Three-dimensional finite element analysis of mini-external fixation and Kirschner wire internal fixation in Bennett fracture treatment

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KEYWORDS
Bennett fracture; Fracture of the base of the first metacarpal; Finite element analysis; Mini-external fixation; K-wire internal fixation; Biomechanics; Finite element models

Summary
Objective: To analyze the mini-external fixation and percutaneous K-wire internal fixation for the treatment of Bennett fracture by using finite element analysis and to compare the biomechanical stability and postoperative impact of the two fixations on the fracture.

Methods: Three-dimensional digital models of the first metacarpal bone, second metacarpal bone, and the trapezium were established using Mimics 10.01 software. A solid model and finite element models were created and analyzed using ANSYS 10.0. The same load of 100 N was exerted on both the mini-external fixator and the Kirschner (K)-wire internal fixator for the treatment of Bennett fracture. Finally, the none-line solution was analyzed, and displacement nephograms were obtained.

Results: The displacement nephograms of the distal and proximal fragments of the fracture obtained using the mini-external and K-wire models were established. The X/Y/Z (SUM)-component displacements of 15 nodes aligned with the articular surface fracture were obtained. The relative displacement of the distal and the proximal fragments of the fracture were calculated, and all digits of relative displacement were entered into SPSS 13.0 software. The difference between the X-component relative displacements was statistically significant. Moreover, the comparison of the Y-component, Z-component, and SUM-component relative displacements yielded statistical significance. The average relative displacement in the X-direction was 0.3214 mm in the K-wire model.

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Conclusion: Mini-external fixation is more effective than K-wire internal fixation for secure Bennett fracture stability. Both fixations have similar effects on postoperative traumatic arthritis and postoperative hand functions.

Level of evidence: 1 Biomechanical studies.

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Introduction

Bennett fracture, named after Edward Halloran Bennett, refers to an oblique intra-articular metacarpal fracture that occurs at the ulnar border of the first metacarpal base. Manual traction reduction for such a fracture is easy, but sustaining the reduction is difficult [1—3]. In the clinical setting, various methods can be applied for Bennett fracture treatment [4—6]. Among the different methods, mini-external fixation has been more clinically favorable given its years of development and because of its satisfactory curative effect [7—10]. However, considering the high cost of mini-external fixation, many scholars recommend Kirschner (K)-wire internal fixation as an alternative, with its equal effect at a lower cost [11]. The current study compares the biomechanical characteristics of mini-external fixation and K-wire internal fixation for Bennett fracture treatment to evaluate their respective advantages and disadvantages.

Many scholars currently use the finite element method to represent human body structures in a computer, and assign the same biomechanical characteristics as the actual body parts. The finite element method has certain irreplaceable advantages for studying bone stress-strains and displacements under different stresses, i.e., it can reflect the displacement of a model and the internal stress information in the model, it can offer precise quantitative and visualized qualitative analyses, and has good repeatability and comparability [12—15]. Therefore, finite element models of a hand with Bennett fracture were established in this study via external force exertion using Mimics, Geomagic, and ANSYS computer software to compare the biomechanical stability and the postoperative impact of mini-external fixation and percutaneous K-wire internal fixation on Bennett fracture under similar conditions.

Materials and methods

General materials

Volunteer: a healthy man with normal hands and no other diseases.

CT: GE Healthcare LightSpeed PRO 32 rows 64-line Spiral Computed Tomograph, USA.

Computer: CPU: Pentium Dual-Core T4200 2.0 HG, 512 M NVIDIA GeForce 9600 M GS, 2 GB Memory.

Software: Mimics 10.01, Geomagic Studio 10.0, ANSYS 10.0, and SPSS 13.0.

Mimics is a software specially developed by Materialise for medical image processing. Mimics is used for the segmentation of 3D medical images (resulting from computed tomography [CT], magnetic resonance imaging, microtomography, cone beam computed tomography, ultrasound imaging, and confocal microscopy) that generate highly accurate 3D models of the body anatomy. These patient-specific models can then be used directly for a variety of engineering applications in Mimics or 3-matic and to export the 3D models and anatomical landmark points to 3rd-party software, such as statistical packages, computer-aided design (CAD) applications, and finite element analysis (FEA) packages [16].

Geomagic Studio is the industry's easiest-to-use intelligent solution for transforming 3D scanned data into highly accurate polygon and native CAD models for reverse engineering, product design, rapid prototyping, and FEA (http://www.geomagic.com/zh/products/studio/index.shtml). The ANSYS software offers an unparalleled breadth of solutions across a broad range of disciplines and it can accurately address the structural modeling of any product or process. Such solutions are built within the ANSYS Workbench user environment, which is a single framework that allows quick and efficient performance of FEA simulations at both concept and validation stages of design (http://wildeanalysis.co.uk/fea/software/ansys).

3D modeling

This stage aims to establish 3D digital models of the first metacarpal bone, second metacarpal bone, and the trapezium by using Mimics 10.01. A 64-slice helical CT scanning of the left hand and the distal radius was performed on a volunteer in 2010. During scanning, the volunteer was instructed to put his palm in a prone position with the thumb in a natural abduction. A full ulnar deviation was demonstrated to keep the longitudinal axes of the thumb, the first metacarpal bone, and the radius in line. The slice thickness was 0.625 mm in a 1024 × 1024 matrix. The obtained DICOM data that consist of 198 CT images were saved on a disk and then inputted into the Mimics 10.0 software through a module. The maskings for the left hand and the radius were produced based on the bone density threshold value. The areas of the first metacarpal bone, trapezium, and second metacarpal bone were automatically selected by the computer by using the thresholding and 3D region growing techniques. The marrow cavities were filled up for the new maskings by using the cavity-filling technique. The 3D models were constructed using the Calculate 3D technique. The models cannot distinguish the bone cortex from the medulla, but the reunification of the two sets was found to be homogeneous. All models generated output in the form of point clouds or STL after remeshing, and were then saved on a disk in *.txt format.

Modeling a solid model: The digits were inputted into Geomagic10.0 to mend and obtain a solid volume and

generate digital outputs in the Initial Graphics Exchange Specification *.IGES format. The data were entered into Geomagic to go through point cloud, polygon, encapsulation, and formation processing for further construction. To reduce the amount of calculation involved, the patches should not be extremely dense during Geomagic editing, considering that tedious calculation remains to be done in the late stage to verify the accuracy of the model. Moreover, considering the direct influence of the patches on the quality of the ANSYS mesh dividing method, the patches should be in the form of a regular parallelogram, and extremely small angles should be avoided. Finally, the data were saved in the *.IGES format.

### Finite element modeling

The IGES-form files of the first metacarpal bone and the trapezium were introduced into ANSYS. The material types and attributes that were set up are shown in Table 1. Solid 92 was the type of metacarpal bone used, with its Young’s modulus and Poisson’s ratio similar to those of the cortical bone. Although no standards for the model data have been released up to now, the authors of the current study, based on literature and the experience gained from the current study, found that the attribute of the cancellous bone should be selected for the trapezium because most of the trapezium is cancellous. Solid 185 was the type of external fixator and K-wire used, with its Young’s modulus and Poisson’s ratio similar to those of titanium alloy [12,14–22]. The Bennett fracture model of the first metacarpal bone was established using the cutting technique. By moving the workbench in the modeling menu, the external fixator model was made similar to Orthofix (M101), the semi-screw had a diameter of 2 mm, the external fixator had a diameter of 4 mm, and the universal ball had a diameter of 5 mm. A mini-external fixation frame was constructed through Boolean calculation. The frame was then moved inwards to imitate the operative procedure for the Bennett fracture [7]. The element types and attributes of the first metacarpal bone, the trapezium and the mini-external fixation frame that were characterized are shown in Table 1. Meshes were divided for the mini-external fixation model. The external fixator was sweep-divided using the smart mesh tool because the bones were irregular and contained pinholes. The nodal point and element numbers of the model were obtained (Table 1, Fig. 1). Fig. 2 shows the three contacts that were set between the trapezium and the distal and proximal articular surfaces and the distal and proximal pieces of the fracture surfaces. Similarly, the K-wire internal fixation finite element model was established, with the K-wire diameter of 1.2 mm. The internal fixation procedure was imitated in the percutaneous K-wire internal fixation for the fracture [6]. The models were meshed, the bone tissues were smart-divided, and the K-wire fixator was sweep-divided to obtain the nodal point and element numbers of the model (Table 1, Fig. 1). Three contacts were established between the trapezium and the distal, between the distal and proximal pieces of fracture surfaces, and between the trapezium and proximal fracture surfaces.

### Boundary-constrained conditions and external force

For the externally fixed model, the joint surface between the trapezium and the scaphoid was assumed immovable because the articular surfaces formed by the trapezium and other carpal bones belong to the amphiarthrodial joints. The relationships of the screw and bone are glued and set on the Boolean menu given that the four screws used for the external fixation contained partial threads. Moreover, the same contact frictional coefficient (0.2) was set for the distal and proximal fracture surfaces (0.01) for the joints. For the fracture fragments, only the degree of freedom of the attachment of the proximal fracture fragment to the intermetacarpal ligament was set to 0.5 mm. A 100 N nodal pressure was then exerted on the first metacarpal bone [23]. For the internally fixed model, the second metacarpal and the trapezium displacements were assumed immovable. Despite the frictional contacts between the K-wire and the trapezium and between the first and second metacarpal bones, the relationships of the contacts belonged to complete gluing, given that the relative displacements of the K-wire to the bones were not considered in the current study. The coefficient of friction was set for the distal and proximal fracture surfaces (0.2) and joints (0.01). For the fracture fragments,
Figure 1  Finite element models. A. The models and fixation. B. The finite element models.

Figure 2  Three contacts, between the trapezium and the distal and proximal articular surfaces, the distal and proximal pieces of fracture surfaces.
only the degree of freedom of the proximal fracture fragment’s attachment to the intermetacarpal ligament was set to 0.5 mm. Moreover, a total binding was set for all contacts, and the same nodal pressure was then exerted on the first metacarpal bone (Fig. 3).

**Statistical analysis**

The main observation indices included the relative displacement of the distal and proximal fracture fragments of the first metacarpal bone. Importing all data into SPSS 13.0 yielded the mean and t-test results.

**Results**

A non-linear finite element biomechanical analysis of the mini-external and the K-wire fixation finite element models under the X-axial load of 100N was conducted. Figs. 4 and 5 show the obtained displacement nephograms of the proximal and distal fracture fragments, respectively.

**Discussion**

Bennett fracture is also referred to as intra-articular fracture dislocation of the base of the first metacarpal bone with the fracture line through the carpometacarpal joint. In Bennett fracture, the ulnar fragment remains in the correct position and shows a triangular form because of its attachment to the carpometacarpal ligament. Unlike the ulnar fragment, the radial fragment causes carpometacarpal dislocation or incomplete dislocation as a consequence of the tension from the abductor pollicis longus muscle or the oblique joint surface, and the distal fragment is subluxated in the dorsal, radial, and proximal directions. The state of
Table 2  Displacement vector of 15 nodes of K-wire fixation model.

<table>
<thead>
<tr>
<th>NS</th>
<th>DV</th>
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<tbody>
<tr>
<td>UX (mm)</td>
<td>UY (mm)</td>
</tr>
<tr>
<td>PDV</td>
<td>DDV</td>
</tr>
<tr>
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</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<td>4</td>
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<td>-0.058108</td>
</tr>
<tr>
<td>15</td>
<td>-0.036480</td>
</tr>
</tbody>
</table>

DV: displacement vector; NS: nodes; PDV: proximate displacement vector; DDV: distal displacement vector; UX: uranium X; UY: uranium Y; UZ: uranium Z; USUM: uranium SUM.

Table 3  Displacement vector of 15 nodes of mini-external fixation model.

<table>
<thead>
<tr>
<th>NS</th>
<th>DV</th>
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<tbody>
<tr>
<td>UX (mm)</td>
<td>UY (mm)</td>
</tr>
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<td>PDV</td>
<td>DDV</td>
</tr>
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<tr>
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<tr>
<td>12</td>
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<tr>
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<td>-0.19974</td>
</tr>
<tr>
<td>15</td>
<td>-0.19136</td>
</tr>
</tbody>
</table>

DV: displacement vector; NS: nodes; PDV: proximate displacement vector; DDV: distal displacement vector; UX: uranium X; UY: uranium Y; UZ: uranium Z; USUM: uranium SUM.

a Bennett fracture is very unstable, and improper treatment can lead to osteoarthritis, thumb functional weakness, or even thumb functional incapacitation. Bennett fractures can be caused by both direct and indirect violence, but they mostly occur as results of indirect violence, such as falling onto a thumb and a punch of the fist, among others [24]. K-wire internal fixation and mini-external fixation are two major methods that have been widely adopted for Bennett fracture treatment in the clinical setting [4,7,8,25–27].

Both methods have their respective advantages. The advantages of the K-wire internal fixation include easy and flexible operation, small trauma, fast fracture healing, low operative cost, and satisfactory curative effect [27,28]. The disadvantages of the K-wire internal fixation include the susceptibility of the wire hole to inflammation, requirement of four weeks to six weeks of unadjustable plaster fixation after operation, which greatly limits the early functional rehabilitation of the patient, and the frequent loosening of


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the K-wire [29]. On the other hand, the advantages of mini-external fixation are as follows: it can be extensively applied to different fracture types, especially to complicated comminuted fractures; it causes slight trauma and it only slightly damages the blood transportation at the fracture ends; it has high degree of stability and exerts sustained traction of the fracture fragments (a sufficient and sustained traction plays a key role in fracture healing and postoperative hand function recovery [24]); and finally, a patient treated using this technique can participate in functional rehabilitation, which substantially help in fracture healing and hand function recovery [30, 31]. The disadvantages of the mini-external fixation are as follows: the pin hole is susceptible to inflammation, and the tendons and nerves are at high risks of damages [32]; it entails high costs; and the operation has to be performed under an X-ray or C-arm X-ray machine, which can cause phototaxis to a certain degree.

The mini-external fixation is generally better than the K-wire treatment method based on the discussions above, but most researchers only have a summary of the clinical efficacy of the results and do not know the difference between the two therapeutic methods. The finite element model of the two treatments aims to evaluate the two treatment methods from a biomechanical point of view. Experimental models were created, are closed completely reset with external fixation or percutaneous Kirschner wire fixation in the treatment of Bennett fracture model. The two treatment methods fixed onto the formation of reduction and fixation of the fracture fragments are minimally invasive, largely protect the integrity of the surrounding soft tissue and periosteum, promote fracture healing, and prevent the impact of trauma on the joint function. Moreover, the two treatment methods are comparable to the clinical treatment of choice in surgery.

With the development of computer technology and interdisciplinary permeation, the finite element method has been increasingly applied in osteo-biomechanical analysis. The current study established the two treatment models by using the Mimics, Geomagic, and ANSYS software based on the experiences of other researchers in model establishment, and the established models satisfied the basic requirements of FEA. The nephograms of displacement of the distal and the proximate pieces of fracture of the two models were listed in the ANSYS General Postprocessor. The X/Y/Z/SUM-component displacements of 15 nodes on the articular surface fracture were determined, and the relative displacement of the distal and the proximate pieces of the fracture were calculated. The relative displacement and t-value were obtained after inputting the digits of relative displacement into SPSS 13.0.

In the current study, the curative effects of mini-external fixation and K-wire internal fixation on fracture fixation stability were compared by observing 15 nodes aligned with the articular surface fracture of the distal and proximal fracture fragments. Comparing the X-component relative displacements of the two models yielded a t-value of 4.741 (P < 0.01), which is statistically significant. Likewise, comparing the Y-component relative displacements yielded a t-value of 5.649 (P < 0.01), which is also statistically significant. Comparing the Z-component relative displacements yielded a t-value of 5.625 (P < 0.01), whereas comparing the SUM-component relative displacements yielded a t-value of 4.558 (P < 0.01), both of which are statistically significant.

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significant. Statistical analysis easily demonstrates that mini-external fixation is better than the K-wire treatment.

Traumatic arthritis, which is one of the sequels to Bennett fractures, seriously influences a patient’s quality of life and hand functions. The occurrence of traumatic arthritis is closely correlated with the anatomical position and alignment of the surgical fracture [5,24,33,34]. More studies suggested that the resetting the relative displacement of fracture fragments should be less than 1 mm [35–37]. Soyer [4] considers that the resetting of fracture fragments with a relative displacement less than 1 mm would greatly reduce the incidence of traumatic arthritis. In the current study, the curative effects of K-wire internal fixation and mini-external fixation on traumatic arthritis were compared by observing the average relative displacements of the distal and proximal fracture fragments. A 100N [23] nodal pressure was then exerted on the distal articular surface of the first metacarpal bone. The highest strength of the thumb and four-finger pinch was 10 kg. The simulated pressure was the biggest external force of the thumb with initiative activities. In the model coordinates, the X-direction was positioned along the longitudinal axis of the first metacarpal bone pointing remotely, the Y-direction was positioned along the coronal plane pointing to the ulna, and the Z-direction was positioned along the sagittal plane pointing to the palm side. The main observation indices include the average of the relative displacements in the X-direction, which is the fracture of the relative displacement of the articular surface. The average of the relative displacements in the X-direction was 0.3214 mm in the K-wire model and is 0.0321 mm in the mini-external model (0.0321 mm < 0.3214 mm < 1 mm < 2 mm), indicating that the two fixations have the same effects on reducing the incidence of traumatic arthritis [4]. However, the effects of the two methods do not have an obvious difference in terms of postoperative hand function recovery considering that a dislocation less than 2 mm after fracture fragment reduction will have no substantial influence on postoperative hand functions [38]. Hence, mini-external fixator and K-wire treatment for Bennett fractures can reduce the incidence of traumatic arthritis and promote the recovery of hand functions.

Conclusion

In summary, mini-external fixation was found to be more effective than the K-wire internal fixation for fracture fixation stability. Both methods have similar effects on postoperative traumatic arthritis and postoperative hand functions.

The current study poses several limitations. First, the mechanical properties of the biomaterials were hypothesized to be homogeneous (i.e., the cortical bone and the medullary substance were composed of the same material), continuous, and isotropic. This hypothesis is not applicable in reality, in which entity materials are anisotropic. Second, the absence of tendons and muscles around the models was deemed to have a degree of influence on the accuracy of the results.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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