

Biomechanical study on the stress distribution of the knee joint after residual rotation deformity of tibial fracture

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Research article

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Abstract

Objectives

To investigate the effect of residual rotation deformity on the stress distribution of the knee joint after surgery to treat middle and upper tibial fractures.

Methods

Fourteen adult cadaver specimens that were preserved with formalin were included, and the tibiae were randomly positioned at 0 degree, 5 degrees, 10 degrees, and 15 degrees from the line of force of the lower limb. These positions modeled deformities of 5 degrees, 10 degrees, and 15 degrees from the line of force. Low-pressure pressure-sensitive film technology measured the stress distribution of the knee joint under different degrees of rotation deformity.

Results

Under a vertical load of 400 N, the difference between the medial and lateral stress of the knee joint was significantly different between the different tibia deformities ($P < 0.05$), and the medial stress of the knee joint was higher than the lateral stress. The current study showed that there were statistically significant differences in the medial stress on the knee joint at all angles (including the neutral position of 0 degrees) ($F = 89.753$, $P < 0.001$). There was a statistically significant difference in the lateral stresses of the knee joint between different rotation deformities (including the neutral position of 0 degrees) ($F = 102.998$, $P < 0.001$).

Conclusions

Residual rotation deformity after fracture of middle and upper tibia can lead to poor alignment of lower limb force and change of articular contact characteristics of knee joint, especially external rotation of tibia. Therefore, orthopedic surgeons should correct the malalignment of lower limbs to the greatest extent and reduce the rotation deformity as far as possible.

Introduction

The incidence of proximal tibial fractures due to high-energy trauma increased gradually, accounting for 5%-11% of all tibial fractures^[1-2], and often accompanied by different degrees of soft tissue, blood vessel and nerve injuries. Surgical treatment of these traumas remains a major clinical challenge^[3], and its final outcome is affected by many variables, including the mechanism of the injury, the severity of the initial injury, etc. Continuous improvement of internal fixation devices and surgical techniques has improved the therapeutic effect of such fractures^[4-6]. However, the incidence of malunion of the tibial shaft and poor mechanical lower extremity remains underestimated^[6, 7]. Kyro et al^[8] reported a rotational deformity in 6% of patients. Puloski et al^[9] used CT to measure the rotational deformity of the tibial shaft fracture and

found the 22% (5/22) incidence rate of significant rotational deformity (> 10 degree). In the study of Milner^[10], approximately 30% of the tibial shaft fracture sustainers had an angular deformity of more than 5 degrees in the coronal plane.

The relationship between tibial fractures and poor line of force and osteoarthritis has also been extensively studied. Studies show that lower limb deformity is an important factor for knee and ankle joints to develop traumatic arthritis (TA). In order to further explore the pathogenesis of osteoarthritis and the effects of different interventions, some scholars have done a lot of work using techniques such as imaging, biomechanics and finite element analysis^[11-13]. Kettelkamp et al.^[14] conducted a long-term follow-up study on patients with femoral shaft fractures, and found that knee fracture TA can occur after 32 years due to deformity and long-term weight bearing, and local symptoms are obvious. Patients with previous knee fractures who have severe arthritis and need total knee arthroplasty are not infrequent. Accordingly, improved biomechanical understanding of tibial rotational malunions will help to formulate improved treatment modalities.

In this study, cadaver models of middle and upper tibial fractures were established. The degree of deformity was measured under different rotational deformities. Pressure-sensitive films were used to quantify the impact of different reduction masses on the weight and stress distribution of the medial and lateral space of the knee joint. Through a comprehensive analysis of the above studies, we hope to clarify the quantitative relationship between residual rotational deformity and knee joint stress changes after fracture healing in the middle and upper tibia.

Materials And Methods

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.

1. Specimen Preparation

Fourteen adult cadaver specimens that were preserved with formalin were included; samples from those who had rheumatism, tuberculosis, tumors, osteoporosis and other pathological or anatomical changes were excluded. All samples were required to be without visible deformities of the knee joint; have articular cartilage integrity; have unrestricted knee flexion and extension; have retained the joint capsule, ligaments, patella retinacular tissue, femoral head four tendon and patellar tendon; and have all muscular tissue removed. Before the experiment, all the structures of each specimen, especially the knee joint, were examined by X-ray to determine the uniformity of the knee joint, confirm that there were no imaging abnormalities, and confirm that there was a smooth joint surface. Then, the upper part of the femur was dissected, and the soft tissue was removed with a scalpel. The femur was generally kept at 25 cm, and the tibia and fibula were kept at 25 cm. The specimens were maintained in standby packages to prevent dehydration, kept at -20 °C for cryopreservation.

2. experimental method

Thawed the cadaver specimens at room temperature 12 hours before the experiment began. Then, middle and upper tibial fracture models were made, along with the internal rotation deformity (5 degrees, 10 degrees, 15 degrees) and the external rotation deformity (5 degrees, 10 degrees, 15degrees). Finally, along the lower edge of the femur, horizontal incisions of approximately 3–4 cm were made into the ligaments on both sides of the patellofemoral ligament and at the level of the joint gap. The subcutaneous fat was separated, the bursa was cut, and the joint space was exposed. The anterior and posterior cruciate ligaments and the medial and lateral menisci were preserved so as not to affect the normal distribution of contact stress in the joint.

The specimen was then erected and the proximal end of the femur was embedded with denture base resin (type II self-setting dental powder) and denture base resin solution (type II self-setting dental tray water), and fixed perpendicularly to the homemade iron groove, as illustrated in Fig. 1. After the dental tray powder has solidified, fix the tibial end of the same specimen in the same way. Then attach the two-end clamp to the BOSE Electroforce 3520-AT biomechanical testing machine (Fig. 2), adjust the fixed position of the femoral and tibia stumps, so that the lower limb mechanical axis is close to the position when standing naturally. Then, an ultra-low-sensitivity pressure-sensitive tablet (0.5 to 2.5 MPa) was used to measure the contact pressure. The pressure-sensitive sheet is trimmed into a suitable shape and sealed in a polyethylene film bag. The total thickness of the pressure-sensitive sheet and the polyethylene film bag is controlled to 250 μm . Carefully place the pressure-sensitive film under the knee meniscus^[13] separately at the medial and lateral knee incisions, while trying to keep the depth and position of each insertion, and tightly sutured to the open joint capsule is shown in Fig. 2. Finally ,the specimen was pressurized to 200 N at 10 N/s to eliminate creep. After stabilization, a vertical load was applied to the specimen at a rate of 10 N/s to 400 N for 2 min; then, the pressure-sensitive film was carefully removed from the knee joint. The measurement for each lower limb specimen was repeated 3 times.

The pressure values were read with the FPD-305E densitometer and FPD-306E pressure transducer. The stress values were uniformly and accurately read, the stress area of each pressure-sensitive film was divided into four quadrants (front outer, front inner, rear inner and rear outer), five values were read in each quadrant for a total of 20 values, and finally, the average was calculated.

3.Selection and use of pressure-sensitive film

This experiment used a double-page ultralow pressure-sensitive film (LLW type). Precompression was performed in the knee joint before performing biomechanical experiments. First, a template was cut from thin cardboard according to the shape of the articular surface of the tibial plateau, and then the ultralow pressure-sensitive film was cut according to the shape of the template. The pressure-sensitive film was trimmed into a suitable shape by the color distribution of the pressure-sensitive sheet and sealed in a polyethylene film bag. Since the color of the pressure-sensitive film material varies with humidity and temperature, humidifiers and air conditioners were used during the experiment to keep the indoor temperature at 25 ~ 30 °C and the relative humidity at 35% RH ~ 80% RH.

4. Statistical processing

The experimental data were processed by SPSS 21.0 statistical software. To ensure that the conditions of the parametric test are met, the normality of the measured variables is verified using the Shapiro-Wilk test, and the uniformity of the variance is verified using the Levene test. Calculate the mean stress and standard deviation of the tibia at different rotation angles. The analysis of variance was used to compare the stress of different rotation angles under the action of vertical load, and the SNK (Student-Newman-Keuls) test was used to make a pairwise comparison between the multiple sample means. $P < 0.05$ was considered statistically significant.

Results

1. Comparisons of the internal stress of the knee joint between different rotational deformities

For the medial compartment of the knee joint, there was a statistically significant difference in the knee internal stress between different rotational deformities (including the neutral position of 0 degrees) ($F = 89.753$, $P < 0.001$). The results are shown in Table 1. There was statistical significance between the pairwise internal rotation deformities of 15 degrees, 10 degrees, 5 degrees, and neutral position of 0 degrees and external rotation deformities of 5 degrees, 10 degrees, 15 degrees, etc ($P < 0.05$). As the angle of the external rotation increased, the stress on the inner side of the knee joint showed a gradual increase trend. As the angle of internal rotation deformity increased, the stress on the inner side of the knee joint showed a gradual decline. The results are shown in Fig. 3.

Table 1

Internal and external stresses of the knee joint with different angles of tibia deformity under a vertical load

Bending Angle	Inside stress (MPa)	Lateral stress (MPa)	t-value	P-value
External rotation 15 degrees	1.678 ± 0.133	1.528 ± 0.118	-2.914	0.008 ^c
External rotation 10degrees	1.511 ± 0.144	1.375 ± 0.125	-2.476	0.21 ^c
External rotation 5 degrees	1.335 ± 0.154	1.213 ± 0.123	-2.125	0.043 ^c
Neutral position 0 degrees	1.145 ± 0.155	1.027 ± 0.112	2.129	0.045 ^c
Internal rotation 5 degrees	0.976 ± 0.123	0.929 ± 0.103	-1.024	0.317 ^c
Internal rotation 10degrees	0.846 ± 0.066	0.783 ± 0.054	-2.582	0.017 ^c
Internal rotation 15 degrees	0.753 ± 0.078	0.723 ± 0.062	1.071	0.296 ^c
F-value	89.753	102.998		
P-value	< 0.001 ^a	< 0.001 ^b		
Note: a: Comparison of the internal stresses of the knee joint with different rotational deformities. b: Comparison of the lateral stresses of the knee joint with different rotational deformities. c: Comparison of stresses on the medial and lateral sides of the knee joint with different rotational deformities.				

2. Comparisons of lateral stress of knee joint between different rotational deformities

For the lateral knee joint compartment, there was a statistically significant difference in the lateral stress of the knee joint under different rotational deformities (including the neutral position of 0 degrees) ($F = 39.730$, $P < 0.001$). The results are shown in Table 1. There was statistical significance between the pairwise internal rotation deformities of 15 degrees, 10 degrees, 5 degrees, and the neutral position of 0 degrees and external rotation deformities of 5 degrees, 10 degrees, 15 degrees, etc ($P < 0.05$). The external stress of the knee joint showed a gradual increase with the increase of the external rotation angle. With the increase of the internal rotation angle, the lateral stress of the knee joint showed a gradual decline. The results are shown in Fig. 4.

3. Comparisons of internal and external stresses of the knee joint with different rotational deformities

Under a 400 N vertical load, the average internal stress of the knee joint was 1.145 ± 0.155 MPa, and the average lateral stress of the knee joint was 1.027 ± 0.112 MPa. the differences between the medial stress and the lateral stress of the knee joint were statistically significant; the results are shown in Table 1. Namely, the medial stress of the knee joint was higher than the lateral stress of the knee joint.

Discussion

Our study showed that the stress on the medial knee joint was significantly higher than that of the lateral knee joint at the same angle. The medial stress of the knee was increased with increasing angles of external rotation deformity and was decreased with increasing angles of internal rotation deformity. In contrast, the lateral stress of the knee tended to increase with increasing angles of external rotation deformity and decreased with increasing angles of internal rotation deformity.

Residual rotation deformity after proximal tibia fracture will not only affect fracture healing, but also affect the adjacent tibia joints to varying degrees. Research points out that biomechanical factors are important contributing factors to arthritis^[15]. In the late, uneven gravity conduction and unbalanced joint surface bearing weight would result in changes of mechanical characteristics of the abnormal joint surface and even cause knee joint traumatic arthritis^[16-18]. Brouwer et al^[19] analyzed data from 1501 patients (2664 lateral knees) and found a significant correlation between poor mechanical lower extremity and the occurrence and progression of osteoarthritis, especially in overweight patients.

A large number of clinical data show that the tibial rotation deformity is closely related to the tibial joint degenerative joint disease^[20-22], but the pathological mechanism is still unclear. However, it has been confirmed that excessive or too small stress load is an important factor in the degeneration of cartilage damage and secondary degenerative osteoarthritis. In this study, it was found that the medial stress and the lateral stress of the knee joint increased with the increase of the external rotation angle when the tibia was deformed. With the increase of the angle of internal rotation, the stress on the inside and outside of the knee joint decreases gradually. Turner et al^[23] indicate that when the angle of rotation is too large, it is easy to cause instability of the patella joint, resulting in softening of the tibia; however, when the angle of rotation is too small, knee arthritis is more likely to occur. Yagi et al^[24] found that patients with pain in the knee joint of knee arthritis had a lower sacral rotation angle than normal people, and the smaller the rotation angle of the tibia, the more severe the degree of osteoarthritis. This study also showed that both internal rotation and external rotation deformities altered the normal distribution of knee stress.

This study has some limitations. First, due to the limited source of specimens, the number of experimental specimens is small, which will reduce the credibility of experimental data (type II error). Second, this study is based on cadaver specimens without normal muscle dynamics, so it is impossible to simulate the lower limb biomechanical state of the tibial rotational deformity under intact human conditions.

In conclusion, residual rotational deformity after middle and upper tibial fractures can cause significant changes in contact characteristics of the knee joint. Therefore, orthopedic surgeons should correct the lower limb force lines to the greatest extent during the reduction process to minimize rotational deformities.

Declarations

Abbreviations

TA Traumatic Arthritis SNK :Student-Newman-Keuls

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Author Contributions

CW designed the study and searched relevant studies. WN, CW, JZ, YY and DH analyzed and interpreted the data. LM and ZY wrote the manuscript and contributed equally to this work. CW contributed most in the revision of this manuscript and approved the final version of the manuscript.

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Availability of data and materials

Not applicable

Ethics approval and consent to participate

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.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures



Figure 1

Specimens attached to the biomechanical testing machine



Figure 2

Insertion of the pressure-sensitive films

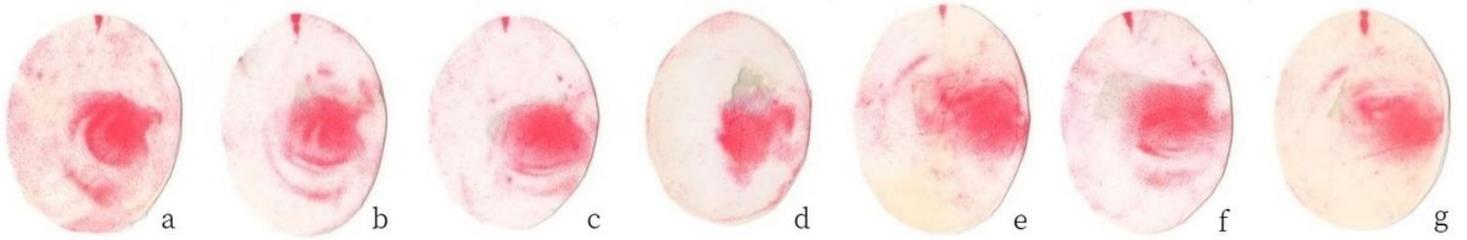


Figure 3

Pressure sensitive film of the medial platform of knee joint at different angles.a, External rotation 15 degrees; b, External rotation 10 degrees; c, External rotation 5 degrees; d, neutral position 0 degrees; e, Internal rotation 5 degrees; f, Internal rotation 10 degrees; g, Internal rotation 15 degrees.

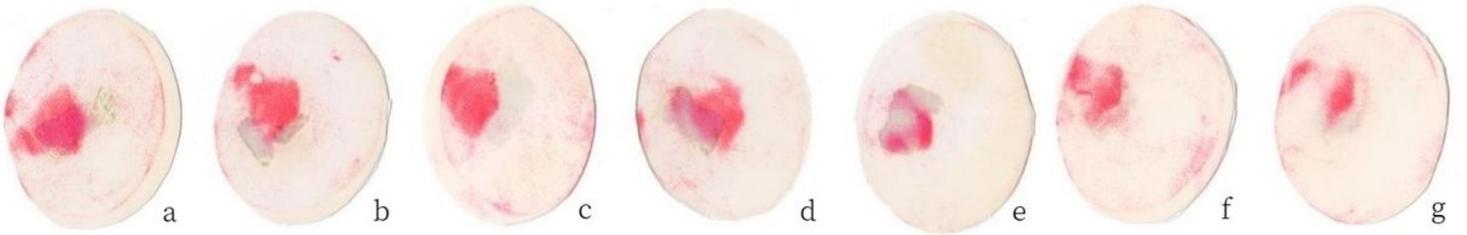


Figure 4

Pressure sensitive film of the lateral platform of knee joint at different angles.a, External rotation 15 degrees; b, External rotation 10 degrees; c, External rotation 5 degrees; d, neutral position 0 degrees; e, Internal rotation 5 degrees; f, Internal rotation 10 degrees; g, Internal rotation 15 degrees.