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Article

Kinematic Characteristics of the Knee Joint during Squatting in Patients after TKA Based on Motion Capture

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Abstract: This study comprehensively investigated the limitation of high-flexion knee function in patients following total knee arthroplasty (TKA), a critical factor affecting postoperative quality of life. By comparatively analyzing the squat kinematics of postoperative patients and healthy individuals, the research aimed to enrich the existing knee kinematics database. Furthermore, it sought to provide robust data support and theoretical guidance for optimizing postoperative rehabilitation strategies and designing advanced artificial prostheses. The Optotrak Certus motion capture system was utilized to precisely collect three-dimensional coordinate data of body-surface markers during deep squatting exercises in a cohort comprising 15 patients after TKA and 20 healthy control subjects. Subsequently, MATLAB-based data processing techniques were employed to accurately calculate the six-degree-of-freedom kinematic parameters of the femur relative to the tibia. The three-dimensional kinematic differences of the tibiofemoral joint during the squatting motion between the TKA patients and the healthy individuals were systematically compared and analyzed to identify specific biomechanical deficits. Ultimately, this study successfully verified the feasibility and accuracy of integrating motion-capture technology with custom MATLAB algorithms in complex knee kinematic analysis. The findings clearly revealed the persistent functional limitations and altered biomechanics of the knee joint during squatting after TKA. These insights provide a crucial experimental basis for optimizing targeted postoperative rehabilitation training strategies and significantly improving the high-flexion stability design of future artificial knee prostheses.

Keywords: total knee arthroplasty; squat kinematics; motion capture; joint kinematics; biomechanics; rehabilitation

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1. Introduction

Total knee arthroplasty (TKA) is a widely utilized surgical intervention for addressing knee joint disorders [1]. This procedure has demonstrated exceptional clinical outcomes, achieving a success rate exceeding 90% in numerous cases. It effectively alleviates knee pain and restores joint functionality, allowing many patients to regain a relatively normal quality of life and activity level. Despite the high success rate of the surgery, both clinical observations and research findings reveal that significant kinematic differences persist between prosthetic knees and natural knees. These differences highlight the need for further investigation into the biomechanical implications of TKA and the optimization of prosthetic designs to better mimic natural knee function.

Studies have identified notable differences in knee joint motion between individuals who have undergone TKA and those with healthy knees. Patients post-TKA often exhibit reduced flexion angles, along with increased external rotation, posterior translation, and superior translation. Additionally, the constraints imposed by prosthesis design on rotational degrees of freedom may contribute to compensatory increases in external rotation. However, the majority of prior research has concentrated on gait and low-flexion activities, leaving a gap in understanding the mechanisms underlying knee function during high-flexion activities such as squatting. Squatting is particularly significant as it subjects the knee joint to loads ranging from three to six times body weight and involves coordinated movements across multiple directions, including flexion, internal-external rotation, and anterior-posterior translation. This makes squatting a critical indicator for evaluating high-demand knee functionality [2]. Quantitative analysis of squatting motion can provide valuable insights for optimizing prosthesis designs and enhancing postoperative rehabilitation strategies. Figure 1 illustrates the anatomical structure of a normal knee joint alongside a fluoroscopic image of a knee joint following TKA.

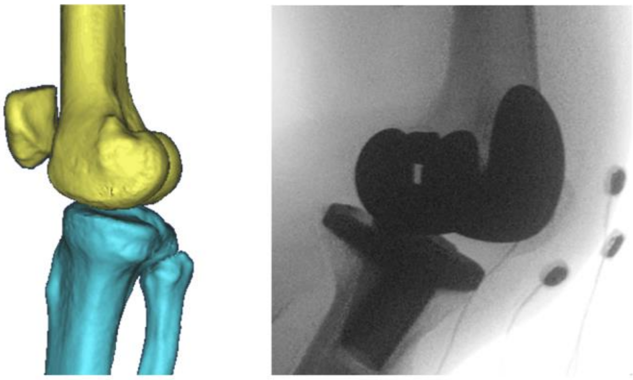

Figure 1. Anatomical illustration of a normal knee joint and fluoroscopic image of a knee joint after TKA

The human knee joint exhibits complex three-dimensional motion, encompassing both patellofemoral and tibiofemoral movements. These motions involve the relative movement between the patella and femur, as well as between the tibia and femur, incorporating translations in three directions and rotations about three axes [3]. This study aims to conduct a comparative analysis of tibiofemoral motion during squatting between patients post-TKA and healthy individuals. By integrating motion capture technology with MATLAB algorithms, the research seeks to explore the biomechanical relationship between postoperative flexion limitations and compensatory external rotation, the impact of prosthesis design on translational stability, and the clinical utility of motion-capture methodologies. The findings are expected to address the existing research gap concerning high-flexion activities and provide theoretical support for clinical practices aimed at improving patient outcomes. Figure 2 depicts the spatial motion of the femur relative to the tibia within the human knee joint.

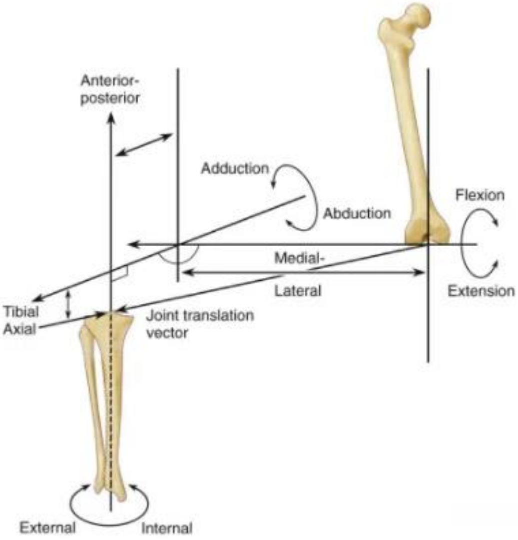

Figure 2. Spatial motion of the femur relative to the tibia

2. Materials and Methods

2.1. Subjects

This study involved 15 patients who had undergone unilateral total knee arthroplasty (TKA), aged between 48 and 75 years, alongside a control group of 20 healthy individuals matched for age. The healthy participants were carefully selected based on strict criteria to ensure the reliability of the study outcomes. These criteria were designed to exclude any individuals with conditions or factors that could potentially influence knee function or movement patterns, thereby maintaining the integrity of the comparative analysis between the two groups [4, 5].

The inclusion criteria for healthy subjects were defined as follows: participants must not have any history of major knee diseases or injuries, must exhibit no signs of knee deformities, and must not experience chronic knee pain [5]. These parameters were established to ensure that the control group represented a baseline of normal knee function, allowing for accurate comparisons with the TKA patient group.

The exclusion criteria were equally stringent, disqualifying individuals with any form of knee disease or injury, those unable to perform the experimental movements required for the study, and pregnant individuals. These measures were implemented to eliminate confounding variables that could compromise the validity of the experimental results and to ensure the safety and feasibility of participation for all subjects [6].

Ethical approval for the study was obtained from the relevant institutional review board, ensuring compliance with established ethical standards. Informed consent was secured from all participants prior to their involvement, aligning the study with the principles outlined in the Declaration of Helsinki [6]. This process underscored the commitment to ethical research practices and the protection of participant rights throughout the study.

2.2. Motion Capture System Configuration

In this study, the Optotrak Certus motion-capture system was employed for data acquisition. The hardware configuration of this system included two position sensors, a virtual marker probe, and a calibrator, as illustrated in Figure 3 and Figure 4. This system is renowned for its high precision, offering a sampling frequency of 100 Hz, an accuracy of 0.1 mm, and a resolution of 0.01 mm [7, 8]. During the data acquisition process, a total of 500 frames were collected for each trial, ensuring a robust dataset for analysis. The system was integrated with Northern Digital Inc. NDI 6D Architect software, which facilitated real-time acquisition and reconstruction of three-dimensional motion data. The experiments were conducted in a dedicated motion-capture laboratory, as depicted in Figure 5. This laboratory provided a controlled and stable environment, minimizing external disturbances and ensuring the reliability of the collected data.

Figure 3. Position sensors of the motion capture system

Figure 4. Calibration tools of the motion capture system.

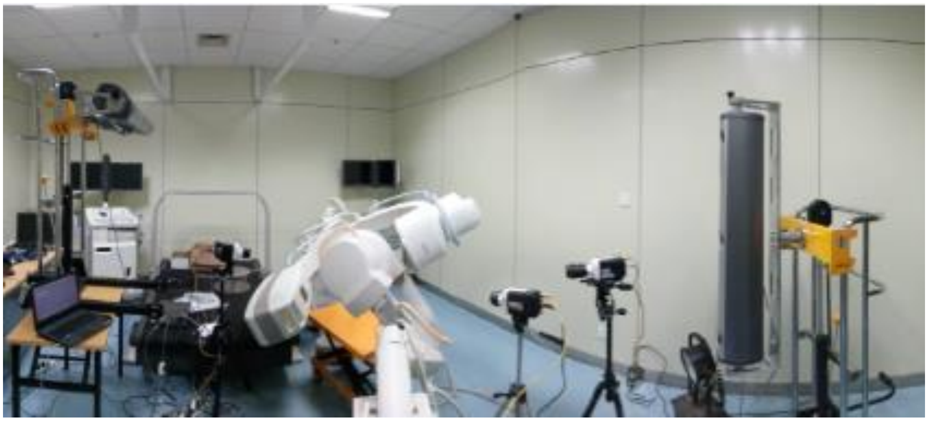

Figure 5. Panoramic view of the motion-capture laboratory.

In the marker placement scheme utilized in this study, the thigh and shank of each volunteer were modeled as rigid bodies to ensure accurate motion tracking. Four single markers were strategically attached to the thigh and another four to the shank. This configuration enabled precise measurement of six-degree-of-freedom motion parameters within three-dimensional space. The placement of these markers was carefully designed to optimize data accuracy and minimize potential errors. Figure 6 illustrates the specific positions of the single markers attached to the subject's thigh and shank, providing a visual reference for the experimental setup. This marker placement scheme was critical for capturing detailed kinematic data, forming the basis for subsequent analyses [3].

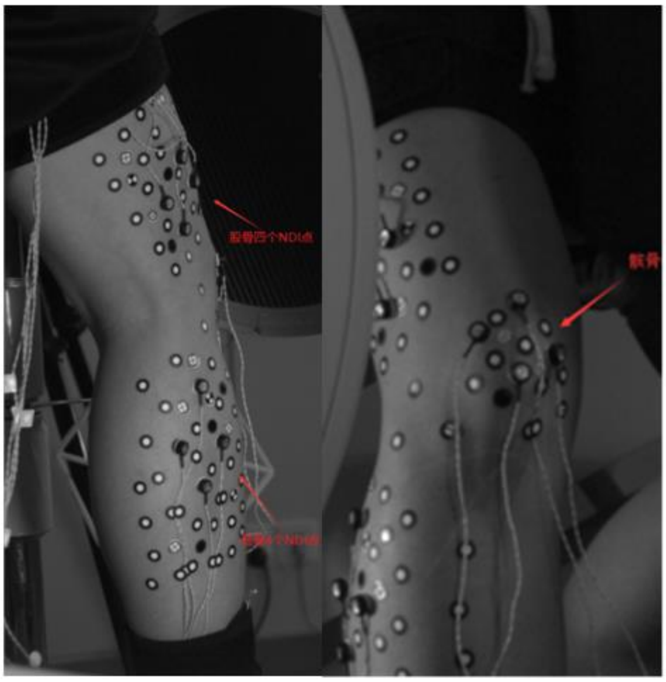

Figure 6. Marker placement on the thigh and shank.

To address the issue of skin-motion artifacts, which can affect the accuracy of anatomical landmark points during movement, this study employed a virtual-marker technique for compensation. Using the NDI probe tool, seven key bony landmarks were calibrated: the greater trochanter, lateral femoral condyle, medial femoral condyle, medial tibial plateau, lateral tibial plateau, lateral malleolus, and medial malleolus. The tip position of the probe was used to represent the true location of each anatomical landmark with high precision [1]. This calibration process was essential for defining the local coordinate systems of the femur and tibia at the knee joint. These coordinate systems served as the foundation for calculating the three-dimensional coordinates of virtual markers. Additionally, they enabled the determination of tibiofemoral kinematic parameters, such as flexion angle and rotational displacement, which are critical for understanding joint mechanics and movement patterns.

2.3. Experimental Procedure

In this experiment, the NDI motion-capture system and two position sensors were employed to gather precise data on the squatting motion of the participants. Initially, markers were strategically affixed to the knee joint as well as the lateral sides of the thigh and shank to ensure accurate tracking of movement. A comprehensive position calibration process was conducted using the NDI system, which included several critical steps: initial calibration, establishment of the coordinate system, calibration of seven specific bony landmark points, and calibration of ground reference points. The squatting motion was carefully defined to standardize the procedure. Participants began by standing upright with their feet positioned shoulder-width apart and their arms crossed over the chest [3]. They then flexed their knees from a fully extended position to the maximum achievable angle before gradually returning to the upright posture. Throughout the process, the movement speed was meticulously controlled through verbal instructions provided by the researchers to ensure consistency and reliability in the data collection.

2.4. Data Processing

The marker data collected in this study were processed using MATLAB software to ensure precise and reliable analysis. Missing data encountered during the experiment were addressed using cubic spline interpolation, a method that effectively reconstructs gaps in datasets while maintaining smooth transitions. This approach was critical for ensuring the integrity and consistency of the data. During the construction of the coordinate systems, a transformation relationship was established between the rigid-body coordinate system and the anatomical coordinate system. This was achieved by correlating seven specific bony landmarks with rigid-body markers, enabling the creation of localized coordinate systems for the femur and tibia. Figure 7 illustrates the detailed process of establishing these coordinate systems. For the femoral coordinate system, the origin was defined at the midpoint of the intercondylar notch, with the Z-axis aligned along the long axis of the femur, extending from the greater trochanter to the intercondylar notch. The X-axis was oriented perpendicular to the sagittal plane. Similarly, the tibial coordinate system was defined with its origin at the center of the tibial plateau. The Z-axis was aligned along the long axis of the tibia, extending from the tibial tuberosity to the ankle joint center, while the X-axis pointed laterally. Following the construction of these coordinate systems, coordinate-transformation algorithms were applied to convert the global coordinates of markers at various motion instants into the local coordinate systems of the femur and tibia. This enabled the extraction of motion parameters for the knee joint across six degrees of freedom, encompassing flexion-extension, adduction-abduction, internal-external rotation, and anterior-posterior, superior-inferior, and medial-lateral translation.

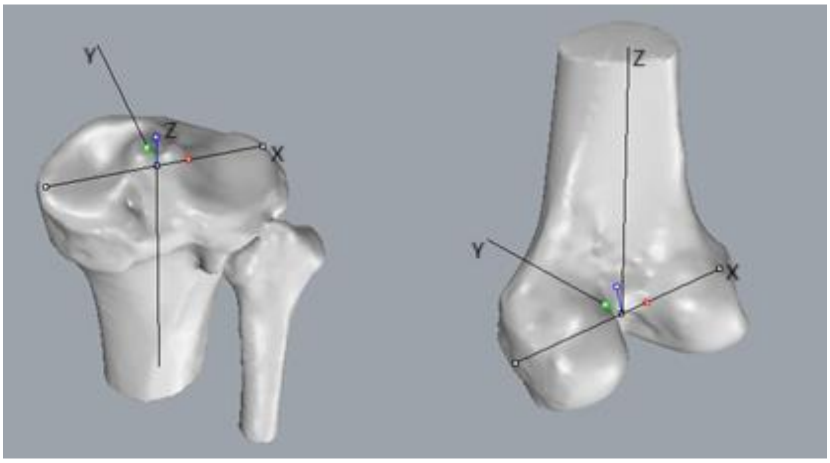

Figure 7. Schematic diagram of the establishment of femoral and tibial coordinate systems

3. Results

3.1. Kinematic Characteristics of Knee Joint during Squatting in the Healthy Group

As illustrated in Figure 8, the kinematic parameters of the knee joint in healthy individuals during squatting demonstrated coordinated and stable biomechanical characteristics. The horizontal axis represents the frame number, with a total of 500 frames collected for each trial. In the first subplot, the flexion angle increased continuously and smoothly over time, beginning at 0 when the subject stood still, rising linearly to a peak of 140 ±2.5 degrees at the lowest squatting position, and then gradually decreasing back to 0 as the subject returned to an upright posture. The second and third subplots depict the changing trends of internal-external rotation and adduction-abduction of the tibiofemoral joint throughout the squatting process. Additionally, the angular values of the femur relative to the tibia in the three rotational directions are presented at each time point, providing a comprehensive view of the joint's dynamic behavior during the movement.

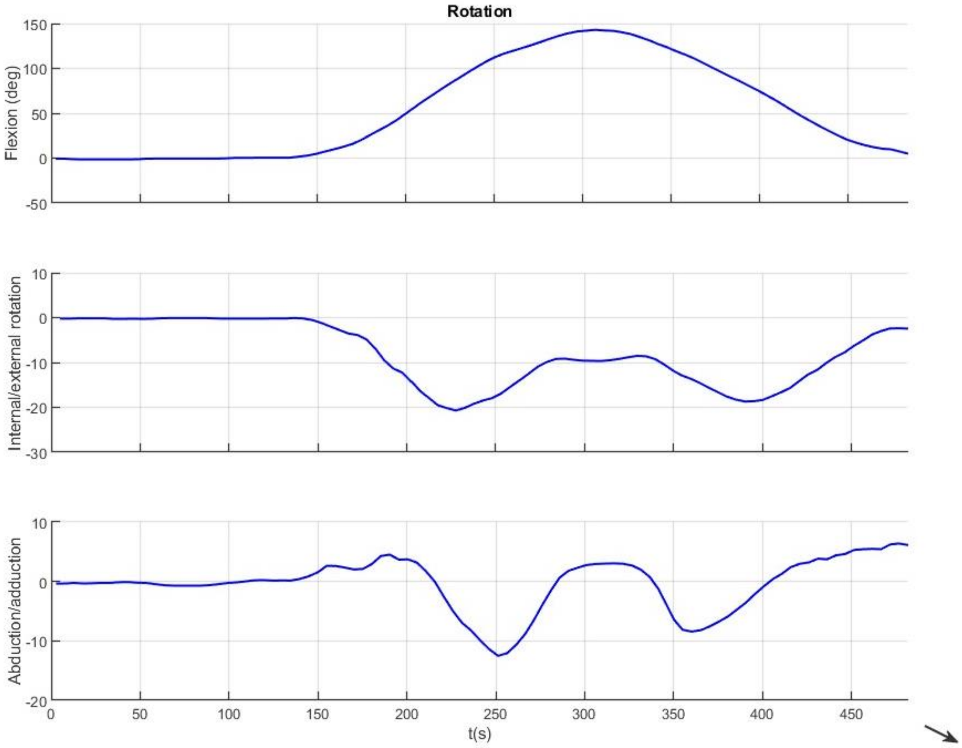

Figure 8. Relative rotational motion of the tibiofemoral joint during squatting in healthy subjects: flexion-extension, internal-external rotation, and adduction-abduction.

Based on the temporal changes in flexion angle obtained from the aforementioned test, the relative rotational and translational motions of the femur with respect to the tibia can be derived by using the flexion angle as the horizontal axis [9]. This approach enables a detailed analysis of the biomechanical interplay between the femur and tibia during squatting, offering valuable insights into the functional characteristics of the knee joint under varying flexion levels.

As depicted in Figure 9, during squatting in healthy individuals, the knee joint exhibited distinct three-dimensional rotational characteristics of the femur relative to the tibia at different flexion levels. The magnitude of femoral external rotation increased progressively with the flexion angle, reaching a peak of 10.24 degrees at a flexion angle of 86 degrees. Subsequently, it decreased to 4.75 degrees at maximum flexion as the knee flexion deepened further. Concurrently, during the early stages of knee flexion-extension, the femur displayed an adduction trend relative to the tibia, which later transitioned into abduction, peaking at a maximum abduction of 6 degrees at approximately 115 degrees of flexion. Following this, the femur reverted to an adduction trend relative to the tibia until maximum flexion was achieved, highlighting the dynamic rotational interplay between these two components of the knee joint.

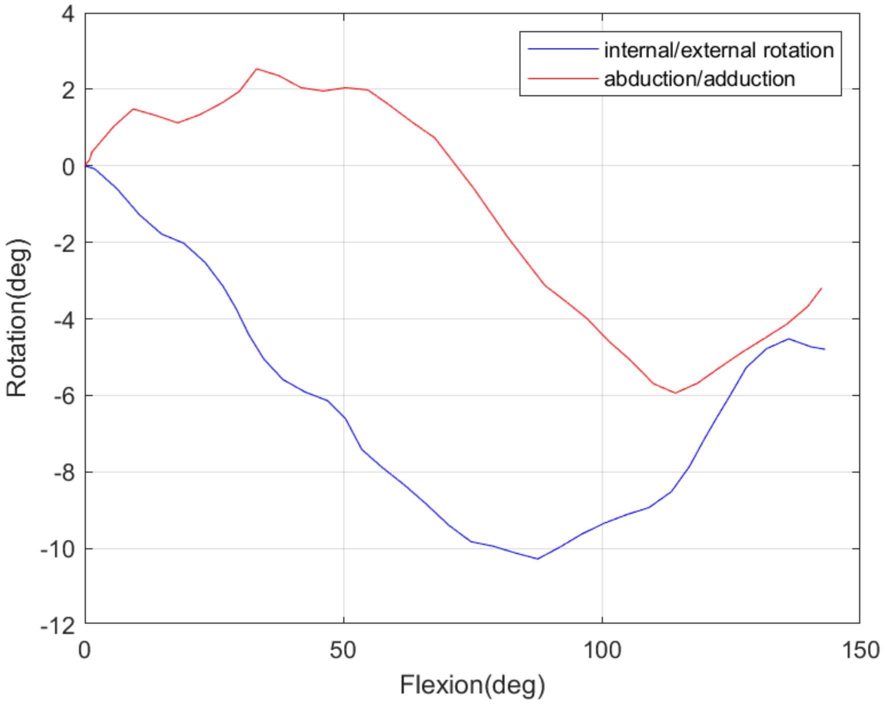

Figure 9. Relative rotational motion of the femur with respect to the tibia at different flexion levels during squatting in healthy subjects: adduction-abduction and internal-external rotation

As shown in Figure 10, during squatting in healthy individuals, the knee joint demonstrated distinct three-dimensional translational characteristics of the femur relative to the tibia across varying flexion levels. Starting from the upright position, the femur exhibited noticeable anterior translation relative to the tibia as flexion increased. When the flexion angle reached 95 degrees, the anterior translation peaked at 4.43 mm, after which it transitioned into posterior translation, culminating in a relative displacement of 6.9 mm at maximum flexion. Along the Z-axis, the femur relative to the tibia displayed continuous superior translation, followed by a brief decline. Meanwhile, along the X-axis, the femur consistently maintained a lateral translation trend, resulting in a lateral offset of 4.34 mm at maximum flexion. These translational movements provide a detailed understanding of the spatial dynamics of the femur relative to the tibia during the squatting motion.

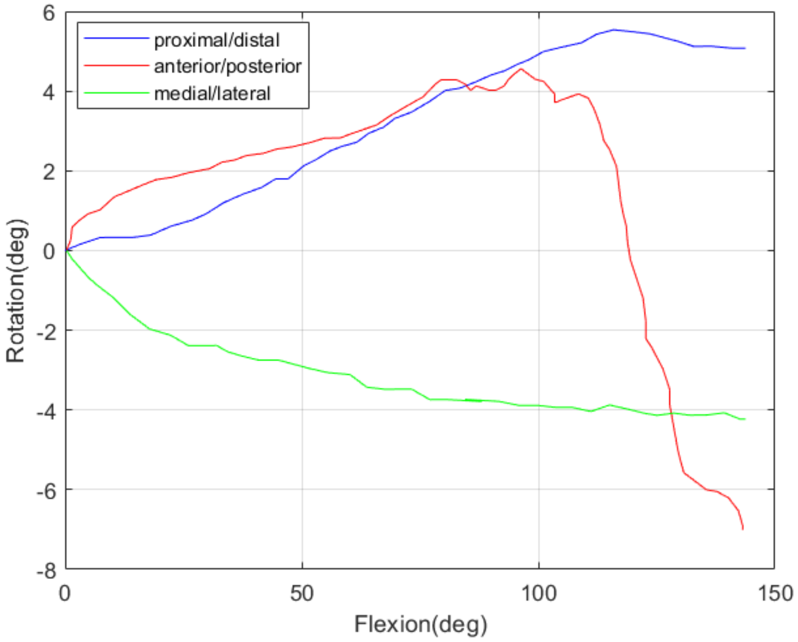

Figure 10. Relative translational motion of the femur with respect to the tibia at different flexion levels during squatting in healthy subjects: medial-lateral, anterior-posterior, and vertical translation.

3.2. Kinematic Characteristics of Knee Joint during Squatting in the Post-TKA Group

In the kinematic evaluation of the knee joint in patients after TKA, limited flexion function and changes in dynamic motion demonstrated distinct characteristics [10]. As illustrated in Figure 11, the motion characteristics of the femur relative to the tibia at various time points during squatting in post-TKA patients are presented. This figure highlights the dynamic changes in internal-external rotation and adduction-abduction of the tibiofemoral joint during squatting in TKA subjects, while simultaneously recording the angular parameters of the femur relative to the tibia in three spatial dimensions. In the first subplot, the flexion angle is shown to change over time as the TKA subject transitions from an upright position to squatting and then back to standing. The data indicate that the flexion angle begins at 0, reaches a maximum flexion angle of approximately 100 at around frame 330, and subsequently returns to 0. The second and third subplots depict the adduction-abduction and internal-external rotational motions of the tibiofemoral joint, respectively, providing a comprehensive view of the joint's dynamic behavior during the squatting motion.

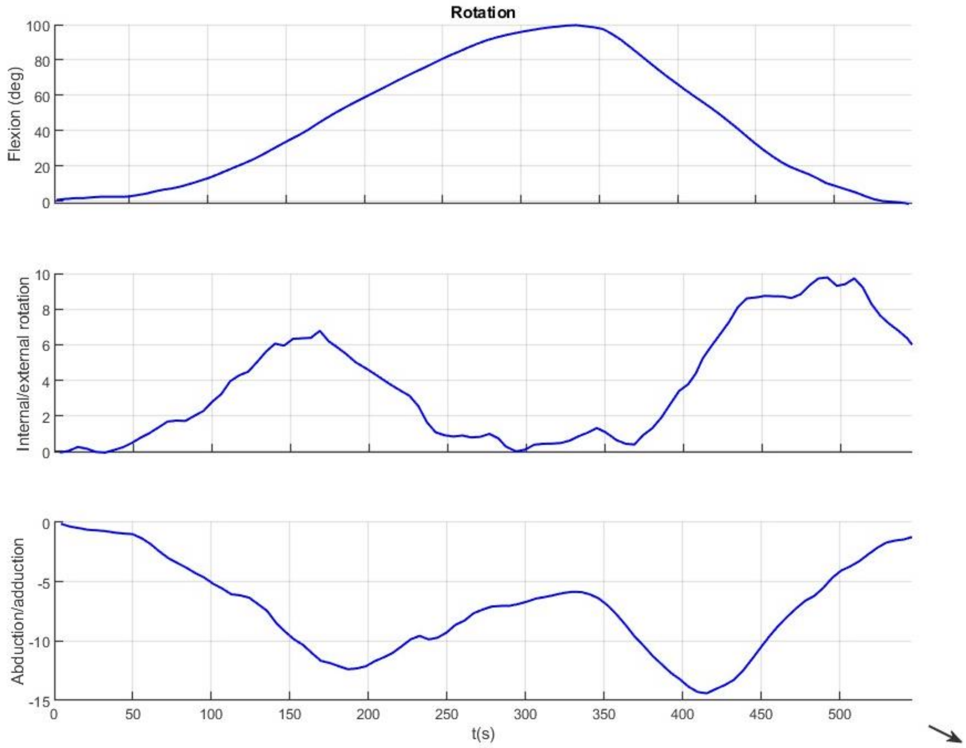

Figure 11. Relative rotational motion of the tibiofemoral joint during squatting in TKA subjects: flexion-extension, adduction-abduction, and internal-external rotation.

Based on the temporal changes in flexion angle obtained from the aforementioned test, the relative rotational and translational motions of the femur with respect to the tibia can be derived by using the flexion angle as the horizontal axis. This approach allows for a detailed analysis of the knee joint's kinematic behavior, offering insights into how the femur moves in relation to the tibia during different phases of squatting. Such an analysis is critical for understanding the biomechanical implications of TKA and for optimizing rehabilitation strategies to improve joint function and patient outcomes.

As depicted in Figure 12, during squatting in TKA subjects, the knee joint exhibited three-dimensional rotational characteristics of the femur relative to the tibia under varying flexion levels. The figure reveals that during knee flexion from 0 to 51.8, the femur continuously externally rotated, reaching a peak of 12.3 at 51.8. Beyond this point, the femur transitioned to internal rotation, with the external rotation value decreasing to 5.75 at the maximum flexion angle of 100. Concurrently, from 0 to 43.2, the femur abducted to a peak of 6.85, after which it progressively adducted until the terminal flexion angle. These findings underscore the complex rotational dynamics of the knee joint post-TKA, highlighting the interplay between external rotation, internal rotation, abduction, and adduction during the squatting motion.

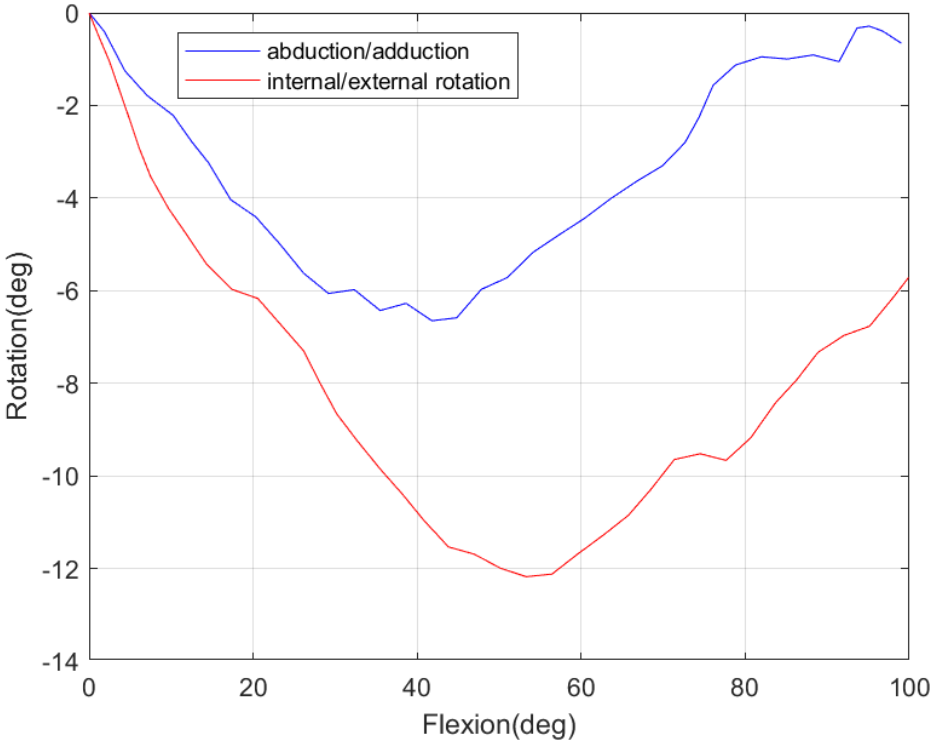

Figure 12. Relative rotational motion of the femur with respect to the tibia at different flexion levels during squatting in TKA subjects: adduction-abduction and internal-external rotation.

As illustrated in Figure 13, during squatting in TKA subjects, the knee joint demonstrated three-dimensional translational characteristics of the femur relative to the tibia under varying flexion levels. Along the Y-axis, the femur continuously translated posteriorly relative to the tibia from 0 to 99, achieving a maximum displacement of 11.2 mm at 99. Along the Z-axis, the displacement initially increased, reaching a maximum of 7.56 mm at a flexion angle of 76.2, before subsequently decreasing to 5.03 mm. Along the X-axis, the femur exhibited continuous lateral translation relative to the tibia, with a maximum displacement of 6.23 mm observed at the highest flexion angle [5, 11]. These translational patterns provide valuable insights into the mechanical behavior of the knee joint post-TKA, emphasizing the importance of understanding these movements for improving surgical techniques and rehabilitation protocols.

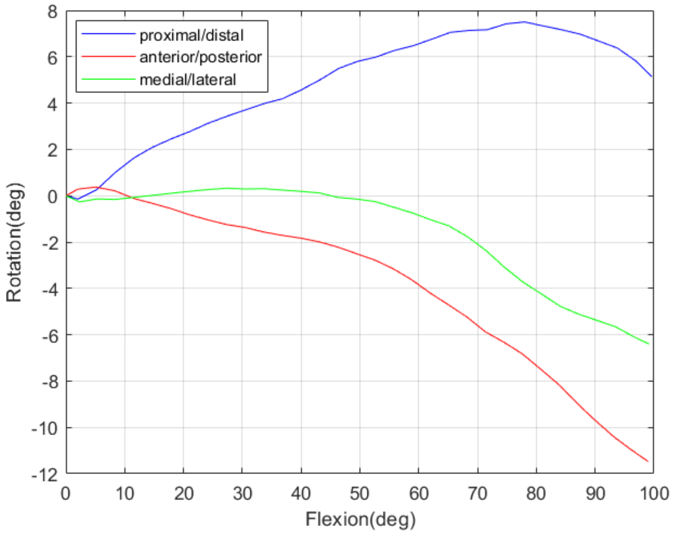

Figure 13. Relative translational motion of the femur with respect to the tibia at different flexion levels during squatting in TKA subjects: medial-lateral, anterior-posterior, and vertical translation

3.3. Intergroup Comparative Analysis

Based on the analysis presented, notable differences in knee kinematic parameters during squatting were identified between healthy individuals and patients who have undergone total knee arthroplasty (TKA). Healthy subjects demonstrated a maximum flexion angle of 140 ±2.5 degrees, whereas TKA patients exhibited a reduced flexion angle of 100 degrees [12]. Regarding rotational motion, TKA patients showed a peak femoral external rotation of 12.3 degrees, which exceeded the 10.24 degrees observed in healthy individuals. Additionally, the range of abduction was larger in TKA patients. Translational motion also revealed disparities, with TKA patients experiencing femoral posterior translation of 11.2 mm and superior translation of 7.56 mm, both of which were higher than the corresponding values in healthy subjects. Furthermore, while both groups exhibited continuous lateral translation of the femur relative to the tibia, the amplitude was notably smaller in healthy individuals at 4.34 mm, compared to 6.23 mm in TKA patients. These findings underscore the biomechanical alterations associated with TKA and their implications for joint function during squatting.

4. Discussion

4.1. Kinematic Characteristics of the Knee Joint during Squatting After TKA

The experimental data revealed that the peak femoral external rotation during squatting in post-TKA patients increased by 2.06 compared with healthy individuals. This increase may be attributed to the restricted rotational degrees of freedom following prosthesis implantation. In a normal knee, progressive external rotation during flexion is facilitated by the sliding-rolling mechanism of the femoral condyles. However, post-TKA patients often exhibit altered motion patterns due to structural changes in the joint and adjustments in soft-tissue balance after surgery. Furthermore, the observed postoperative increase of 4.3 mm in femoral posterior translation suggests that the prosthesis design or postoperative structural modifications may not fully preserve posterior femoral stability [13]. This could potentially elevate shear stress on the articular surface, thereby accelerating wear of the polyethylene insert. These findings align with broader trends in research on high-flexion prostheses. Additionally, this study provides a detailed description of the coordinated changes in posterior translation and external rotation, suggesting that these two factors may collectively influence the altered motion patterns observed in the knee joint after surgery. Such insights underscore the importance of optimizing prosthesis design and surgical techniques to better replicate natural joint mechanics and minimize postoperative complications.

4.2. Analysis of the Compensatory Mechanism After TKA

Patients who have undergone TKA exhibit noticeable kinematic alterations during squatting activities. Specifically, the maximum flexion angle is reduced by 28.6%, highlighting a significant limitation in achieving high-flexion postures following the procedure. Additionally, these patients demonstrate a pronounced increase in peak external rotation and greater posterior translation of the femur compared to healthy individuals. These biomechanical changes likely represent compensatory motion patterns that arise due to the restricted flexion functionality. Such compensatory mechanisms may also contribute to altered loading dynamics within the patellofemoral joint, potentially impacting joint health and overall movement efficiency [14].

4.3. Comparison with Existing Studies

In terms of flexion angle, the findings of this study align with previous research, demonstrating that anterior-posterior translation of the knee joint in patients who have undergone total knee arthroplasty (TKA) is increased when compared to healthy individuals. This suggests that current TKA procedures are unable to fully replicate the natural motion of the knee joint [8]. Regarding rotational motion, the results indicate that in TKA patients with knee flexion exceeding 90 degrees, there is an increase in femoral posterior translation and tibial internal rotation. This further supports the observation that the rotational dynamics of the knee joint are significantly altered following TKA, highlighting the need for advancements in surgical techniques and prosthetic designs to better restore normal knee functionality.

5. Conclusions and Prospects

5.1. Conclusions

This study quantitatively analyzed the kinematic characteristics of the knee joint during squatting in patients after TKA using an optical motion-capture system. The findings revealed significant differences in postoperative knee mechanics compared to healthy individuals. Specifically, the maximum postoperative flexion angle was reduced by approximately 28.6%, highlighting the persistent limitation in high-flexion movement after TKA. Additionally, the peak femoral external rotation increased by 2.06 degrees compared to the healthy group, with the peak occurring earlier, indicating an altered rotational pattern during squatting. Femoral posterior translation reached 11.2 mm at 99 degrees of flexion, which was 4.3 mm greater than that observed in the healthy group at the same angle. Furthermore, the peak superior translation was measured at 7.56 mm, exceeding that of the healthy group. These results underscore that postoperative knee motion during squatting differs from that of healthy subjects in both rotational and translational behaviors. Such insights provide a valuable experimental basis for understanding the biomechanical changes following TKA. They also emphasize the need for targeted rehabilitation strategies and advancements in prosthesis design to address these limitations and improve patient outcomes.

5.2. Prospects

Although this study achieved meaningful results, it is important to acknowledge its limitations. The limited sample size restricted the ability to account for variables such as age, sex, and prosthesis differences, which could influence the findings and potentially lead to one-sided conclusions. Additionally, the study focused solely on the squatting motion, whereas the knee joint is involved in a wide range of complex activities in daily life. The motion and loading patterns of the knee vary significantly across different tasks, and the exclusive measurement of a single movement limits the broader applicability of the findings in clinical practice. Addressing these limitations is crucial for enhancing the generalizability and clinical relevance of future research.

Future studies should aim to address these limitations by increasing the sample size and incorporating a more diverse population to account for factors such as age, sex, and prosthesis variations. Expanding the range of motion tasks to include activities beyond squatting will provide a more comprehensive understanding of knee joint mechanics in various functional scenarios. Furthermore, integrating advanced research methods, such as electromyography, finite-element simulation models, and imaging techniques, can offer a multidisciplinary perspective on the kinematic mechanisms underlying knee joint behavior. These approaches could help identify novel kinematic indicators, refine the evaluation of knee function after TKA, and support the development of personalized prosthesis designs and rehabilitation strategies. By promoting continuous advancements in TKA technology, such research has the potential to improve patient prognosis, enhance functional outcomes, and contribute to the overall quality of life for individuals undergoing TKA.

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