Pressure Change Of Fixed Rotational Deformities In The Femur In Human Cadaver Knees-A Biomechanical Study

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Research Article

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Abstract

Background: Closed intramedullary interlocking nailing is a standard treatment for femoral shaft fractures, but incidences of rotational malalignment after operation is really high. Poor reduction and postoperative malunion lead to many clinical symptoms and long term degenerative arthritis. It has been proved that uneven stress is the mechanical cause of knee joint degeneration, but few studies pay attention to the effect of femur rotational deformity on knee joint contact pressure.

This study aim to quantitatively evaluate the relation between residual rotational deformity in femur and contact pressure of knee joint.

Methods: Fourteen cadaveric Lower limbs were selected and autopsied, rotatory fixation model with different angles were then made. Connect each model on the biomechanical machine and apply a vertical load to 400N. The contact pressure was quantitatively measured using ultra-low-pressure sensitive film technology. FPD-305E density meter and FPD-306E pressure converter were used to read relative pressure values. Contact pressure on medial and lateral tibial plateau in different femoral rotational deformities were compared. Analysis were done using SPSS software.

Results: The medial group show a significant difference on tibial plateau (F=92.114, P<0.01), further test showed statistically significant differences of pairwise comparisons between 0°, 5°, 10°, 15° internal rotation deformity (P<0.05). There is no significant difference in lateral group (χ^2=9.967, P<0.01). The medial contact pressure is 0.940±0.177 MPa and the lateral is 1.008±0.219 MPa at neutral position, no statistically significant was found, so is 5° of internal rotational deformity. But the medial contact pressure are all higher than the lateral side at 5°, 10°, 15° of external rotation, and 10°, 15° of internal rotation.

Conclusion: Obvious contact pressure changes on tibial plateau were observed in rotatory deformity femur, which is closely related to the occurrence of knee osteoarthritis. Doctors should detect rotational deformity as much as possible during operation and perform anatomical reduction, for patients with residual rotational deformities, indication of osteotomy should not be too broad.

Introduction

Currently, closed intramedullary interlocking nailing is a standard treatment for femoral shaft fractures, though assessing intraoperatively the rotational malalignment is still a great challenge to orthopedic surgeons as tubular-shaped femur shaft enveloped by surrounding abundant muscles[1]. Many studies referred really high incidences (8%-43%[1−4]) of rotational malalignment using ultrasound or Computed Tomography (CT).

Poor reduction and postoperative malunion lead to many clinical symptoms[5, 6] and in long term severe degenerative arthritis might be developed[4,7,8−12]. Kettelkamp[8] mentioned that patients with residual femoral rotational deformities developed degenerative arthritis and obvious local symptoms after 32 years abnormal weight bearing.

It has been proved that uneven stress is the mechanical cause of knee joint degeneration, but few studies pay attention to the effect of femur rotational deformity on knee joint contact pressure. In order to quantitatively evaluate the relation between residual rotational deformity in femur and contact pressure of knee joint, we proposed this biomechanical and cadaver study.

Materials And Methods

This study has been approved by the Institutional Review Board (IRB) of the Third Hospital of Hebei Medical University.

Specimen Preparation: Fourteen fresh-frozen cadaveric lower limbs with intact soft tissue were autopsied (all cadavers were provided by the Department of Human Anatomy, Hebei Medical University), average height of the donors was 171 cm (range, 163 to 181 cm), average age was 55 years (range, 42 to 65 years). Each had complete femur, tibia and knee joint, there were no gross deformities of the knee, i.e. hyperflexion, hyperextension, varus and valgus. Passive joint motion are freely. Furthermore, inner knee structures were examined by X ray, pathological (osteoporosis, rheumatism, tuberculosis, or tumors) or anatomical deformities (unsymmetrical joint surface, bone hyperplasia, or other imaging abnormalities) were excluded(Fig. 1).

After all muscular tissues were removed, anatomical axes along the length of the intramedullary canals of the femur and tibial were marked based on the method proposed by Moreland[15]. In order to carry out this biomechanical experiment, we reserved approximately 25 cm of the distal femur, proximal tibia and fibula, wrapped dissected cadaveric knees with polyethylene films to prevent dehydration and cryopreserved at −20°C.

Establishment of rotatory fixation model: The cadaveric knees were thawed at room temperature for 12 hours before experiment. Cut a horizontal incision about 3–4 cm long at the level of joint space, both sides of the patellar ligament. Separate the subcutaneous fat, cut the sac, and expose the joint space, attention must be paid to reserve anterior and posterior cruciate ligaments, as meniscus is a weight-bearing structure that can buffer pressure and affect the expansion[13]. Then saw the femoral shaft transversely at distal 1/3, guarante that each cut is basically at the same level to eliminate heterogeneity. Take the previously drawn anatomical axes as the measurement benchmark, and predetermined angle was measured with a bone protractor, finally fixed two stumps with plates and screws. In our study, we chose neutral position (0°, anatomically reduced), the internal rotation 5°, 10°, 15° and the external rotation 5°, 10°, 15° as experimental factors.

Pressure-sensitive film inserted

An ultra-low-pressure sensitive film (LLW type, Fujifilm Investment Co. Ltd. Japan) (0.5–2.5 MPa) is used to reflect the contact pressure on tibial plateau, in order to ensure the quality of the pressure-sensitive film, we set the room humidity to 35%RH and the temperature to 20°C. Trim the pressure-sensitive film into somehow match shape according to our preliminary experiment, then seal it with a polyethylene film bag, a total thickness must be less than 250μm, thereafter carefully insert it under the meniscus and fully accessed into the joint cavity, suture the capsule tightly, leakage, bending, breakage of the sealed bag means failure[14] (Fig. 2). In order to distinguish the anterior and posterior side, the corresponding anterior side of the pressure sensitive sheet is clamped with a hemostatic forceps in advance to make an impression.

Specimen Assembled

Clamp the femur and tibial end perpendicularly and reinforce with the denture base resin and solution (type II self-setting dental powder and tray water) (Fig. 3–4). Then transfer and assemble the combination to the biomechanical testing machine (Electroforce 3520-AT, Bose company, USA). As the measurement work will be done dozens of times, so we are intended to ensure conformity between each step.

To simulates a normal male adult in naturally standing state ,we chose 400N load. Start the biomechanical machine, load the test bench, pressurize to 200N at a speed of 10N/s to eliminate creep. After stabilizing, apply a vertical load to the specimen to 400N at a speed of 10N/s and uphold for 2 minutes, unload and get the pressure-sensitive film out.

Pressure value read

FPD-305E density meter and FPD-306E pressure converter were used to read relative pressure value. We divided the contact pressure area (the red area) of each pressure-sensitive film into 4 quadrants (anterolateral, anterior medial, posterior medial and posterior lateral), each quadrant randomly and equally read 5 values, total 20 values in one film, take the average as final values.

Statistical Analysis

The experimental data were organized and computed by SPSS 21.0 software (SPSS, Chicago, IL, USA). The normality is verified using the Shapiro–Wilk test and expressed as $\bar{x}\pm s$, we used T-test of two independent samples to access difference between medial and lateral groups, the Student–Newman–Keuls test for pairwise comparisons between the multiple sample measurements. Using the Levene test for variance consistency, and analysis of variance (ANOVA) for random block groups. Data doesn't fit normality expressed as the median (quartile) and using Mann-Whitney U test to access difference between medial and lateral groups. Kruskal-Wallis H test for random block groups, significance was $P<$ 0.05.

Results

The contact pressure on tibial plateau at internal and external rotation under 400 N vertical stress are computed and presented in Table 1–2.

Table 1
Contact pressure value of medial tibial plateau at various rotation deformity (MPa)

Rotation deformity	Average contact pressure(Mpa)	*F*	*P*
Neutral position (0°)	0.952 ± 0.168	92.114	0.000*
external rotation 5°	1.601 ± 0.093		
external rotation 10°	1.472 ± 0.075		
external rotation 15°	1.172 ± 0.096		
internal rotation 5°	1.151 ± 0.082		
internal rotation 10°	1.493 ± 0.085		
internal rotation 15°	1.645 ± 0.088		
*: $P < 0.01$			

Table 2
Contact pressure value of lateral tibial plateau at various rotation deformity (MPa)

Rotation deformity	Average contact pressure(Mpa)	χ^2	*P*
Neutral position (0°)	1.023 ± 0.208	9.967	0.126
external rotation 5°	1.141 ± 0.208		
external rotation 10°	1.209 ± 0.121		
external rotation 15°	1.067 (0.206)		
internal rotation 5°	1.098 ± 0.333		
internal rotation 10°	1.221 (0.225)		
internal rotation 15°	1.114 ± 0.243		

The medial group show a significant difference on tibial plateau ($F = 92.114$, $P < 0.01$), further test show statistically significant differences between neutral position and other rotational deformities ($P < 0.05$), significant differences between every two rotational deformities are also found. In external rotation group medial contact pressure decrease gradually with the increase degree of external rotation ($P < 0.05$). in the internal rotation group, medial contact pressure increase gradually with the increase degree of internal rotation($P < 0.05$). However, we can't find a significant difference in lateral group ($\chi^2 = 9.967$, $P < 0.01$) (Table 2, Fig. 5,6).

The medial contact pressure is 0.952 ± 0.168 MPa and the lateral is 1.023 ± 0.208 MPa at neutral position, no statistically significant was found, so is 5° of internal rotational deformity. While the medial contact pressure in other five groups are all higher than the lateral contact pressure(Table 3).

Table 3
Comparison of contact pressure between medial and lateral tibial plateau

	Neutral position(0°)	external rotation 5°	external rotation 10°	external rotation 15°	internal rotation 5°	internal rotation 10°	internal rotation 15°
t/Z	0.998	-7.525	-6.909	-2.160	-0.578	-4.251	-7.673
P	0.327	0.000*	0.000*	0.031*	0.572	0.000*	0.000*
*: $P < 0.05$							

Discussion

Residual malrotational alignment in femur remains a gordian knot after IM surgery[16, 17]. Incidences of rotational malalignment ≥ 10° were as high as 41.7% compared with the unaffected side using CT[5]. Bråten[1] in 1993 used ultrasound in their study and found 19% rotational malalignment of 15° or more after IM nailing for femoral fractures. Sennerich [2] reported 40% patients had more than 10° of rotational malalignment and 16% more than 20°. Winquist [3] conducted a study on 520 femoral shaft fractures treated with intramedullary nails and noticed that 8% had postoperative external rotation deformities more than 10°. Yang [4] reported 9.5% of 42 patients had malrotation deformities more than 15°. Tobias [18] documented 22% of 82 patients had a rotation deformity more than 15° after intramedullary nails. Thoresen BO[19] found a even higher incidence. Such a high incidence of deformity causes many clinical symptoms in patients, lower limb discrepancy, restriction of movement, poor muscle strength, uncoordinated movement of hip, knee, ankle and patellofemoral joints, gait disorders, etc. Which directly affect patients' daily activities, waling, climbing stairs or running, and in long term developed degenerative arthritis[4,7,8–12].

Degenerative arthritis of knee is a well-known long-term complication of rotational malalignment[20, 21]. And among all the causes of degenerative arthritis, biomechanical changes are the most recognized factors. So we created different rotational malalignment models on cadaveric knee to quantify the contact pressure in tibial plateau after distal femoral shaft fracture. In this experiment, we simulated the pressure of a standing adult male in neutral position, and chose 400N for one foot which is in line with half pressure load of an average normal body weight of Chinese adult male. We found the medial contact pressure on tibial plateau is close to the opposite side at 0°, 5° internal rotation, while at the other degree of torsional deformities, the medial contact pressure are all higher than the lateral side. Our findings just agreed with the conclusion of Foroughi[22], that medial compartment of the degenerative arthritis had the most significant change, incidence rate was 10 times than the lateral compartment. Thorp[23] concluded that the contact pressure on the medial compartment during walking in patients with knee osteoarthritis was significantly higher than a normal person. Our biomechanical study confirmed that the contact pressure on medial tibial plateau increase in external or internal rotation deformity, and to some extent, it proved that existence of rotation deformities can increase the risk of osteoarthritis. Reasons might be the changing of intra-articular pressure and asymmetric load-bearing during movement exceed the elastic potential energy tolerance of cartilage and subchondral bone. In addition, the original axial pressure is partially converted into shear force due to rotationary deformity, causing local biochemical cascade, aggravating the degeneration process of articular cartilage, and finally leading to knee joint TA to different degrees[24, 25].

Early detection during operation can help surgeons improving fracture reduction quality, but once rotational deformity is found after operation, osteotomy is feasible to correct this deformity. Osteotomy is a very mature treatment but the surgical indication is unclear due to patient's subjective feelings and heterogeneity between different studies. While Lee [26] believed that as long as the deformity is obvious, it can be corrected by osteotomy. In addition, Piper [27] believe that internal rotation deformities exceeding 10 degree can be corrected by osteotomy. Some authors[2, 28] concluded that torsional deformity of less than 20° will not usually be a handicap. Other studies have found that the maximum clinical osteotomy rotation angle can be relaxed to 15 degree, as external or internal rotation deformities exceeding 15 degrees can severely affect knee joint activities and even lower limb function abnormalities[29]. We found that the contact pressure on the medial side of knee joint decreased with the aggravation of external rotation deformity, and increased with the aggravation of internal rotation deformity, but were both higher than the medial side in neutral position. Doctor should pay more attention on internal rotation deformity than external rotation deformity. From our point of view that indications of osteotomy should not be too broad, though some patients can tolerate a certain degree of torsion alignment, more than 15 degrees will cause dysfunction or need to be corrected by surgery again, so it should be avoided as much as possible during the original treatment.

Certain limitations are obvious in this study, we mainly summarized in four points. Firstly, this study had smaller specimens and based on cadaver, which is not equal to normal human muscle dynamics. Therefore, the data obtained in this project may be different from human femoral rotation deformity. Secondly, the anatomical axis had slight different from the mechanical axis of femur. The anatomical axes are lines drawn along the length of the intramedullary canals of the femur. The mechanical axis is a line drawn from the centre of the femoral head to the centre of the talus, and is commonly referred to as Maquet’s line. The anatomical axis of normal human femur refers to the line from piriformis muscle to the center of knee joint, while the mechanical axis of femur refers to the line from the center of femoral head to the center of knee joint. the femoral joint surface mechanical-anatomical (FMA) angle is about 6° of valgus[30], our study fixed the model along anatomical axis of the femur, which may increase the medial contact pressure on tibial plateau. Thirdly, this study mainly simulates a normal adult in naturally standing state and chose 400N, but 400N is definitely too small for standing on one foot or walking in human beings, we try to use a higher pressure but the film are too dark red and fail to read pressure values, we need to find better experimental materials and improve technological methods. Finally, femoral model was repeatedly used to create different rotation deformities, which may had mutual influence between each other and affect the experimental results. We hope that future research will be supplemented and improved.

Abbreviations

CT: Computed Tomography

IRB: Institutional Review Board

FMA: femoral joint surface mechanical-anatomical

2D: 2-dimensional

Declarations

Ethics approval and consent to participate

This study has been approved by the Institutional Review Board (IRB) of the Third Hospital of Hebei Medical University. All methods were performed in accordance with the relevant guidelines and regulations.

Consent for the storage and use of the bodies for research purposes was given by all body donors before death or by their next of kin. We express our sincere gratitude to the body donors; thanks to their generosity, science is able to advance.

Consent for publication

Not applicable.

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Yuwen Peizhi and Wei Chen designed the study, Lv Hongzhi, Zhu Yanbin, Chang Wenli, Wei Ning, Guo Jialiang made substantial contributions to collect and judge all data, Yuwen Peizhi, Chen Wei, Lv Hongzhi analyzed data and performed statistical analysis; Peizhi Yuwen and Wei Chen drafted the manuscript; Wang Haicheng, Ding Kai, Zhang yingze give specific suggestions about the writing. All authors had read and approved the final manuscript.

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Figures

Figure 1

General photos and X-ray of cadaveric knee

Figure 2

Insert ultra-low-pressure sensitive film

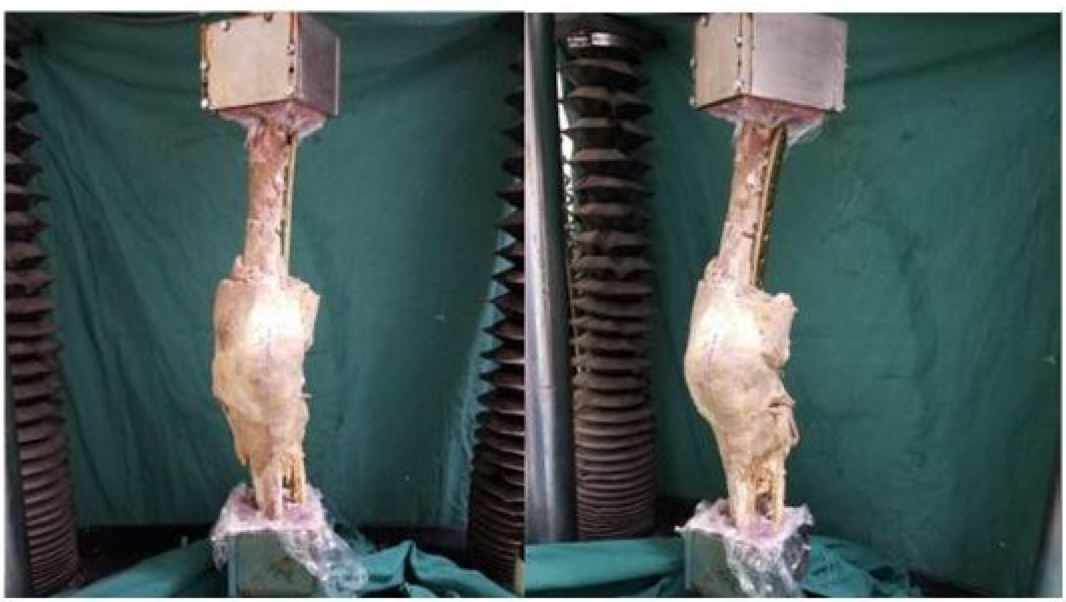

Figure 3

The specimens were assembled to the BOSE Electroforce 3520-AT biomechanical testing machine, and the femoral and tibia stumps was adjusted so that the lower limb mechanical axis was close to naturally standing position. Model of external rotation deformity

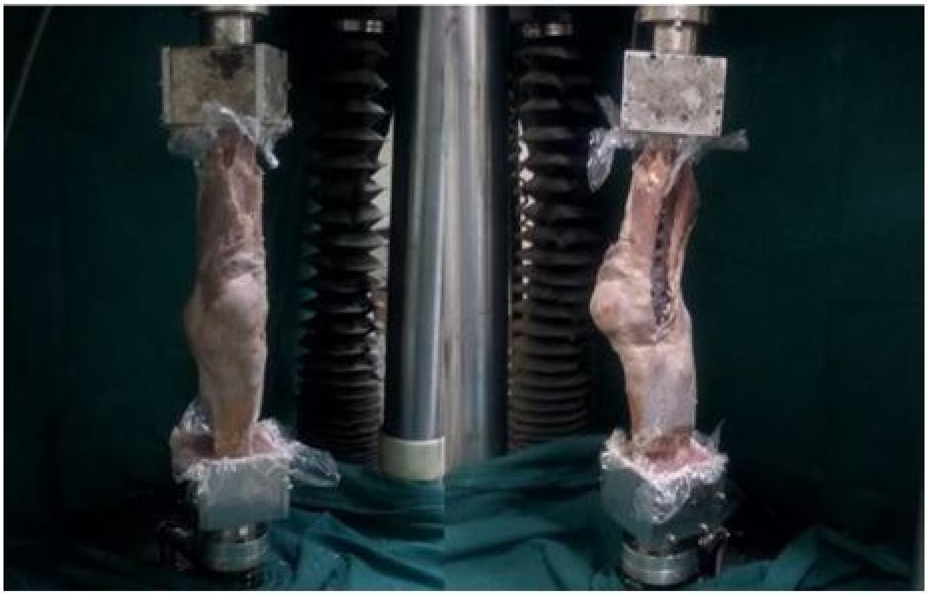

Figure 4

The specimens were assembled to the BOSE Electroforce 3520-AT biomechanical testing machine, and the femoral and tibia stumps was adjusted so that the lower limb mechanical axis was close to naturally standing position. Model of internal rotation deformity

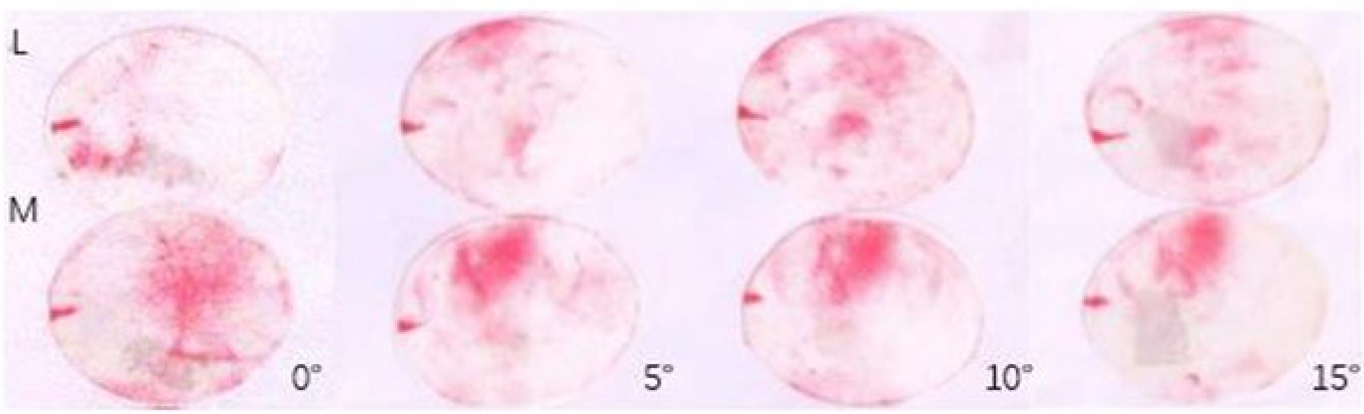

Figure 5

Ultra-low-pressure sensitive film of all external rotation deformities L: Lateral part; M: Medial part

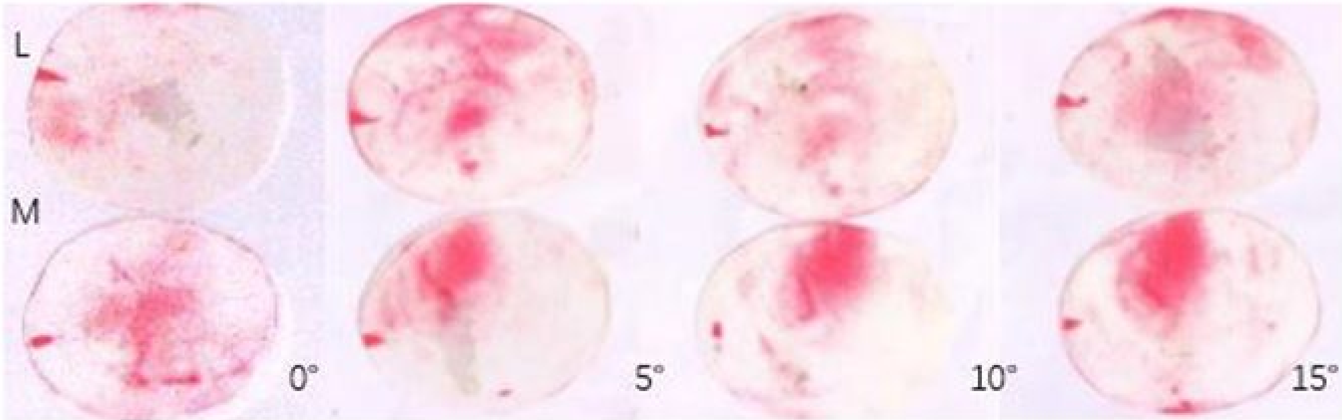

Figure 6

Ultra-low-pressure sensitive film of all internal rotation deformities L: Lateral part; M: Medial part