis

Shapiro–Wilk test was used to determine the normality of continuous data. The mass and volume of intermediate fragments were presented as the mean ± standard deviation or median (interquartile range). Deviations from the average of volume and mass that measure individual differences between individual and the mean of population of every fragment were calculated and visualized using one-dimensional histogram. GraphPad Prism (8.3.0 version) and “ggplot2” package in R software (3.6.3 version) were used for data analysis and visualization, respectively.

3. Results

Satisfactory osteotomies of all composite Sawbones were achieved (Figure 7). The mean volume and mass of intermediate fragments were 21.0 ± 1.5 mm³ and 19.0 ± 1.2 g, respectively. Range of deviation from average of volumes was −1.9 – 2.8 mm³ and most of these deviations fall within the range of −1.4 – 2.1 mm³. Range of deviation from average of mass was −2.0 – 1.6 g and most of these deviations fall within the range of −1.4 – 1.6 g. One-dimensional histogram of deviation from average shows the precise and stable osteotomy performed based on modules accordingly (Figure 8).

4. Discussion

Precise and shape-matching osteotomy models are determinants of the experimental homogeneity in the assessment of orthopedic implants mechanical properties.
Here, we designed a new method of osteotomy-aided module production for bone biomechanical study with 3D printing and CAD and verified the accuracy of osteotomy. To the best of our knowledge, unlike the traditional design research, this is the first work that describes the design of osteotomy-aided modules using 3D printing and CAD techniques. In addition, this study provides insight into the application of digital orthopedic technology in bone biomechanics.

The previous works are some in vitro bone biomechanical studies focusing on the evaluation of mechanical advantage, dynamic stability, and post-operative implant-related complications (Table 2)\[4,5,10,11,23,24\]. The pre-experiment osteotomy methods performed in these studies were in accordance with international fracture classifications. However, we noticed that most of the studies did not involve standard osteotomy techniques. Moreover, the process of osteotomy relies too much on the experience of mechanical researchers, and the accuracy evaluation of osteotomy can be easily neglected. At present, only few osteotomy-aided modules have been introduced in bone biomechanical studies\[8,9,12\]. Windell et al. conducted a study on biomechanical comparison of periprosthetic femoral fracture risk in different implants of the composite Sawbones model. After approximately determining the cutting position, a cutting guide was used to ensure the standard cutting of the femur head and neck\[8\]. However, the comparative analysis of osteotomy accuracy was not performed.

The osteotomy-aided modules for fracture models were first proposed by Windolf et al.\[9\]. They designed a custom-made saw-guide that was fastened to the side-plate and enabled simulation of an unstable 31-B2 fracture. This device could be adjusted in anteroposterior
direction to accommodate different bone morphology. Based on this, the blade of an oscillating saw was guided in circular slots around the bone. Unfortunately, the study did not evaluate the accuracy of osteotomy. The broad access of traditional industrial designs is limited by several disadvantages such as time- and manpower-consuming aspects, high consumption, complexity, high manufacturing cost, and difficulties of refinement and personalization of the products. CAD and 3D printing can help improve this outlook. The same osteotomy-aided module was used by Rupprecht et al. in the biomechanical performance comparison of internal fixation of femoral neck fractures with posterior comminution.

Tang et al. proposed “triangular stability theory” of proximal femur and pointed out that the stabilization of proximal femur relies on structural mechanical model formed by the medial, lateral, and upper sides. The medial side forms the oblique support of proximal femoral cantilever structure, greatly reducing the bending stress and deflection of bone structure. The upper side connects the medial and lateral edges of proximal femur.

<table>
<thead>
<tr>
<th>Indications</th>
<th>Number of subjects</th>
<th>Osteotomy methods</th>
<th>Module</th>
<th>Principle</th>
<th>Clinical measure</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMRI elbow</td>
<td>7 cadaveric arms</td>
<td>Manual osteotomy along the outline on the trochlear</td>
<td>None</td>
<td>O’Driscoll type</td>
<td>Contact pressure and area values throughout 0° to 90° flexion arc</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>surface</td>
<td></td>
<td>2-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coronoid-deficient elbow</td>
<td>8 cadaveric arms</td>
<td>Manual osteotomy parallel to flat spot of ulna using</td>
<td>None</td>
<td>Regan-Morrey type</td>
<td>Evaluation of the efficacy of coronoid prosthesis in elbow stabilization</td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>microsagittal saw</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intra-articular tibial plateau</td>
<td>16 cadaveric tibiae</td>
<td>Manual osteotomy in meta-diaphyseal intersection and</td>
<td>None</td>
<td>41-C2 AO-classification</td>
<td>Biomechanical comparison of intramedullar versus extramedullar stabilization</td>
<td>[24]</td>
</tr>
<tr>
<td>fractures</td>
<td></td>
<td>medial epicondyle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femoral neck fractures</td>
<td>30 cadaveric femurs</td>
<td>Manual osteotomy with thin bladed straight sagittal</td>
<td>None</td>
<td>Pauwel type B</td>
<td>Biomechanical analysis of fixation devices</td>
<td>[4,10]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>saw</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odontoid fracture</td>
<td>7 cadavers</td>
<td>Manual osteotomy at the base of odontoid</td>
<td>None</td>
<td>Type II odontoid</td>
<td>Evaluation of the application of cervical collar in the reduction of cervical</td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>fracture</td>
<td>spine motion</td>
<td></td>
</tr>
<tr>
<td>Intertrochanteric femur fracture</td>
<td>24 composite Sawbones</td>
<td>Manual osteotomy with oscillating saw</td>
<td>None</td>
<td>31-A3.3 AO-classification</td>
<td>Biomechanical comparison of different fixation techniques</td>
<td>[5]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periprosthetic Femoral Fracture</td>
<td>26 composite Sawbones</td>
<td>Manual osteotomy according to a cutting guide</td>
<td>Cutting guide</td>
<td>N/A</td>
<td>Analysis of periprosthetic femoral fracture risk in different implants</td>
<td>[8]</td>
</tr>
</tbody>
</table>

PMRI, posteromedial rotatory instability; InterTAN, proximal femoral nail; PFNA, proximal femoral nail anti-rotation; N/A: not applicable
and resists the bending moment caused by physiological loads. The lateral side could effectively reduce the sliding and deflection of the femoral neck under physiological loading. Under physiological loading, the complete mechanical triangular structure could effectively reduce the bending moment of the proximal femur, balance the shearing force of the physiological load, realize the balanced distribution of stress in the structure, and maintain the balance and stability of the proximal femoral mechanical system. Medial sustainable nail was designed to form a triangular structure based on triangular stability theory and its reliable biomechanical performance on fixation stability was verified.  

A major limitation of the study is that the sample size may be insufficient to divide the composite bones into two groups for statistical analysis of interesting parameters. Second, we included only the composite bones characterized by high consistent morphology that differ from human bones. It is necessary, if conditions permit, to use cadaver bone models to verify the accuracy and practicability of this method. The accuracy of osteotomy directly affects the variability of mechanical loading results. In spite of the significance of the precision osteotomy, it is still rather challenging to develop and apply osteotomy techniques in clinical setting. The rapid development of digital orthopedics has facilitated the fine design of medical device, which would gradually become an emerging trend that will shape the orthopedic field going forward. The application of 3D printing and CAD for osteotomy modules in bone biomechanical study would facilitate a shift of osteotomy design from rough operation to precise implementation. We believe that this study could provide a standard method for osteotomy design in bone biomechanical study.

Acknowledgment

We thank the statistician Huanyu Li from China Medical University for her statistical assistance.

Funding

This work was supported by the Special Projection on the Health Care of the Chinese Military Foundation (Grant 14BJZ09), the Special Research Project of Prevention and Treatment of Military Training Injuries (20XLS27), and the Beijing Natural Science Foundation (7222180).

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Conceptualization: Jiantao Li, Hao Zhang, Jitian Li  
Funding acquisition: Jiantao Li

Data curation and Investigation: Daofeng Wang, Lin Han, Gaoxiang Xu  
Methodology: Lin Han  
Formal analysis: Daofeng Wang, Huanyu Li  
Writing – original draft: Daofeng Wang  
Writing – review & editing: Wupeng Zhang, Hua Li, Cheng Xu

References

   https://doi.org/10.1016/j.jse.2013.02.003

   https://doi.org/10.1302/0301-620x.74b3.1587875

   https://doi.org/10.1016/j.injury.2020.11.040

   https://doi.org/10.5435/jaaos-d-17-00155

   https://doi.org/10.1007/s00068-018-1061-1

   https://doi.org/10.1243/09544119jeim409

   https://doi.org/10.1177/0363546517753376

   https://doi.org/10.1016/j.arth.2020.07.061

https://doi.org/10.1016/j.clinbiomech.2008.07.004

https://doi.org/10.1615/critrevbiomedeng.v28.i12.40

https://doi.org/10.1007/s00264-013-1210-1

https://doi.org/10.1007/s00264-010-1199-x

https://doi.org/10.1016/j.injury.2019.02.008

https://doi.org/10.1093/eurheartj/ehx016

https://doi.org/10.1002/adma.201902516

https://doi.org/10.1155/2021/6653967

https://doi.org/10.1007/s10439-009-9887-7

https://doi.org/10.1016/j.jbiomech.2008.08.013

https://doi.org/10.1177/095441191420004

https://doi.org/10.1177/0954411912450998

https://doi.org/10.1016/j.injury.2013.03.003

https://doi.org/10.1097/BOT.0b013e318278112a

https://doi.org/10.1016/j.jse.2017.05.010

https://doi.org/10.1007/s00204-012-1629-x

https://doi.org/10.2106/jbjs.16.01321

https://doi.org/10.1016/j.jhsa.2013.05.004

https://doi.org/10.1371/journal.pone.0260414

https://doi.org/10.1016/j.injury.2013.03.003

https://doi.org/10.1177/0954411912450998

https://doi.org/10.1016/j.injury.2013.03.003

https://doi.org/10.1097/BOT.0b013e318278112a

https://doi.org/10.1007/s00204-012-1629-x

https://doi.org/10.2106/jbjs.16.01321

https://doi.org/10.1016/j.jhsa.2013.05.004

https://doi.org/10.1371/journal.pone.0260414

https://doi.org/10.1016/j.injury.2013.03.003

https://doi.org/10.1177/0954411912450998


**Publisher’s note**

Whioce Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.