Biomechanical evaluation and finite element analysis of axial-loading simulated experiment of wrist fracture

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wrist fracture, biomechanical assessment, finite element analysis, wrist protector
Abstract

Objectives
This study combined mechanical experiments and finite element analysis (FEA), and verified each other, to assess the biomechanical analysis and effect of wrist fracture, providing theoretical basis for the simulation experiments of wrist fracture and optimal design of wrist protector.

Methods and Materials
Six cadaveric wrists were included to create experimental specimens. After grouping, the wrist models were axially loaded under physiological load of 600 N, the stress magnitude and distribution of experimental group and control group were obtained. Moreover, a three-dimensional (3D) wrist finite element model (FEM) of a healthy volunteer was developed to verify the rationality and effectiveness of wrist models.

Results
Within the range of physiological load, the stress of radioulnar palmar unit was high and in shape of pressure, while the stress of radioulnar dorsal unit was relatively lower and in shape of tension. The stresses of radial distal palmar, ulnar distal palmar, radial distal dorsal, ulnar distal dorsal, radial proximal palmar and ulnar proximal palmar units in experimental group were less than those in control group. However, the stresses of radial proximal dorsal and ulnar proximal dorsal units were higher than those in control group.

Conclusions
Under physiological load, wearing wrist protector can apparently reduce the stress on radioulnar distal palmar, radioulnar proximal palmar and radioulnar distal dorsal units, while has no obvious effect on radioulnar proximal dorsal units. During the process of designing and improving the wrist protector, it is reasonable to place the stress center on radioulnar distal palmar and dorsal units.

Background
The incidence of wrist fracture is widespread currently, accounting for 6.7% – 11% of the total body fracture, which inevitably results in high medical costs [1, 2]. The wrist joint is mainly composed of a bony structure and other small joints, which is a composite joint between the forearm and palm [3, 4].
Moreover, not only the bony structure and other small joints have a clear division of labor in structure, but also correspond to each other in function [5, 6]. As the most complicated joint of human body [7], the mechanical mechanism of wrist joint is more complicated. Once the wrist joint is injured, it is likely to cause secondary damage to other wrist structures [8], affecting the function of relevant parts of the upper limbs. Thus, a thorough and detailed study of wrist joint has significance clinical significance.

Currently, researches on preventing wrist fractures are still limited on drugs in the treatment of osteoporosis, osteoporosis fracture predicted by the Quantitative computed tomography (QCT) [9-12]. However, from the perspective of biomechanics and FEA, it is of great practical significance to explore the prevention and treatment of wrist fractures. Based on this, this study combined mechanical experiment of cadaveric wrist models with finite element (FE) wrist simulation analysis, and verified each other, which contributes to assessing the biomechanical analysis and effect evaluation of wrist protector. Moreover, it also provided the theoretical basis for the simulation experiment of wrist fracture and the optimal design of wrist protector.

Methods And Materials

Models and materials

Six wrist samples were collected from cadavers in individuals with an age at mortality of 20-50 years at the Department of Human Anatomy of Basic Medicine, Nanchang University (Nanchang, Jiangxi, China). Prior to storage at -20℃, in order to exclude the skeletal defects, dislocations, lesions and tumors, the X-ray examination and bone mineral density (BMD) of wrists were performed. An unsealed cuboid container (stainless steel materials) with the specification of 80 mm×80 mm×100 mm was designed to display the wrists. PALACOS bone cements with low viscosity, 40 g×20 boxes (Heraus, Germany) were used to implant the wrists vertically into the cuboid container according to the filling technology of bone cement [13], and the bone cements were embedded and fixed until the wrists were completely firm without any slight movement. Moreover, the wrists were equipped with a stress sensing system device (Taizhou, Zhejiang, China), a microelectronic universal testing machine (Jinan, Shandong, China) and four static strain test units (Jinan, Shandong, China), which were
connected by wires. Four static strain test units were respectively marked as A, B, C and D units, of which unit A represented the stress of radioulnar distal palmar unit; unit B represented the stress of radioulnar distal dorsal unit; unit C represented the stress of radioulnar proximal palmar unit; unit D represented the stress of radioulnar proximal dorsal unit. Ethical approval was obtained from Institutional Review Board of Jiangxi Provincial People's Hospital Affiliated to Nanchang University. The computed tomography (CT) data was obtained from a 30-year-old healthy Chinese volunteer, whose age and forearm size strictly met the requirements of above cadaver specimens. In order to ensure the normal anatomy of wrist, the X-ray of his wrist was also performed to exclude the fracture, lesions and other conditions. The experimental devices in this current study included a dual-source CT (Siemens, Berlin, Germany), a computer (Dell, Landrock, USA), Mimics 19.0 software (Materialise, Leuven, Belgium), Geomagic Studio 12.0 software (Raindrop, North Carolina, USA) and Abaqus 6.51 (Dassault Simulia, Providence, USA).

**Biomechanical testing methods**

The biomechanical experiment in this study belonged to the impact test of static loading within the yield strength. The specimens wearing wrist protectors were divided into experimental group, and the naked wrist specimens were divided into control group. In experimental group, the wrist protectors were made of 20 mm thick soft sponge materials and 2 mm thick polypropylene hard materials. Then, the mechanical axial compression mode was selected, the strain sensing system on wrist models was installed and the static resistance strain gauges were connected. With the palm facing upward, the wrist models were fixed according to the above method, 90 degrees perpendicular to the ground, and the pressure hammer was aimed at the center of the navicular and lunar bone. The initial loading speed was set at 2 mm/min, and the loading range was 0-600 N (Fig. 1). The strain values of all target units were recorded for every 20 N load, and each specimen was tested three times under the same conditions.

**Construction of 3D FEMs**

The volunteer was scanned transversely by CT, ranging from proximal forearm to fingertip. During scanning, the volunteer referred to the direction of axial-loading and the posture maintained when...
the wrist models were tested. It was determined that the established wrist model was set to 75 degrees of dorsiflexed and 10 degrees of pronated, the scanned data was saved in the Digital Imaging and Communications in Medicine (DICOM) format. Then, the data was input into the Mimics19.0 software to initially establish the 3D geometric model of wrist. The contours of forearm cortex, loose tissue and surrounding soft tissue were extracted by the tools of Thresholding and Manual drawing, and the STereoLithography (STL) format data were obtained. Then, input the data into the Geomagic Studio 12.0 software, and conducted with deeper level of hole filling and smoothing for each part of model to prevent the occurrence of poor grids. Finally, the data of generated solid 3D model was imported into Abaqus 6.51 software for statistical analysis.

**Statistical analysis**

The data obtained above were statistically analyzed by SPSS 22.0 software (SPSS, Chicago, USA), and was assessed by the paired t-test. $P < 0.05$ was regarded as the difference with statistical significance.

**Results**

*The experimental results of control group*

In axial-loading simulated experiment of control group, the stress magnitude and properties of the wrist model were different. Among them, the stresses of palmar units were apparently higher than the stresses of dorsal units, and the stresses of palmar units were mainly in the shape of pressure. The initial stage of the dorsal units was in the shape of pressure, but the whole process was dominated by tension. The equivalent stresses of the radial distal and proximal palmar units under 600 N load were 36.6 MPa and 58.5 MPa. Under the same loading conditions, the equivalent stresses of the ulnar distal and proximal palmar units were close to those on the radial distal and proximal palmar units, which were 37.9 MPa and 37.4 MPa, respectively. In all groups of units, the stresses of the dorsal units were all less than those of the palmar units. Moreover, the stresses of ulnar distal and proximal dorsal units and radioulnar proximal dorsal units were in the shape of pressure at the initial stage of the experiment, while transformed into tension at the middle and late stages. The maximum stresses of the radioulnar distal dorsal units were 9.3 MPa and 13.4 MPa, while the maximum stresses of the
radioulnar proximal dorsal units were 10.5 MPa and 15.6 MPa, respectively.

**The experimental results of experimental group**

In axial-loading simulated experiment of experimental group, the stress magnitude and properties of the wrist model were also different. The stresses of palmar units were apparently higher than the stresses of dorsal units, and every unit was mainly dominated by pressure. The initial stage of the radial proximal dorsal unit was in the shape of pressure, while transformed into tension at the middle and late stages. In addition, tension was the main manifestation of the radioulnar distal and dorsal units and ulnar proximal dorsal unit. Under the same loading conditions, the stresses of radioulnar proximal palmar units were all higher than those of radioulnar distal palmar units. The equivalent stresses of the radioulnar proximal palmar units under 600 N load were 36.6 MPa and 58.5 MPa, while the equivalent stresses of the radioulnar distal palmar units were 20.2 MPa and 24.2 MPa, respectively. In all groups of units, the stresses of the dorsal units were all less than those of the palmar units. The maximum stresses on the radioulnar distal dorsal units were 5.6 MPa and 4.7 MPa, while the maximum stresses on radioulnar proximal dorsal units were 10.2 MPa and 13.2 MPa, respectively (Fig. 2).

**The comparison of results between control group and experimental group**

The comparison of stress peak and decline between two groups was derived as (Table 1). In all 8 groups, besides the radioulnar proximal and dorsal units, there was no significant stress difference between the control group and experimental group at the late stage of experiment. However, the stresses of remaining 6 units in experimental group were decreased by 44% compared with control group on average (Fig. 3).

**The constitution of 3D FEM**

Based on the extension, flexion, retraction and rotation of normal human wrist, the 3D FEM of wrist was composed of 136897 units of bone, 9166 units of cartilage and 228,893 units of soft tissue, totaling 374,956 units (Table 2).

**The stress distribution in the models of control group and experimental group.**

At late stage of experiments, the stress distribution in the models of control group and experimental
group was shown in (Fig. 4). The results of FEA well confirmed the conclusions of the biomechanical experiments above. That is, besides the radioulnar proximal and dorsal units, there was no significant stress color difference between the control group and experimental group at the end of experiments. However, the stress color of the remaining 6 units in experimental group were lighter than those in control group, indicating the stresses of the experiment group were less than those of control group. This result further verified the rationality and effectiveness of the biomechanical experiments above.

Discussion

As the aging process of population continues to evolve, the increase in proportion of the elderly has led to a surge in patients with wrist fractures to a certain extent [14–16]. Especially in middle-aged and elderly women, due to the menopause and estrogen loss, the physical function and ability to deal with emergencies has declined inevitably, which brings about the high incidence of wrist fractures [13, 17–19]. In addition, wrist fractures are also common in young and middle-aged people during daily exercise and work [20, 21]. In order to improve the prevention ability of wrist fracture in different ages and update the wrist protectors with poor effectiveness in the current state, this study combined the mechanical experiment of cadaveric wrists with FE wrist simulation analysis to evaluate the effect of the wrist external forces from multiple angles.

During axial-loading experiments, it is found that despite the complex anatomical structure of wrist joint, the external forces were mainly transmitted from navicular and lunar bone down to the radioulnar joints, and then continued to the proximal end of the forearm. In this process, the radioulnar joint was regarded as a composite joint, and the compressive deformation occurred on the radioulnar palmar units, presenting as the compressive stress. The tensile deformation occurred on the radioulnar dorsal units, presenting as tensile stress. In addition, under the normal circumstances, during the deformation of the radioulnar joint under external forces, the palmar and dorsal units with the same axis distance had the same bending moments [22]. However, in this experiment, the axial center was biased to the dorsal units under the impact, and all units had larger palmar bending moments and smaller dorsal bending moments, which explains that the absolute values of the palmar units were greater than those of the stress of dorsal units.
Secondly, according to the comparison of two groups, it is found that wearing wrist protector can effectively reduce the stress on radioulnar distal palmar, radioulnar proximal palmar and radioulnar distal dorsal units, while has no obvious influence on radioulnar proximal dorsal units. In experimental group, the stresses of radioulnar distal palmar and dorsal units were apparently reduced by 44% compared with the control group on average, which was related to the absorption and shunting of the impact load on the wrist protector. Hence, when designing and improving the wrist protector, it is reasonable to place the stress center on the radioulnar distal palmar and dorsal units. Similar to the findings of this experiment, Sun et al. [23] have designed a hip protector and screened 3 volunteers to perform a certain intensity of simulated human side fall test. The results indicated that average peak impact force could reach (1738.88 ± 215.66) N in the group without hip pad, while the average peak impact force in the group with hip pad increased apparently to (1907.44 ± 441.42) N. This result reflected that wearing a hip protector can increase the peak impact force of hip, which could prevent the occurrence of hip fracture to a certain extent.

In addition, certain limitations in this study should be recognized and pointed out. Firstly, the cadaveric specimens lack the natural soft tissue tension and stress protection mechanism of normal human body, which is unable to accurately reflect the true stress and strain of normal human wrist [24–26]. Subsequently, the experimental sample size was only six, which was relatively small. Thirdly, the force mechanism of wrist fracture caused by external force impact is complex. However, this study was limited to the vertical axial-loading of wrist joint, which simplified the actual force of human body. Ultimately, the FEA method also has certain limitations. The FE simulation can only be approximated to the real situation, and the authenticity and validity of results need to be mutually verified with experiments, which leads to the deviation of experimental results to a certain extent [27].

Conclusion
It can be concluded in this study that the stresses of radioulnar palmar units were high and in shape of pressure; while the stress of radioulnar dorsal units were relatively lower and in shape of tension. Under the physiological load, wearing the wrist protector can apparently reduce the stress on
radioulnar distal palmar, radioulnar proximal palmar and radioulnar distal dorsal units, while has no obvious influence on the radioulnar proximal dorsal units. During process of designing and improving wrist protector, it is reasonable to place the stress center on the radioulnar distal palmar and dorsal units.

**Abbreviations**

FEA  
Finite element analysis  

3D  
Three-dimensional;  

FEM  
Finite element model;  

QCT  
Quantitative computed tomography;  

FE  
Finite element;  

BMD  
Bone mineral density;  

CT  
Computed tomography;  

DICOM  
Digital imaging and communications in medicine;  

STL  
STereoLithography.

**Declarations**

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Not applicable.

**Authors’ contributions**

YZ, LX, ZH, XX, SZ and LD participated in the experimental design, data analysis and interpretation. YZ, ZH and LD contributed to conduct the specific experimental procedures. YZ and LD wrote and edited the manuscript. LX, WN and LD contributed to the critical revision of the manuscript. All authors read and approved the final manuscript.
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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
The Ethics Committee of Jiangxi Provincial People’s Hospital Affiliated to Nanchang University approved this study.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Tables

Table 1 The comparison of stress peak and decline between two groups

| Unit                          | The peak of control group/MPa | The peak of experimental group, |
|-------------------------------|-------------------------------|--------------------------------|
| Radial distal palmar unit     | 36.6                          | 20.2                           |
| Ulnar distal palmar unit      | 37.9                          | 24.3                           |
| Radial distal dorsal unit     | 9.4                           | 5.7                            |
| Ulnar distal dorsal unit      | 13.4                          | 4.8                            |
| Radial proximal palmar unit   | 58.5                          | 30.1                           |
| Ulnar proximal palmar unit    | 37.4                          | 24.9                           |
| Radial proximal dorsal unit   | 10.5                          | 10.3                           |
| Ulnar proximal dorsal unit    | 15.3                          | 13.8                           |
Table 2 The number of nodes, unit types and numbers of the FEM

|                  | Bone    | Cancellous bone | Soft tissue | Rigid ground | Sc |
|------------------|---------|-----------------|-------------|--------------|----|
| Unit number      | 136897  | 9166            | 228893      | 2500         | 12 |
| Nodes            | 228808  | 20499           | 356621      | 2603         | 4  |
| Unit Type        | C3D10M  | C3D10M          | C3D10M      | S4R          | C3 |

Figures

(A) The axial-loading experiment on wrist specimens; (B) The establishment of four static strain test units
The comparison of load and stress of each unit in experimental group and control group

The load and stress curves of each unit between the experimental group and control group
Figure 4

The stress distribution in the FEMs of control group and experimental group. (A) Without buffer of wrist protector, the stress color of control group was apparently deeper than the experimental group in radioulnar distal palmar, radioulnar proximal palmar and radioulnar distal dorsal units. (B) Under the protection of wrist protector, the overall stress color of the experimental group was light