Biomechanical Study on the Stress Distribution of the Knee Joint After Distal Femoral Fracture Malunion With Residual Varus-valgus Deformity

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Research article

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Abstract

Background

This study aims to examine the biomechanical influence of residual varus and valgus deformity after malunion of distal femoral fractures on the knee joint.

Methods

We selected 14 adult cadaver specimens to establish the femoral fractures models and subsequently fixed them at neutral position and malunion positions, i.e. at 3°, 7° and 10° at valgus and varus positions, respectively. Ultra-low pressure sensitive film technology was used to quantitatively measure the stress distribution on the medial and lateral plateau of the tibia.

Results

At neutral position, with 400 N vertical load applied, the stress values of the medial and lateral plateau of tibia were 1.162±0.114 MPa and 1.103±0.144 MPa, respectively. Compared with those measured at neutral position, the stress on the medial plateau of the valgus tibia significantly increased, while that on the lateral plateau of the valgus tibia significantly decreased (both $P<0.05$). In contrast, the stress on the lateral plateau of the valgus tibia significantly increased, while that on the medial plateau of the valgus tibia significantly decreased (both $P<0.05$). The medial plateau of tibia demonstrated significantly higher stress values than those on the lateral plateau at neutral position and 3°, 7°, 10° varus deformities, respectively (all $P<0.05$), but showed significantly lower values than the those on the lateral plateau at 3°, 7°, 10° valgus deformities, respectively (all $P<0.05$).

Conclusions

The residual varus and valgus deformities after mulunion of the distal femoral fracture resulted in significant changes of the stress distribution of the knee joint. Anatomical reduction and firm fixation of distal femoral fracture should be as possible to be obtained to avoid possible varus and valgus deformities.

Background

Distal femoral fractures are commonly seen in high-energy trauma, accounting for approximately 1% of all fractures and 4–6% of femoral fractures [1–4]. Currently, distal femoral fractures are predominantly treated by open surgery and are mainly stabilized by distal femur locking plates, compression plates, variable angle locking plates, and less invasive stabilization system (LISS) plates [5–6]. During the past years, continuous improvement of internal fixation devices and surgical techniques has significantly improved the therapeutic effect of femoral fractures [7–8]. However, malunion of the distal femoral fracture and malalignment of lower extremities still occur occasionally [9–10]. It was reported that nonunion rate following surgical management of distal femoral fracture was 0 to 4.2%, although relatively low, if any, that could present a huge challenge to the orthopaedic surgeon [11–13]. Phillips et al. [14] showed that the incidence of mildly symptomatic arthritis of the affected knee joint after femoral fracture malunion and malalignment was significantly higher than that of the healthy side, and symptomatic traumatic arthritis (TA) of the knee joint could occur at long-term follow-up [15]. Nonunion or malunion of fractures can disrupt the normal joint movement, causing non-physiological stress change and secondary knee joint pain [16–17].

A variety of techniques such as imaging, biomechanics and finite element analysis have been introduced and applied to investigate the pathogenesis of traumatic arthritis [18–20]. Palmu et al.[21]followed up 52 femoral fracture patients over 10 years old, and found residual deformity was positively correlated with knee arthritis. They believed that although children have a high potential for remodeling, substantial angular deformities should not be tolerated in the treatment of fractures. Childhood femoral fracture may lead to premature knee-joint arthritis. Therefore, improved understanding of biomechanical influence of femoral varus or valgus malunions on stress change of the knee joint will help develop better treatment algorithms.

Given that, we conducted this this biomechanical study, using the cadaver specimens of middle and lower femoral fractures, with first aim to investigate the changes of the stress on the medial and lateral tibial plateaus after femoral fracture malunion in comparison with the normal stress values, and second aim to identify the relationship between the stress on the plateaus and the residual varus or valgus deformity.

Methods

This study has been approved by the Institutional Review Board of the third Hospital of Hebei Medical University, before it was commenced. This study conformed to the provisions of the Declaration of Helsinki. The flowchart of this biomechanical test was summarized in Fig. 1.

Fourteen formalin-soaked specimens were from cadavers donated by adult men, provided by the department of human anatomy, Hebei Medical University. Digital radiography was used to exclude osteoporosis, pathological or anatomical deformities, irregular joint surfaces or other imaging abnormalities. The ligaments and tendons around the knee joint and the joint capsule should be intact to be included. Muscle tissues of each specimen were then removed and the upper part of the femur and the distal part of the tibial and fibula were resected, leaving the sample of 25cm long for the index test. The specimens were maintained in spare packages to prevent dehydration, and stored at -20°C.

Before the experiment, the cadaver specimens were thawed at 20–25℃ for 12 hours. The middle and lower femoral fracture models were established and fixed with locking plates and screws to simulate the various residual deformities (valgus, 3 degrees, 7 degrees, 10 degrees; neutral, 0 degrees; and varus, 3 degrees, 7 degrees, 10 degrees). A horizontal incision of about 3-4cm in length was made at the level of the joint space on both sides. The subcutaneous fat was separated, and the bursa was cut to expose the joint space. The anterior and posterior cruciate ligaments and the medial and lateral meniscus were retained to avoid them affecting the normal distribution of contact stress in the knee joint.

The specimen was first established and the femoral end was vertically fixed on the self-made forceps with denture base resin and solution (type II self-fixing powder and tray water). After the tooth powder and tray water have solidified, the tibia end of the specimen was fixed in the same way. Both ends of the clamp were then assembled on a biomechanical testing machine (Electroforce 3520-AT, Bose Company, USA) to adjust the fixation position of the femur and tibia stump so that the mechanical shaft of the lower limb was close to its natural standing position (Fig. 2).

The contact pressure of the medial and lateral plateaus of the tibia was measured with a 0.5 to 2.5 Mpa ultra-low pressure sensitive film. The pressure sensitive film was trimmed into a appropriate shape and sealed in a polyethylene film bag. The total thickness of the pressure sensitive film and the polyethylene film bag was controlled within 250 μm. The fixed specimen was loaded under 200 N tension, the knee was stretched, and the pressure sensitive films were carefully placed under the knee meniscus of the knee through the medial and lateral incisions respectively (Fig. 3). The incisions were sutured tightly to close the joint capsule. After stabilization, the sample was pressurized to 200N at a rate of 10 N/s to eliminate creep. A vertical load was applied on the specimen at a rate of 10 N/s up to 400 N and keep that for 2 min. Then, the pressure sensitive film was carefully removed from the knee joint. As the pressure-sensitive film material change with the humidity and temperature, the color development is also different. Therefore, humidifiers and air conditioners are used in this experiment to keep the indoor temperature at 25 ~ 30℃ and the relative humidity at 35% RH ~ 80% RH[22].

FPD-305E densitometer and FPD-306E pressure transducer (Fuji Company, Japan) were used to read the stress values of the ultra-low pressure sensitive films. The contact area of each pressure sensitive film was divided into four quadrants (front outer, front inner, rear inner and rear outer). Five points were selected in each quadrant to read the stress value. A total of 20 values were recorded for each film and an average was calculated for the final analysis.

Statistical analysis

SPSS 21.0 (SPSS, Chicago, IL, USA) was used for all statistical analyses. Shapiro-Wilk test was used to examine the normality of the continuous variables (e.g. stress values) and the Levene test was used to examine the variance equality. Normally distributed data were recorded as mean ± standard deviation. The analysis of non-parametric methods was used to compare the stress values on the medial or lateral plateau at different angles of femur varus or valgus deformity under vertical load. The Student-Newman-Keuls (SNK) test was applied to make pairwise comparisons between the multiple sample measurements. Differences in the stress data between medial and lateral plateaus were tested using the paired samples *t* test. A *P*-value less than 0.05 was considered significance.

Results

The stress values on the medial plateau of tibia measured at different varus and valgus deformity under 400 N vertical load are summarized in Table 1. When the valgus deformity was 10 degrees, 7 degrees, and 3 degrees, the pressure of the medial platform was 0.743 ± 0.092 MPa, 0.890 ± 0.137 Mpa, 1.007 ± 0.127 Mpa, respectively. When the varus deformity was 3 degrees, 7 degrees, and 10 degrees, the pressure of the medial platform was 1.277 ± 0.121 MPa, 1.447 ± 0.145 Mpa, 1.652 ± 0.153 Mpa, respectively ($P < 0.001$). Our results revealed statistically significant differences in the stress values on the medial plateau among different varus and valgus deformities (including the neutral position) ($P < 0.001$). SNK test revealed statistically significant differences in the stress values on the medial plateau between pairwise comparisons among 10 degrees, 7 degrees and 3 degrees varus deformities, neutral position (0 degree) and 3 degrees, 7 degrees, 10 degrees valgus deformities. The stress values on the medial plateau measured at 3 degrees, 7 degrees and 10 degrees varus deformities were significantly higher than that measured at neutral position ($P = 0.019$, $P < 0.001$, $P < 0.001$, respectively). On the contrary, the stress values on the medial plateau measured at 3 degrees, 7 degrees and 10 degrees valgus deformities were significantly lower than that measured at neutral position ($P = 0.002$, $P < 0.001$, $P < 0.001$, respectively). From 10 degrees of valgus deformity to 10 degrees of varus deformity, the stress values on the medial plateau of the tibia increased proportionably (Fig. 4, Fig. 5).

Table 1
The stress values (Mpa) on the medial and lateral plateau of femur measured on the models of different varus and valgus deformity under 400N vertical load

Deformity Angle	**Medial plateau (n = 14)**	**Lateral plateau (n = 14)**	**statistic**	**P-value**
Valgus 10 degrees	0.743 ± 0.092	1.567 ± 0.158	16.79	< 0.001[c]
Valgus 7 degrees	0.890 ± 0.137	1.367 ± 0.101	10.42	< 0.001[c]
Valgus 3 degrees	1.007 ± 0.127	1.244 ± 0.136	4.767	< 0.001[c]
Neutral position (0 degree)	1.162 ± 0.114	1.103 ± 0.144	1.741	0.094[c]
Varus 3 degrees	1.277 ± 0.121	1.059 ± 0.239	-3.048	0.005[c]
Varus 7 degrees	1.447 ± 0.145	0.898 ± 0.164	-9.374	< 0.001[c]
Varus 10 degrees	1.652 ± 0.153	0.809 ± 0.118	-16.31	< 0.001[c]
statistic	70.418	83.903		
P-value	< 0.001[a]	< 0.001[b]		

Note: a: Comparison of differences in the stress data on the medial plateau of femur at different deformed angle. **b**: Comparison of differences in the stress data on the lateral plateau of femur at different deformed angle. **c**: Comparison of differences in the stress data between medial and lateral plateau of femur at different deformed angles.

The stress values on the lateral plateau of tibia measured at different varus and valgus deformity under 400 N vertical load are recorded and summarized (Table 1). When the valgus deformity was 10 degrees, 7 degrees, and 3 degrees, the pressure of the lateral platform was 1.567 ± 0.158 MPa, 1.367 ± 0.101 Mpa, 1.244 ± 0.136 Mpa, respectively. When the varus deformity was 3 degrees, 7 degrees, and 10 degrees, the pressure of the lateral platform was 1.059 ± 0.239 MPa, 0.898 ± 0.164 Mpa, 0.809 ± 0.118 Mpa, respectively ($P < 0.001$). Our results revealed statistically significant differences in the stress values on the lateral plateau among different varus and valgus deformities (including the neutral position) ($P < 0.001$). There were statistically significant differences between pairwise comparisons among 10 degrees, 7 degrees and 3 degrees varus deformities, neutral position and 3 degrees, 7 degrees, 10 degrees valgus deformities according to SNK test. The stress values on the lateral plateau measured at 3 degrees, 7 degrees and 10 degrees valgus deformities were significantly higher than that measured at neutral position ($P = 0.020$, $P < 0.001$, $P < 0.001$, respectively). Conversely, the stress values on the lateral plateau measured at 3 degrees, 7 degrees and 10 degrees varus deformities were significantly lower than that measured at neutral position ($P = 0.045$, $P < 0.001$, $P < 0.001$, respectively). From 10 degrees of valgus deformity to 10 degrees of varus deformity, the stress values on the lateral plateau of the tibia decreased proportionably (Fig. 6, Fig. 7).

Under 400 N vertical load, the stress on the medial plateau of the tibia was 1.162 ± 0.114 MPa at the neutral position, and the value of 1.103 ± 0.144 MPa on the lateral plateau of the tibia. However, there was no statistical difference between the medial plateau and the lateral plateau in the neutral position($t = 1.741$, $P = 0.094$). Under 400 N vertical load, the stress values on the medial plateau of tibia were significantly higher than the corresponding values on the lateral plateau at 3 degrees, 7 degrees, 10 degrees varus deformity positions, respectively (all $P < 0.001$), and significantly lower than the corresponding values on the lateral plateau at 3 degrees, 7 degrees, 10 degrees valgus deformity positions, respectively (all $P < 0.001$).

Discussion

In our study, we found that the stress at the knee joint at the 7-degree and 10-degree valgus deformity of the lateral knee joint is significantly less than the stress at the corresponding deformity angle of the medial platform (both $P < 0.05$), but not significant when the deformity is 3 degrees. We also found that as the deformity angle increases, the increase in the medial platform is more prominent than that of the lateral platform. Our research also showed that the stress on the lateral plateau is significantly higher at valgus deformities than the stress on the lateral plateau measured at neutral position as well as the corresponding data measured on the medial plateau.

Femoral fractures are common injuries in traumatic orthopedics. Open or closed reduction and internal fixation is the standard treatment options for displaced femoral fractures. However, during the closed reduction and intramedullary nailing, the fractures can not be always reduced anatomically, and various residual fracture deformity and complications may occur. Winquist et al.[23] reported that 520 cases of femoral fractures were treated with intramedullary nail, and 8% of the patients had external rotation deformity of more than 10 degrees. Braten et al.[24] measured the anteversion angle of bilateral femur in 110 patients with interlocking intramedullary nails for unilateral femoral fractures, and 21 (19%) of them had rotation deformity. The change in the mechanical axis of the lower limbs after fracture malunion can lead to the changes in the tension of the ligaments and joint capsules, and patella malacia in a long time. If not corrected in time, it can affect the biomechanical characteristics of knee and ankle joints and ultimately result in TA, following impaired knee function. Maquet[25] also believed that the uneven distribution of stress on the joint surface and the excessive stress concentration is one of the important causes of traumatic arthritis of the knee. Therefore, malunion and malalignment of the lower limb is an important contributing factor to traumatic arthritis of knee joint.

When malunion and malalignment occurs after femoral fracture, the contact characteristics of knee joint will be altered. In patients with knee varus deformity, the mechanical axis of the lower limbs inclines from the center of the knee to the medial plateau, which causes the stress distribution within the joint to be redistributed, so that the load is mainly concentrated on the medial plateau of the knee. Our findings reveal that the stress on the medial plateau of tibia is significantly higher at varus deformities when compared with those measured at the neutral position, and significantly higher than the corresponding stress values on the lateral plateau. When the knee is at valgus position, the mechanical axis is offset laterally and the lateral compartment load increases. Studies have shown that the high stress load on joints can increase the damage pressure of articular cartilage, accelerate the wear of articular cartilage, and is an important factor leading to cartilage degradation[26]. Therefore, in order to reduce the risk of long-term arthritis in patients, orthopedic surgeons should reduce the fractures anatomically to avoid the malalignment and malunion of lower limbs fractures[27].

Varus or valgus deformity around the knee can cause knee progressive degeneration. Brouwer et al.[28] analyzed the data of 1501 patients (2664 lateral knees), and found that there was a significant correlation between malalignment of lower extremities and the occurrence and progression of arthritis, especially in overweight patients. However, Some studies have found that the deformity of varus or valgus within 5 degrees can be accepted after treatment. Brown and Sarmiento et al.[29] found 5 degrees of varus or valgus at any level to be cosmetically and functionally acceptable. When Bryant [30] studied the biomechanical effect of residual deformity after total knee arthroplasty, they found that the deformity angle of 5 degrees had no effect on the patellofemoral contact characteristics. Our research showed that the stress change of the knee joint was not remarkable within the deformity angle of 3 degrees, but highly remarkable at 7 or 10 degrees of valgus or varus deformity. Therefore, our data supported postoperative corrective deformity within 3 degrees to maintain necessary biomechanical balance of knee joint. It is a pity that we had no data on the 5 degrees of deformity. In the future, clinical cohort study with long-term follow-up data are needed to ascertain our finding, to continue investigation of the relationship between deformity extent and the responsive traumatic arthritis, and to define the more reasonable and clinically applicable cut-off value for deformity.

Alignment of the lower limb is a prerequisite for ensuring a reasonable distribution of joint stress. Under normal conditions, the lower limb mechanical axis is from the center of the hip joint to the center of the ankle joint, passing through the center of the knee joint, so that the load and stress on the knee joint can be reasonably dispersed [31]. However, in a human gait, the center of body gravity will move to the contralateral side during the stance phase, with resultant increase of compressive force in the medial compartment of knee. Therefore, it is likely that this imbalanced stress change between medial and lateral platforms cause the final skewed stress distribution and the secondary osteoarthritis. Moreover, during this process, a varus deformity plays a more critical role, compared to valgus deformity. Therefore, in orthopaedic practice, varus deformity should be corrected or avoided as a priority, with aims to prevent the occurrence of potential osteoarthritis.

In biomechanics research, the contact position, contact area and contact stress between joint surfaces are often measured. At present, there are a variety of experimental measurement methods for joints, including 3D photoelastic measurement, pressure sensing and finite element analysis[32–33], but these methods have a large error in the measurement of joint stress and the operation method is relatively complex. Therefore, we choose pressure-sensitive film technology, which can not only directly measure the pressure value, but also can measure the contact area, intuitively see the distribution of pressure, has obvious advantages.

This study has some limitations. Firstly, the sample size is small due to the limited source of specimens, which will reduce the credibility of experimental data (type II error). Secondly, this study is based on cadaver specimens and can not take the action of muscles into consideration. Thirdly, dynamic load on the knee joint was not taken and the current model can not simulate the stress distribution during knee motion. The last, We excluded specimens of osteoporosis, but in clinical practice, distal femoral fractures are very common in older adults with osteoporosis, which may affect the external validity of clinical work. However, the current findings guarantee further biomechanical studies on the stress distribution of knee joint under dynamic load, clinical studies on the quantitative relationship between residual malunion and traumatic arthritis, and the endeavor to reduce complex fractures anatomically in closed fashion or minimally invasive way.

Conclusions

In conclusion, femoral fracture malunion with residual varus or valgus deformity can lead to significant changes in the stress distribution and contact characteristics of the knee joint. Therefore, orthopedic surgeons should reduce the fractures anatomically to avoid malunion of the fractures and malalignment of the affected lower extremities, accordingly improving the functional recovery and reducing the risk of traumatic arthritis in the long term.

Abbreviations

LISS: Less invasive stabilization system;

TA: Traumatic arthritis;

SNK: Student-Newman-Keuls;

Declarations

Ethical approval

This study has been reviewed and approved by the Institutional Review Board (IRB) of the Third Hospital of Hebei Medical University and that it conformed to the provisions of the Declaration of Helsinki

Availability of data and materials

Please contact author for data requests.

Competing interests

The authors declare that they have no competing interests.

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Author contribution

WC, Zhu YB and QZ designed the study and searched relevant studies. HD, Chang WL and NW analyzed and interpreted the data. ML, PH and Ma LJ wrote the manuscript and contributed equally to this work. QZ and WC contributed most in the revision of this manuscript and approved the final version of the manuscript.

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Conflict of interest statement:

All authors have read and contributed to the submitted manuscript and have no conflict of interest to declare. This study was approved by the Institutional Review Board of The Third Hospital of Hebei Medical University.

Compliance with ethical standards

This study conforms to the provisions of the Declaration of Helsinki and has been reviewed and approved by the Institutional Review Board of The Third Hospital of Hebei Medical University.

Conflicts of Interest

The authors declare that they have no conflict of interest.

References

1. Court-Brown CM, Caesar B. Epidemiology of adult fractures: a review. Injury. 2006;37:691–7.
2. Kolmert L, Wulff K. Epidemiology and treatment of distal femoral fractures in adults. Acta Orthop Scand. 1982;53(6):957–62.
3. Phelps EE, Tutton E, Griffin X, Baird J. A qualitative study of patients' experience of recovery after a distal femoral fracture. Injury. 2019;50(10):1750–55.
4. Ma CH, Chiu YC, Wu CH, et al. Plate-on-plate technique for treating peri-implant fractures of distal femoral locking plate: a retrospective study of 11 patients. Arch Orthop Trauma Surg. 2019;139(9):1245–51.
5. Tank JC, Schneider PS, Davis E, et al. Early mechanical failures of the synthes variable angle locking distal femur plate. J Orthop Trauma. 2016;30(1):e7–11.
6. McDonald TC, Lambert JJ, Hulick RM, et al. Treatment of distal femur fractures with the DePuy-Synthes variable angle locking compression plate. J Orthop Trauma. 2019;33(9):432–37.
7. Cui S, Bledsoe JG, Israel H, Watson JT, Cannada LK. Locked plating of comminuted distal femur fractures: does unlocked screw placement affect stability and failure? J Orthop Trauma. 2014;28(2):90–6.
8. Maimaitiyiming A, Amat A, Rehei A, Tusongjiang M, Li C. Treatment of the femoral shaft nonunion with double plate fixation and bone grafting: A case series of 14 patients. Injury. 2015;46(6):1102–07.
9. Krettek C, Miclau T, Blauth M, Lindsey RW, Donow C, Tscherne H. Recurrent rotational deformity of the femur after static locking of intramedullary nails: case reports. J Bone Joint Surg Br. 1997;79(1):4–8.
10. Goodier WD, Calder PR. External fixation for the correction of adult post-traumatic deformities. Injury. 2019;50:36–44.
11. Ricci WM, Streubel PN, Morshed S, Collinge CA, Nork SE, Gardner MJ. Risk factors for failure of locked plate fixation of distal femur fractures: an analysis of 335 cases. J Orthop Trauma. 2014;28(2):83–9.
12. Gwathmey FW Jr, Jones-Quaidoo SM, Kahler D, Hurwitz S, Cui Q. Distal femoral fractures: current concepts. J Am Acad Orthop Surg. 2010;18(10):597–607.
13. Siliski JM, Mahring M, Hofer HP. Supracondylar-intercondylar fractures of the femur. Treatment by internal fixation. J Bone Joint Surg Am. 1989;71(1):95–104.

14. Phillips JR, Trezies AJ, Davis TR. Long-term follow-up of femoral shaft fracture: Relevance of malunion and malalignment for the development of knee arthritis. Injury. 2011;42(2):156–61.
15. Wang JW, Chen WS, Lin PC, Hsu CS, Wang CJ. Total knee replacement with intra-articular resection of bone after malunion of a femoral fracture: can sagittal angulation be corrected? J Bone Joint Surg Br. 2010;92(10):1392–6.
16. Svoboda SJ, McHale CK, Belkoff SM, Cohen KS, Klemme WR. The Effects of Tibial Malrotation on the Biomechanics of the Tibiotalar Joint. Foot Ankle Int. 2002;23(2):102–6.
17. Wang XS, Zhou YX, Shao HY, Yang DJ, Huang Y, Duan FF. Total Knee Arthroplasty in Patients with Prior Femoral and Tibial Fractures: Outcomes and Risk Factors for Surgical Site Complications and Reoperations. Orthop Surg. 2020;12(1):210–7.
18. Sarai T, Inoue T, Fujiwara K, Kuramoto K. Dynamic finite element analysis of impulsive stress waves propagating from distal end of femur. Acta Med Okayama. 2012;66(5):409–15.
19. McErlain DD, Milner JS, Ivanov TG, Jencikova-Celerin L, Pollmann SI, Holdsworth DW. Subchondral cysts create increased intra-osseous stress in early knee OA: A finite element analysis using simulated lesions. Bone. 2011;48(3):639–46.
20. Tsui CP, Tang CY, Leung CP, et al. Active finite element analysis of skeletal muscle-tendon complex during isometric, shortening and lengthening contraction. Biomed Mater Eng. 2004;14(3):271–9.
21. Palmu SA, Lohman M, Paukku RT, Peltonen JI, Nietosvaara Y. Childhood femoral fracture can lead to premature knee-joint arthritis. 21-year follow-up results: a retrospective study. Acta Orthop. 2013;84(1):71–5.
22. Li M, Chang HR, Wei N, et al. Biomechanical Study on the Stress Distribution of the Knee Joint After Tibial Fracture Malunion with Residual Varus-Valgus Deformity. Orthop Surg. 2020;12(3):983–9.
23. Winquist RA, Hansen ST Jr, Clawson DK. Closed intramedullary nailing of femoral fractures. A report of five hundred and twenty cases. J Bone Joint Surg Am. 1984;66(4):529–39.
24. Braten M, Terjesen T, Rossvoll I. Torsional deformity after intramedullary nailing of femoral shaft fractures. Measurement of anteversion angles in 110 patients. J Bone Joint Surg Br. 1993;75(5):799–803.
25. Maquet PGJ. Biomechanics of the knee. With application to the pathogenesis and the surgical treatment of osteoarthritis. Brelin Springer- Verlag. 1984: 165.
26. Hamerman D. The biology of osteoarthritis. N Engl J Med. 1989;18:1322–30.
27. Sanders R, Anglen JO, Mark JB. Oblique osteotomy for the correction of tibial malunion. J Bone Joint Surg Am. 1995;77(2):240–6.
28. Brouwer GM, van Tol AW, Bergink AP, et al. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis Rheum. 2007;56(4):1204–11.
29. Mckellop HA, Sigholm G, Redfern FC, Doyle B, Sarmiento A, Luck Sr JV. The effect of simulated fracture-angulations of the tibia on cartilage pressures in the knee joint. J Bone Joint Surg Am.

1991;73(9):1382–91.

30. Bryant BJ, Tilan JU, McGarry MH, Takenaka N, Kim WC, Lee TQ. The biomechanical effect of increased valgus on total knee arthroplasty: a cadaveric study. J Arthroplasty. 2014;29(4):722–6.
31. Zhu Z, Wang L, Li D, et al. Motion analysis on patients with knee osteoarthritis merged with varus deformity. J Biomed Eng. 2018;35(1):38–44.
32. Giri D, Jouaneh M, Stucker B. Error sources in a 3-D reverse engineering process. Precis Eng. 2004;28:242–51.
33. Li L, Yang L, Zhang K, Zhu L, Wang X, Jiang Q. Three-dimensional finite-element analysis of aggravating medial meniscus tears on knee osteoarthritis. J Orthop Translat. 2019;20:47–55.

Figures

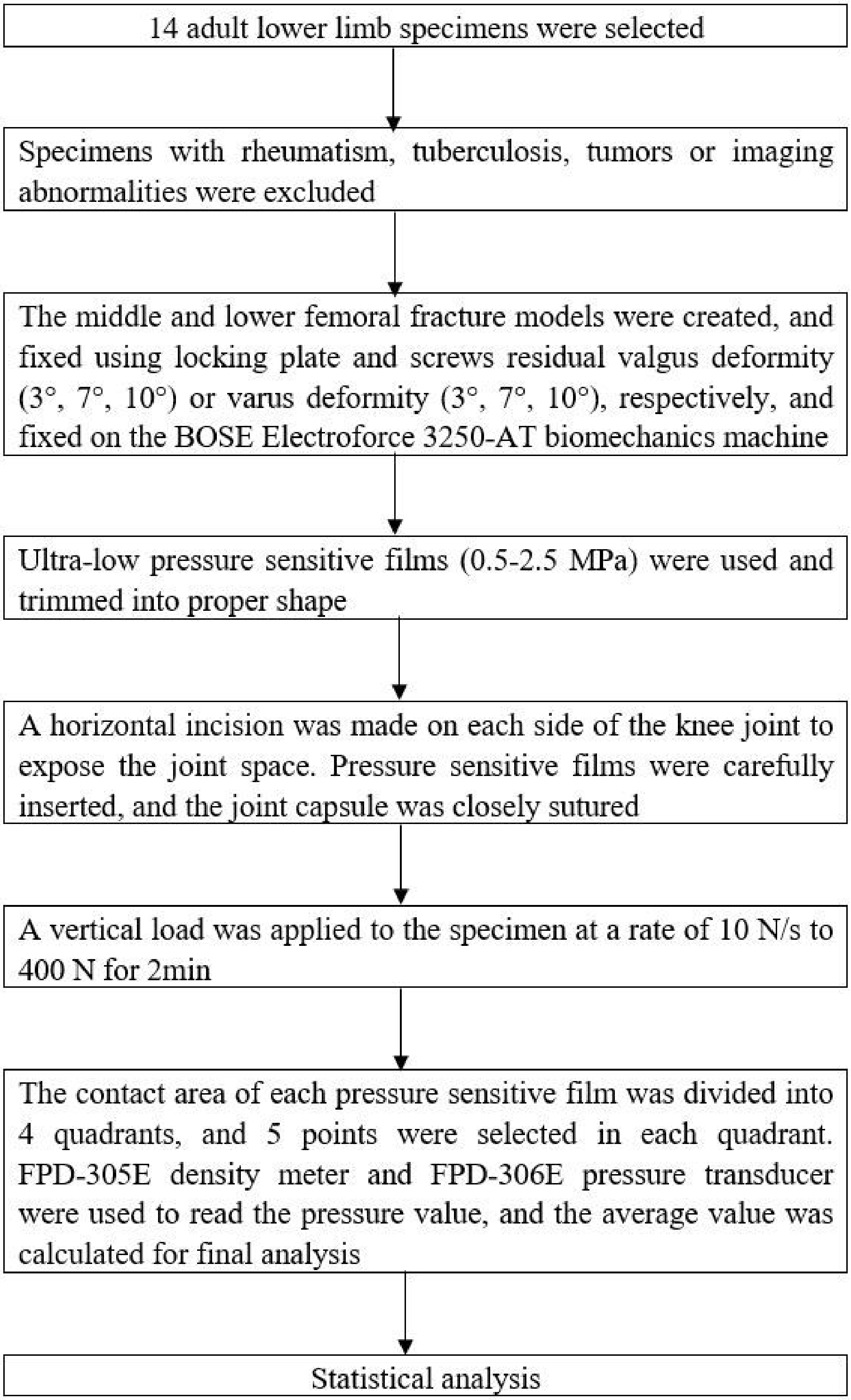

Figure 1

The experimental flowchart of the biomechanical study on the stress distribution of knee joint after malunion of femoral fracture.

Figure 2

The specimens were assembled to the BOSE Electroforce 3520-AT biomechanical testing machine.

Figure 3

The pressure sensitive films were carefully placed under the meniscus.

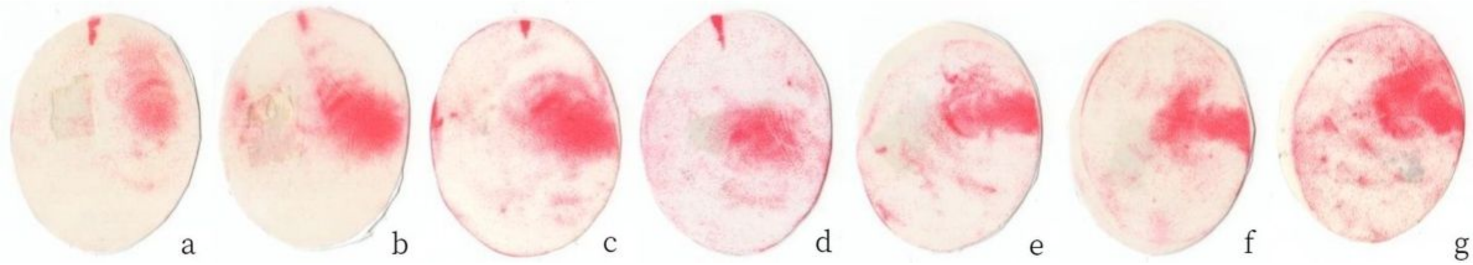

Figure 4

Color changes of the ultra-low pressure sensitive films on the medial plateau at different angles of varus and valgus deformities of the femur. a, valgus 10 degrees; b, valgus 7 degrees; c, valgus 3 degrees; d, neutral position 0 degree; e, varus 3 degrees; f, varus 7 degrees; g, varus 10 degrees.

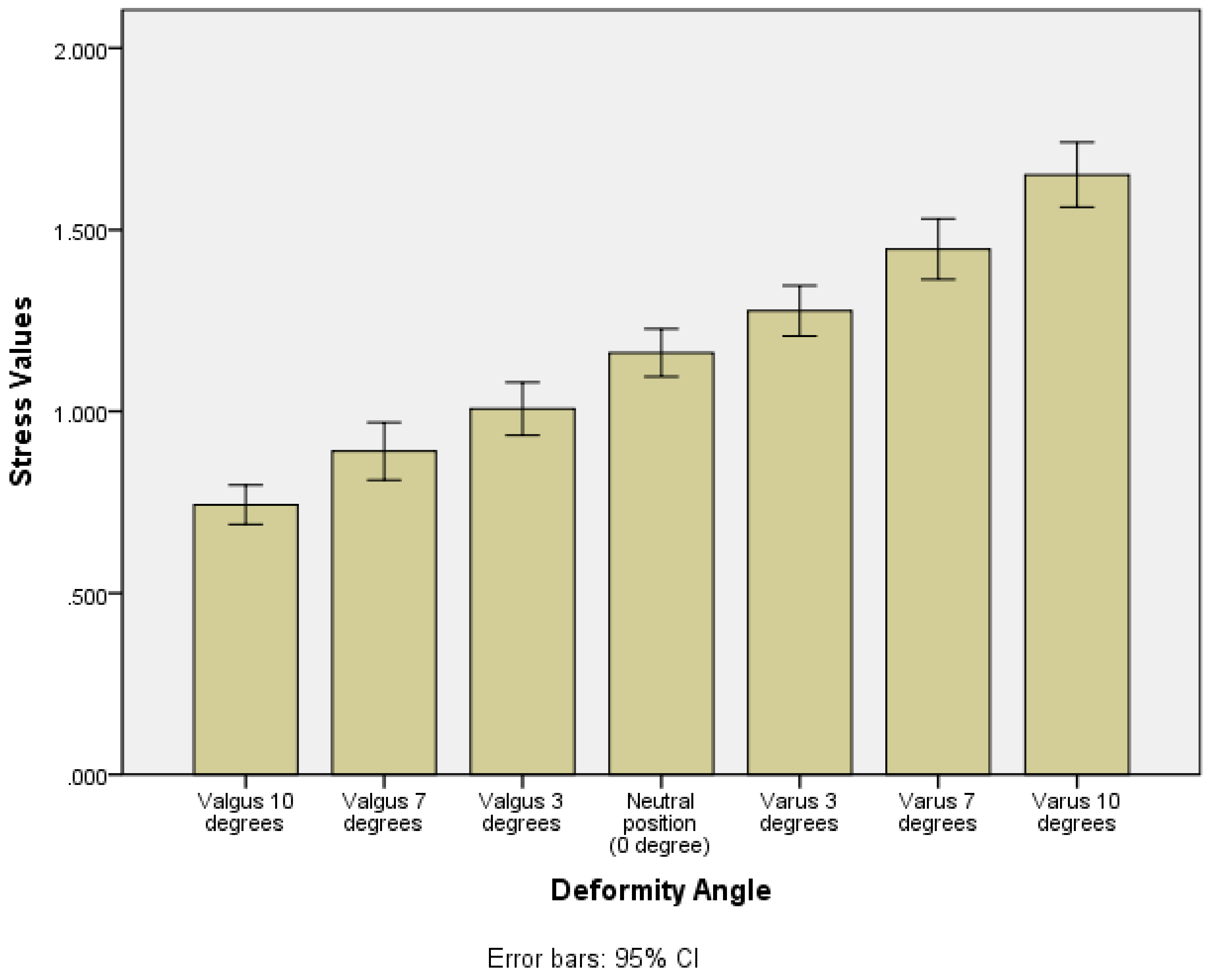

Figure 5

From 10 degrees of valgus deformity to 10 degrees of varus deformity, the stress values on the medial plateau of the tibia increased proportionably.

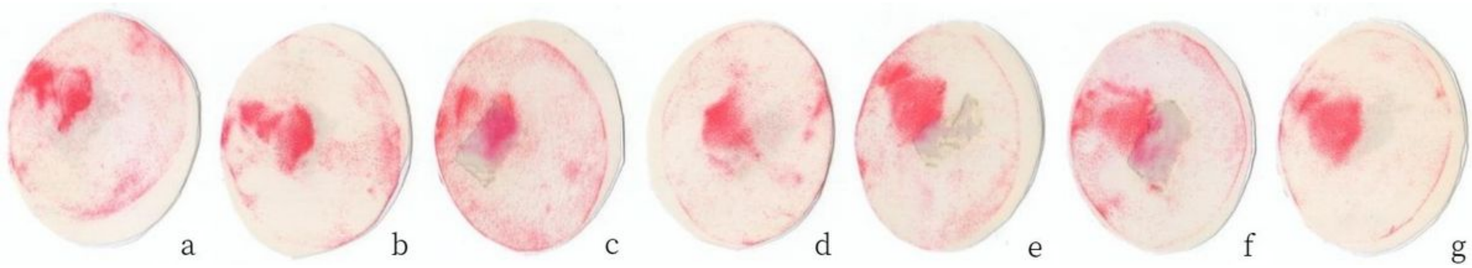

Figure 6

Color changes of the ultra-low pressure sensitive films on the lateral plateau at different angles of varus and valgus deformities of the femur. a, valgus 10 degrees; b, valgus 7 degrees; c, valgus 3 degrees; d, neutral position 0 degree; e, varus 3 degrees; f, varus 7 degrees; g, varus 10 degrees.

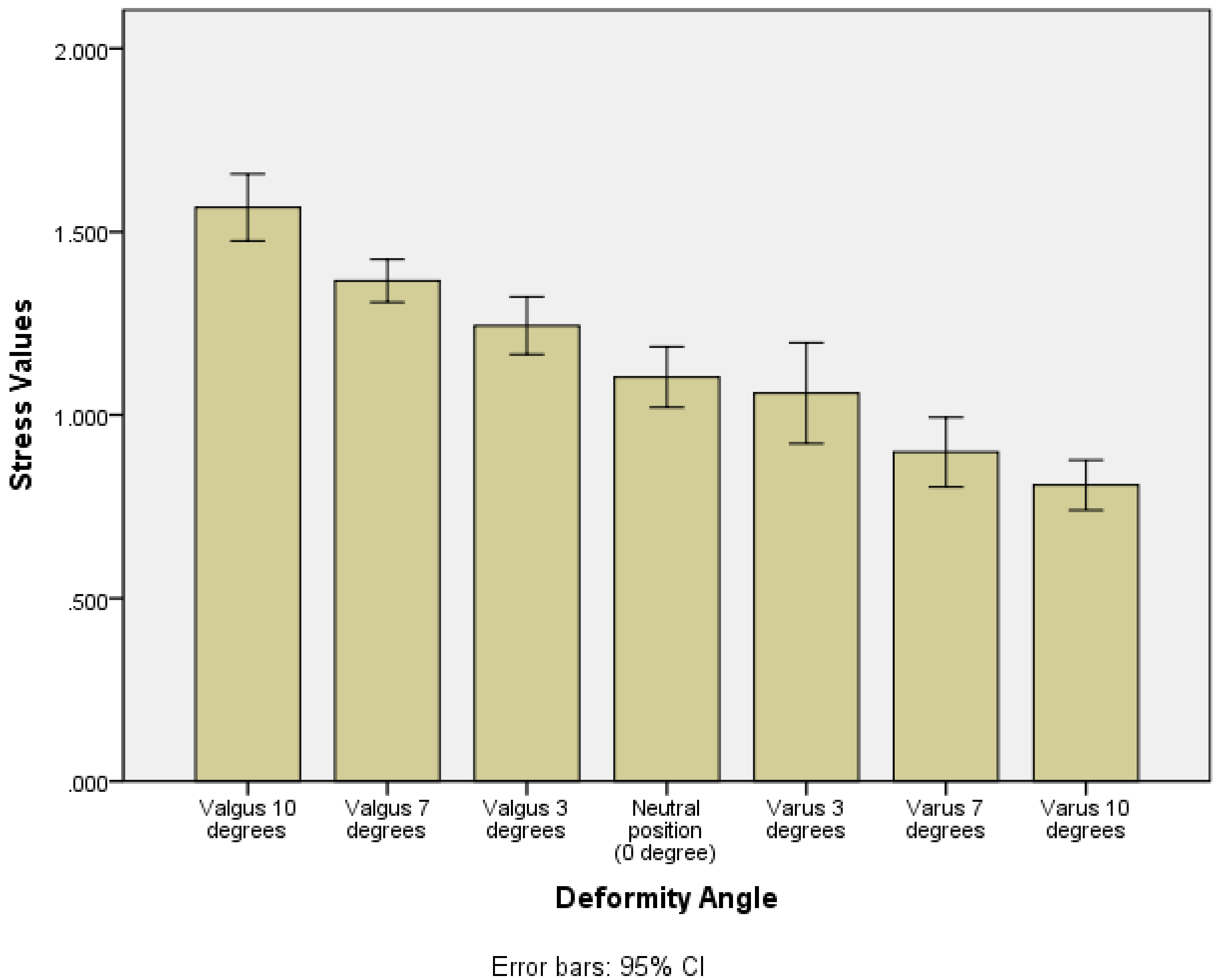

Figure 7

From 10 degrees of valgus deformity to 10 degrees of varus deformity, the stress values on the lateral plateau of the tibia decreased proportionably.