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*Original Article*

# Three-dimensional finite element analysis of the treatment of Kienböck's disease by use of the shift pisiform bone

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**Abstract:** Objective: The aim of this study was to determine the optimal position of the pisiform bone in "Saffar's Procedure" and to evaluate the necessity of combined carpal fusion. Method: A three-dimensional (3D) finite element model of the wrist was established, and we verified its effectiveness using Mimics 16.0 software. Three kinds of shift pisiform bone position models and two kinds of carpal fusion models were established by reassembling the wrist 3D model. The stress analysis of each model was analyzed and compared using Pro/Engineer5.0 and ANSYS14.0 software. 12 patients with Kienböck's disease were treated according to the results of the finite element analysis. Result: The 3D finite element model of the wrist was successfully established and validated. The best substitute position of the pisiform bone was to rotate its pisiform-triangular articular surface to articulate with the radial. And combined STT or scaphoid-capitate carpal fusion was also suggested. The follow-up periods were 12-82 months with an average of 43 months. Pain was relieved in 12 patients, and the VAS score was 1.5±1.8. The wrist grip power was 80.8% of the contralateral hand. The excellent and good rate of the Cooney score was 83.3%. The incidence of osteoarthritis was 16.7%. Conclusion: The optimal replacement position of the pisiform bone and the necessity of combined carpal fusion were determined through the 3D finite element analysis, and we verified it by clinical follow-up. It may optimize the surgical procedure and improve patient prognosis, and it may especially reduce the risk of osteoarthritis or even necrosis of the shift pisiform bone.

**Keywords:** Three-dimensional finite element, wrist, pisiform bone, Kienböck's disease

## Introduction

The replacement of lunate by shift vascularized pisiform was first made by Professor Saffar for the treatment of Kienböck's disease in 1982 [1]. After the long-term follow-up studies of Muneaki Abe [2], Von [3], and Zhong [4], "Saffar's Procedure" had proven to be an effective and commonly used method to treat Kienböck's disease. However, a study by Wolfgang Daecke [5] found that the function of the wrist recovered well, but the procedure only partially restored the arrangement of the carpal bone, and the incidence of osteoarthritis reached 50%. Maydell [6] also confirmed osteoarthritis was a common complications of "Saffar's Procedure". Therefore, achieving a better correction in patients' carpel bone arrangements and the prevention of the incidence of osteoarthritis of the wrist have been the main aims in the development of the surgical procedure.

After decades of development and clinical applications, the best alternative position for pisiform bone shift is still controversial. Most professors believe that the articular surface should be considered in order to reduce the stress on the carpal. But as we all know, the pisiform bone only has one articular surface, called the pisiform-triangular articular surface (PTAS), and the lunate bone involves the scaphoid-lunate joint, the capitate-scaphoid-lunate joint, and the radial-lunate joint. Which joint should the PTAS of the shift pisiform bone par-

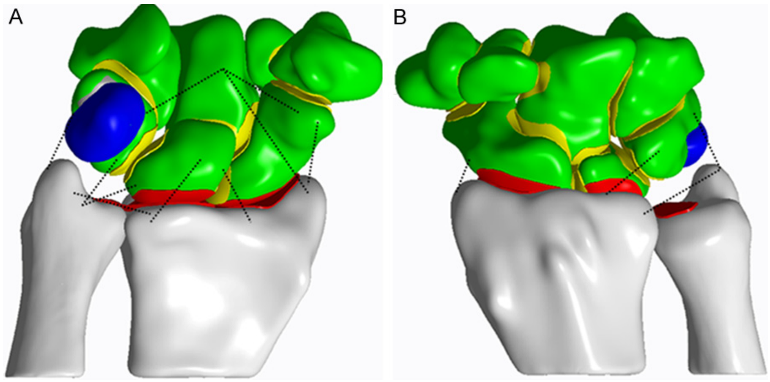


**Figure 1.** Three-dimensional model of the wrist with articular cartilages and important ligaments.

ticipate in? There is still a lot of controversy and no unified conclusion. Wolfgang Daecke [5] and Saffar [7] thought the cartilage surface of the pisiform should articulate with the capitate. But some professors like G Zhong [8] and ZM Yang [9] agreed to rotate the pisiform's articular surface to the radial surface. At present, there is also a controversy about whether or not the combined carpal fusion is required in "Saffar's Procedure" [10-12]. Even though fusion is needed, there is no relevant research to compare which of the two most common fusion techniques is better: scaphoid-trapezium-trapezoid carpal fusion (STT) or scaphoid-capitate (SC) fusion.

Unlike the traditional experimental biomechanics, the 3D finite element can be based on the provided image data to accurately reflect the stress and strain conditions within the model. It can do a stress-strain analysis on objects with complex structures, model morphology, load and material mechanics, and it can perform continuous repeatability experiments by changing some parameters. At present, the 3D finite element analysis has been widely used in clinical applications and in academic research of orthopedic biomechanics. By combining human virtual technology and digital simulation technology, 3D finite element analysis has achieved much.

Therefore, in order to solve the controversial issue of "Saffar's Procedure" and optimize it, we used the 3D finite element method to determine the best alternative position of pedicled pisiform bone and to evaluate the necessity of combining carpal bone fusion.

## Material and methods

### *Three dimensional carpal model*

A 35-year-old healthy male volunteer (height 172 cm, weight 65.5 kg) with no wrist and forearm injury or related disease history was included. The CT scanning parameters are voltage 80 V, layer thickness 0.75 mm, layer spacing 0.5 mm and a 512×512 matrix. The scanning plane was centered on the wrist between the proximal of metacarpal and the distal of radius bone. The wrist thin-section CT data were imported into the Mimics 16.0 (Materialise Corp, Belgium) to reconstruct a 3D surface meshed model of the bones (including cortical bone and cancellous bone) by the software button of threshold segmentation, closed mask defect, filling gap, relaxation re-grid, manual separation of carpal bone and 3D reconstruction.

### *Module reconstruction and assignment*

According to the domestic and international experience and autopsy data, the three-dimensional model of articular cartilage, triangular fiber cartilage disk and important ligaments of the wrist joint was established (**Figure 1**), converted into solid meshes and assignment using Geomagic Studio 12 (Geomagic, USA), Pro/Engineer5.0 (Parametric Technology Corporation, USA) and ANSYS14.0 software and the previous research methods reported by Fischli [13].

### *Boundary conditions and effectiveness validity*

In order to simulate the better mechanical load transfer, the articular surface unit was set as the contact unit and fixed all degrees of the lower end of the radial and ulnar joint. The characteristic of all the materials were set according as **Table 1**. At the contact point between capitate and the third metacarpal, 100 Newton vertical pressure was applied in the direction perpendicular to the contact surface [14]. The contact stress cloud and the von Mises stress distribution were obtained. The effectiveness of the experiment was verified by comparing

**Table 1.** Assignment of material attribute

| Component | Elastic modulus (MPa) | Poisson ratio |
|---|---|---|
| Cortical bone | 10000 | 0.3 |
| Cancellous bone | 100 | 0.3 |
| Cartilage | 10 | 0.45 |
| Ligaments | 300 | 0.4 |

previous studies of the wrist joint on the finite element analysis and experimental mechanics.

*Reassemble the position of the pisiform on a 3D model*

As shown in **Figure 3**, three models of pisiform position the model of pisiform bone translation with no articulation (PNA), the model of pisiform-radius articulation (PRA) and the model of pisiform-capitate articulation (PCA) were established by removing the lunate bone and adjusting the position of the pisiform bone on the effective 3D model of the wrist. After the same assignment and boundary as above, the finite element analysis was carried out to analyze and compare the contact stress cloud and the stress distribution cloud of the model.

*Reassemble the carpal bone fusion models*

Based on the previous step (2.4), to determine the optimal location for pisiform replacement, two combined carpal bone fusion models (STT fusion and SC fusion) were established by adjusting the contact unit of the associated articulation surface on the better position of the pisiform 3D model (**Figure 5**). After the same assignment and boundary as above, the von Mises stress, the contact stress cloud, and the stress distribution cloud were made out.

*Clinical follow-up and efficacy evaluation*

From July 2010 to June 2016, 12 patients with Kienböck's disease in Lichtman stages III-IV were treated using "modified Saffar's Procedure" according to the results of our 3D finite element analysis. We recorded the Lichtman staging and fusion methods, the postoperative Visual analogue scale (VAS) and Range of motion (ROM), the grip strength, the Cooney score and complication, especially the osteoarthritis incidence and the carpal arrangement by outpatient follow-up.

## Results

*Model validation*

In the 3D finite element model of the normal wrist joint, the maximum contact pressure of the radio-scaphoid joint and the Radio-Lunate joint were 5.2446 MPa and 3.5217 MPa respectively. The contact areas between the radio-scaphoid joint and the radio-lunate joint were 68.86 $mm^2$ and 40.01 $mm^2$, respectively. The contact area ratio was 1.721, and the area of the scaphoid and the lunate were 63.25% and 36.75%. The peak von Mises pressure of the distal radius was 2.8289 MPa, while the maximum von Mises pressures of the scaphoid and the lunate were 26.903 MPa and 14.716 MPa (**Figure 2**). The von Mises stresses delivered through the scaphoid and the lunate were 64.46% and 35.36% respectively. Compared with the data reported in the literature, our model closely agreed with that of the previous corpse biomechanics and the finite element analysis of the wrist, which confirmed the effectiveness and rationality of this model, and can provide a theoretical basis and achievable platform for further finite element analysis of the wrist.

*The optimal position of pisiform bone*

In the three pisiform position model (PNA, PCA, and PRA), the finite element analysis showed that the maximum von Mises stress of the shift of the pisiform bone was 44.130 MPa, 18.969 MPa and 15.423 MPa separately, while the peak von Mises stress of the distal radial was 3.202 MPa, 3.021 MPa and 2.828 MPa respectively. There was no difference on the peak von Mises stress of the scaphoid in the three pisiform positions (21.807 MPa, 27.392 MPa and 25.239 MPa), which was also similar to the normal wrist model (26.903 MPa) (**Figure 3**). The contact stress of pisiform on the 3 shift pisiform bone model is shown in **Figure 4**. The maximum contact pressures of the radio-scaphoid joint on PNA, PCA, and PRA were 5.969 MPa, 5.714 MPa and 5.583 MPa, while the maximum contact pressures of the radio-scaphoid joint were 2.013 MPa, 4.081 MPa and 3.424 MPa. The contact area between the radio-pisiform joint on PNA, PCA, and PRA were 10.07

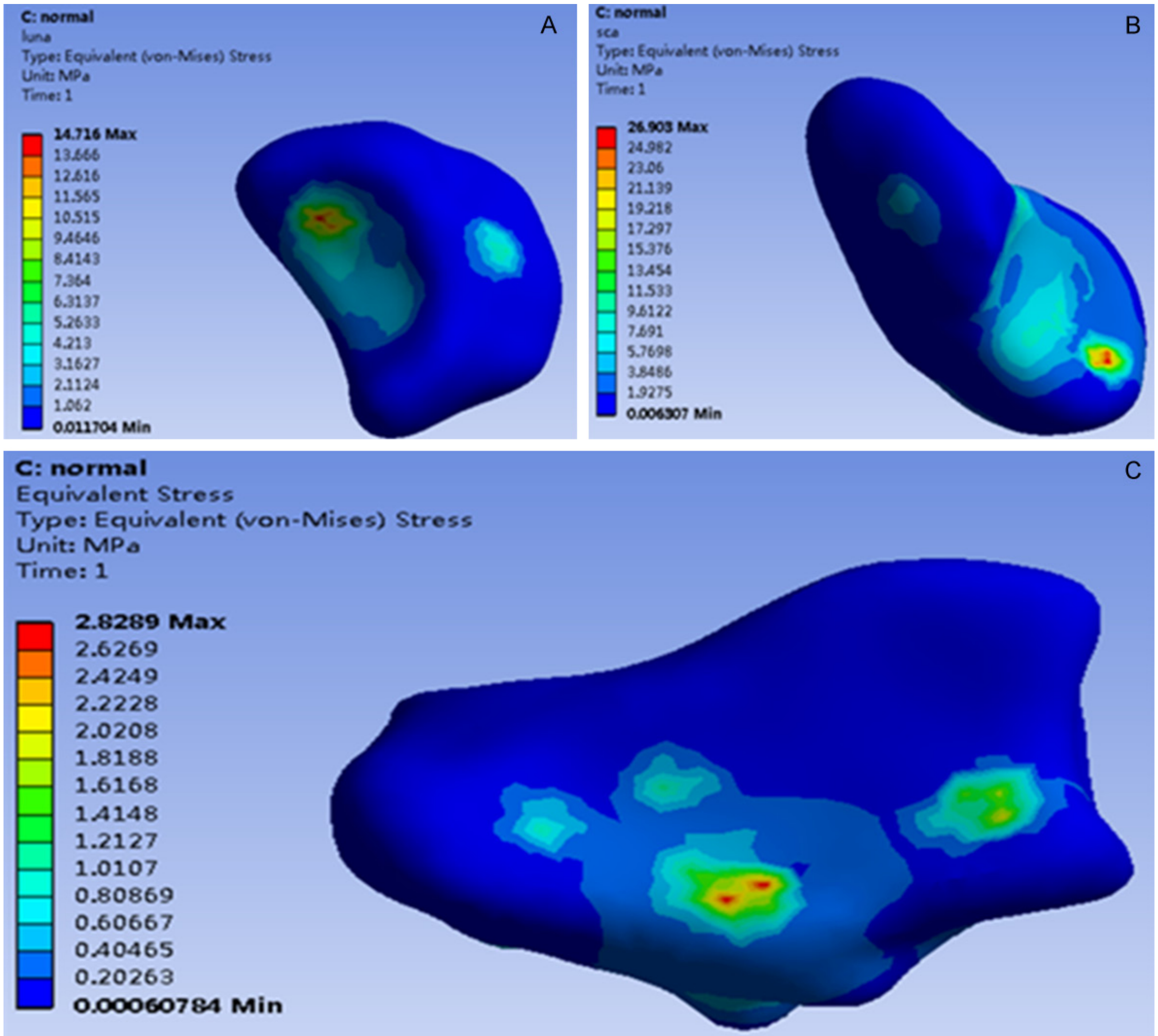


**Figure 2.** Von Mises stress of a normal wrist joint. (A) Lunate, (B) Scaphoid, (C) Distal radius.

mm$^2$, 26.34 mm$^2$ and 37.68 mm$^2$ respectively. There was no difference on the contact area of radio-scaphoid in the three pisiform positions (71.63 mm$^2$, 67.59 mm$^2$ and 68.31 mm$^2$).

*Evaluation of combined wrist fusion*

Base on the previous step, the PRA model and two combined carpal bone fusion models (PRA-STT and PRA-SC) were established. The finite element analysis showed that the maximum von Mises stresses of the shift pisiform bone in PRA, PRA-STT, and PRA-SC was 15.423 MPa, 8.832 MPa, and 1.816 MPa separately, while the maximum von Mises stresses of the scaphoid was 25.239 MPa, 29.875 MPa, and 35.339 MPa. There was also no difference on the peak von Mises stress of the distal radial (2.828 MPa, 2.873 MPa and 2.925 MPa).

*Clinical efficacy assessment*

As shown in **Table 2**, a total of 12 patients (8 males and 4 females) were included in our study. The mean age was 37.3 years (range: 22-64 years). The Lichtman stage was from IIIA to IV. All patients underwent the "improved Saffar's procedure" (PRA operation). 6 patients also had STT fusion and 6 patients also had SC fusion. The mean follow-up period was 43 mouths (12-82 months). Pain was relieved in 12 patients and the VAS score was 1.5±1.8. The wrist grip power was 80.8% and the range of motion (ROM) was 65.8% of the contralateral hand. The excellent and good rate of the Cooney score was 83.3%. 2 patients had wrist osteoarthritis postoperatively. The incidence of osteoarthritis was 16.7%, which was clearly lower than reported previously in the literature [5].

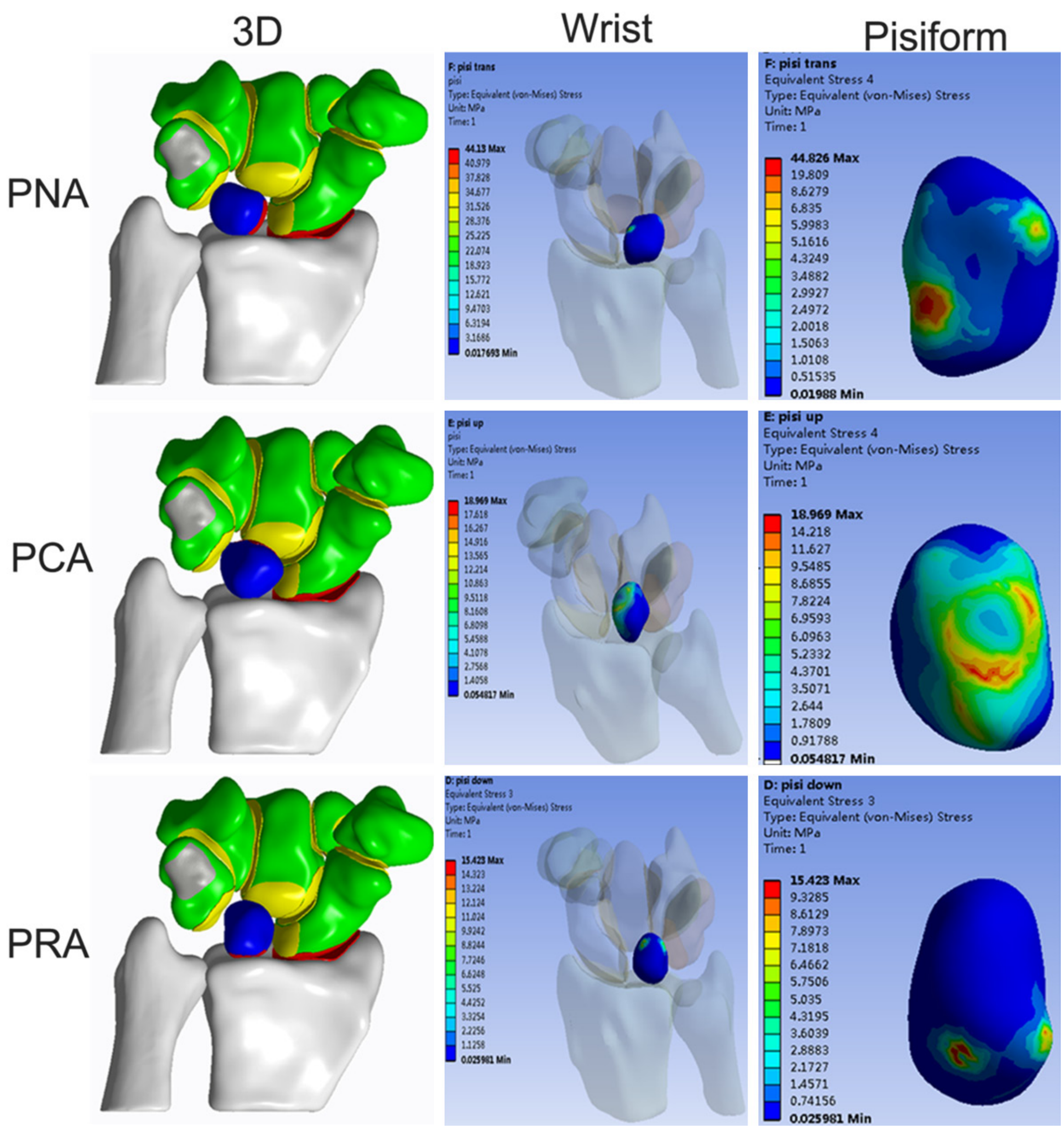


**Figure 3.** Von Mises stress of pisiform on a 3 shift pisiform bone model.

## Discussion

In the current study, the optimal position of pisiform bone in "Saffar's Procedure" and the necessity of combined carpal fusion are still controversial. We tried to resolve the controversy by using the 3D finite element method to verify it through clinical follow-up. If the conventional "Saffar's Method" did not consider the articular surface (PNA model), the model would have had a small radial-pisiform contact area, large radial-pisiform contact stress and large von Mises stress on the pisiform bone (44.130 MPa), which reflected the fact that the internal and external stresses of the pisiform were larger and may explain the high possibility of osteoarthritis in some studies [5, 7].

By establishing and analyzing three models of different pisiform positions, the PRA model sustained minimal von Mises stress on the pisiform bone. The largest contact area of the radio-pisiform joint and similar von Mises pressures of the radial and scaphoid, which may indicate the lowest probability of postoperative osteoarthritis and pisiform fractures. Therefore,

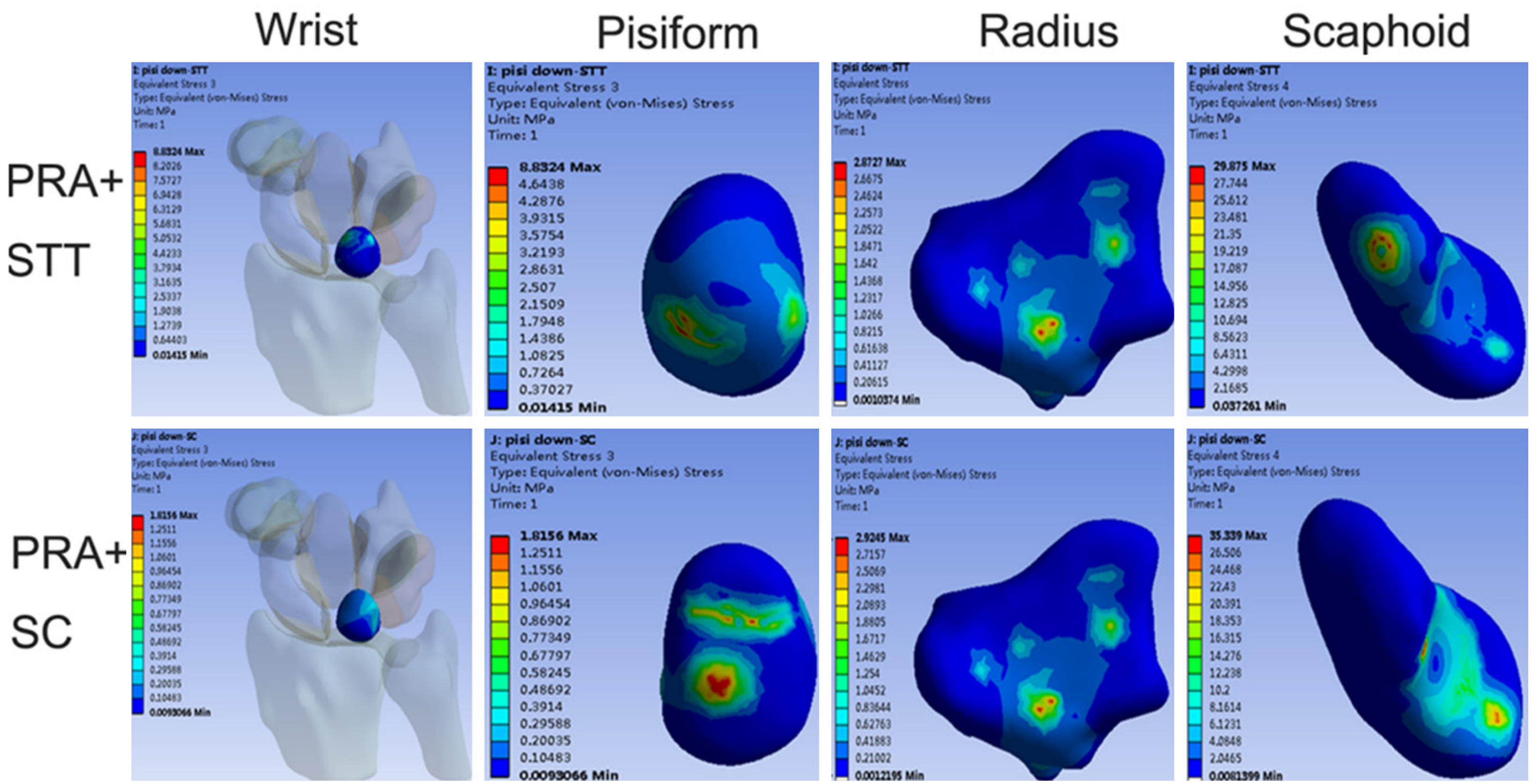


**Figure 4.** Von Mises stresses of pisiform on 2 combined carpal fusions.

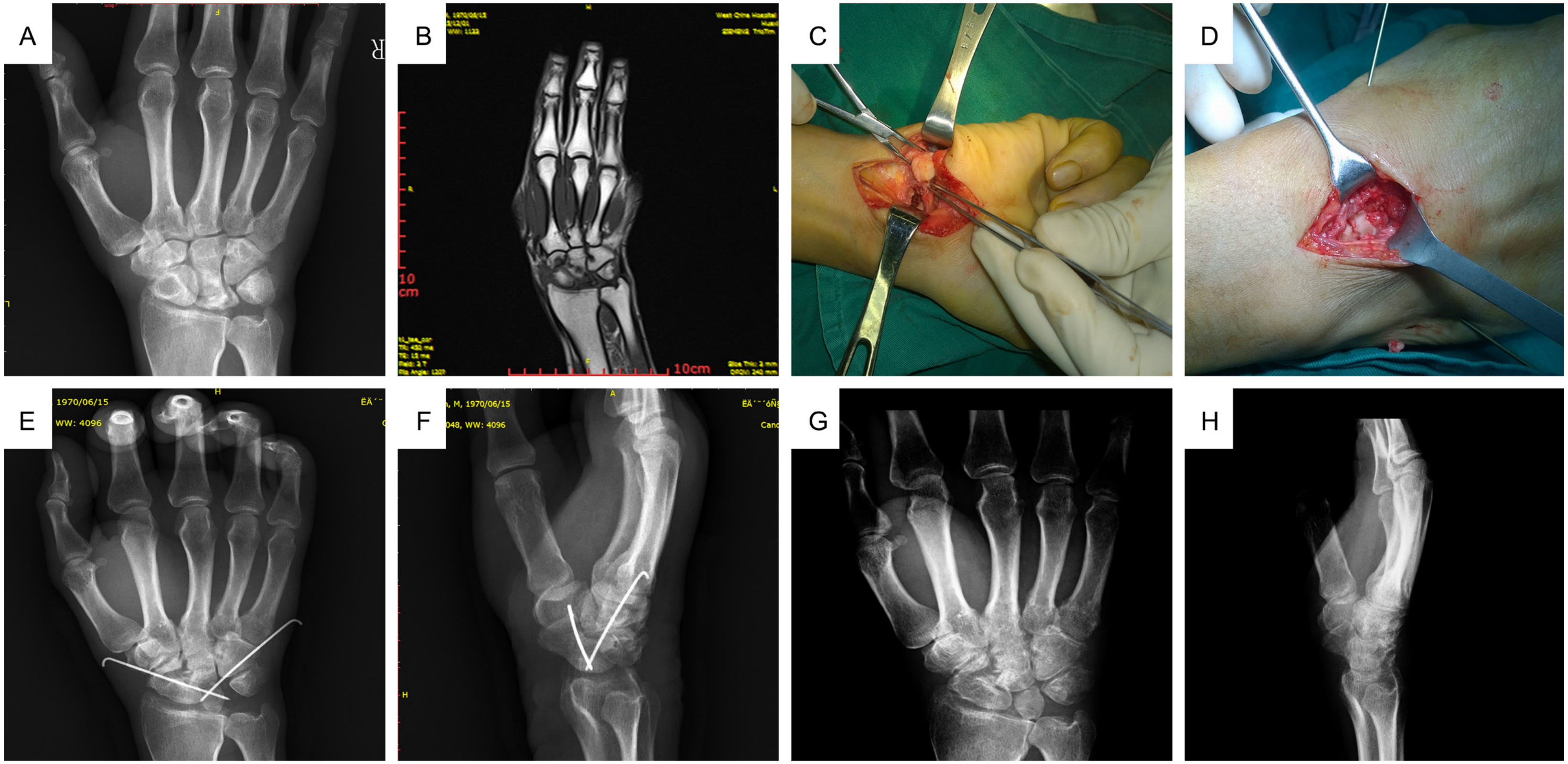

**Figure 5.** The method used in the clinic: A 45-year-old male, diagnosed with right Kienböck's disease (Lichtman IIIB) and treated using "modified Saffar's Procedure" combined with STT fusion therapy. (A and B) were the preoperative wrist X-ray and MRI; (C and D) were the intraoperative situation; (E and F) were postoperative wrist X-rays; (G and H) were radiographs at 18 months postoperatively, which revealed no necrosis of the pisiform or osteoarthritis.

**Table 2.** Characteristics of included patients with Kienböck's disease

| | Total | PRA+STT | PRA+SC |
|---|---|---|---|
| Number (Male/Female) | 12 (8/4) | 6 (4/2) | 6 (4/2) |
| Age (Years) | 37.3 (22-64) | 42.3 (22-64) | 32.3 (22-54) |
| Follow-up (Mouth) | 43.5 (12-82) | 39.3 (18-58) | 47.7 (12-82) |
| VAS score | 1.5±1.8 | 1.7±1.7 | 1.3±1.8 |
| Wrist grip power | 80.8% | 80% | 81.7% |
| Range of motion | 65.8% | 67.5% | 64.2% |
| Cooney score | 83.3% | 100% | 66.7% |
| Wrist osteoarthritis | 16.7% (2/12) | 16.7% (1/6) | 16.7% (1/6) |

the best alternative to our proposal was PRA. That is, the best substitute position of the pisiform bone was to turn the distal of it to the radial side 90 degrees first, and then rotate it again to make the pisiform triangular articular surface be brought against the radial distal surface.

No matter what kind of fusion (STT or SC) is combined, it could reduce the von Mises stresses on the pisiform bone effectively, make the wrist stable and reduce the incidence of carpal bone osteoarthritis. But it is still hard to determine which combined fusion method is better than "Saffar's Procedure".

By comparison, the stress of pisiform in the SC model was lower than the stress of the STT fusion model, but the stress and the contact area of the scaphoid were also improved. Therefore, it is suggested that combined carpal fusion should further optimize the surgical procedure and reduce the incidence of osteoarthritis of the carpal bone. We recommend combined carpal fusion, which can further optimize the surgical regimen and reduce the incidence of osteoarthritis of the carpal bone. But it is difficult to judge which is the better carpal fusion. More experimental mechanics and clinical control studies are needed to determine this.

In all, the six wrist models included the normal wrist model, and the maximum stress area on the scaphoid was located in the waist area, which indicated that the scaphoid waist was the main bearing and transferring pressure area, and this also explained why scaphoid fractures often occur in the waist [15].

Our study also has some limitations, for example, the mechanical loading in finite element analysis did not achieve dynamic loading, only static. Secondly, we did not establish a more realistic wrist to study its activity, and its physiological and pathological status. Thirdly, we used 3D finite element analysis to determine the optimal position of the pisiform bone, to evaluate the necessity of combined carpal fusion and verified it by a clinical follow-up study, but more large samples of experimental mechanics and clinical follow-up studies are needed to continue research and certification.

## Conclusion

Given the current controversy of "Saffar's Procedure", we improved it by using the 3D finite element method and clinical follow-up. Finally, the best substitute position of the pisiform bone was to rotate the pisiform's articular surface to the radial surface and to combine carpal fusion. It could optimize the surgical procedure and improve the prognosis, especially reducing the risk of osteoarthritis or even necrosis of the shifted pisiform bone.

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## Disclosure of conflict of interest

None.

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