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Operative Techniques in
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Concepts and Measurement of In Vivo Tibiofemoral Kinematics

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Recent studies of tibiofemoral kinematics in 6 degrees-of-freedom have given us a new perspective and demonstrated lateral compartmental roll-back centered on a medially oriented axis over a relatively stable medial compartment during functional arcs of sagittal knee motion. This translates into coupled internal tibial rotation with increasing knee flexion, which is altered by anterior cruciate ligament (ACL) injury. During terminal extension, the tensioned ACL provides an internal torque to the lateral femoral condyle with tightening of the lateral collateral ligament, culminating in the 'screw-home mechanism'. Studies of tibiofemoral kinematics in the ACL-deficient knee have demonstrated posterior and medial shifts of the femur relative to the tibia reference point. In addition, the ACL-deficient knee also demonstrates different patterns of tibiofemoral kinematics during gait. Current ACL-reconstruction techniques will restore some functions of the ACL; however, some studies have suggested that anatomical ACL-reconstruction may better restore normal tibiofemoral kinematics. Although in vitro studies have contributed much to our knowledge of knee kinematics, increasingly accurate in vivo measurement techniques now offer new insight on rotational stability. The methodologies of in vivo kinematics include radiological techniques, video-based motion analysis, electromagnetic tracking devices, and ultrasound-based systems. As management of knee pathologies continue to evolve, development of reliable measures of rotational stability may be the next challenge in clinical and functional outcome assessment.
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Evolving techniques of assessing in vivo tibiofemoral kinematics have contributed significantly to current concepts in normal and pathological knee kinematics, challenging previous models extrapolated from 2-dimensional sagittal knee motion. This article presents a review of the literature on tibiofemoral kinematics in the healthy and ACL deficient knee, with emphasis on rotational stability. It also discusses techniques of in vivo knee kinematic measurements as we move toward reconstruction of the ACL designed to improve both translational and rotational stability.

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Tibiofemoral Kinematics in the Healthy Knee

Previous 2-dimensional analysis of sagittal knee motion has described a curved, predictable pathway through flexion with an instantaneous center of rotation through each flexion angle.[1-4] Assuming the ACL and posterior cruciate ligament to be rigid structures, the 4-bar linkage theory allows for sagittal knee motion to be described as a combination of gliding and rolling.[5,6] Recent advances in both in vitro and in vivo techniques have provided a new perspective on 3-dimensional knee kinematics which can be described in 6 degrees of freedom (DOF). The ability to analyze kinematics of the medial and lateral compartment separately on magnetic resonance imaging (MRI) has led to intercompartmental differential femoral roll-back to be interpreted as a longitudinal rotation coupled with tibiofemoral flexion, thus introducing the concept of rotational knee stability and

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motion.[7,8] This progressive tibial internal rotation and lateral femoral roll-back during knee flexion has been described as a helical knee motion.[9]

The complex 3-dimensional tibiofemoral kinematics result from the interaction between bony, soft tissue restraints and the effect of muscular activation during weightbearing and nonweightbearing activities. In sagittal section, the medial femoral condyle comprises the arcs of two circles articulating on two angled 'flats' of the tibia.[10] This contrasts with the lateral femoral condyle, which is composed almost entirely of a single, circular facet similar in radius and arc to the posterior medial facet.[10]

Tibiofemoral Kinematics in 6 DOF in the Healthy Knee

From the arc of 20° to full extension, the articulating posterior condyles shift to the larger radii of the anterior condyles, lifting the posterior condyle away from the tibia.[11] In the last 10° of extension, there is tightening of the capsular and ligamentous structures with "rocking" of the medial condyle forward into contact between the anterior extension facets of the tibia and femur. Laterally, the contact point of the lateral condyle also shifts forward and rotates down to contact the anterior tibial surface.[12] More importantly, the ACL which is already maximally tensioned vertically at 10° flexion, exerts its tension in a horizontal plane and pulls the lateral femoral condyle internally.[13] This accounts for the "screw home mechanism" of the knee first described by Hallen and Lindahl.[14]

Throughout the functional range of flexion (20° to 110°), the medial femoral condyle moves neither anteriorly nor posteriorly in the unloaded cadaveric knee, the unloaded knee in a living subject, or in a loaded knee in the living subject.[10,15] This was postulated to be a result of the firmly attached posterior horn of the medial meniscus, tightening of some fibers of the superficial medial collateral ligament from 20° to 90°, and tension in the bulk of the posterior cruciate ligament at 60° to 120°.[16,17] In contrast, the lateral femoral condyle tended to move backwards together with the more mobile lateral meniscus, thus resulting in external femoral rotation with progressive flexion.[10,15] This pattern of motion was previously suggested when coupling of tibial internal rotation to flexion was demonstrated in vitro with an electromagnetic tracking system and confirmed on further MRI studies, where the medial tibiofemoral contact point and flexion facet center remained unchanged from 30° to 120° flexion whereas the lateral moved backwards by approximately 15 mm.[12,18] Hence, the authors concluded that roll-back does occur in the lateral compartment but not the medial, with the femur rotating externally around a medial center.[12] This axis has been located by Hollister and coworkers to pass through the tibial insertion of the ACL, whereas Matsumoto and coworkers determined that it varies with flexion but largely remains in the area between the 2 cruciate insertions on the tibia.[19,20]

Interaction of bony geometry determines deep knee flexion kinematics. Muscular action appears to have little effect on tibial translation and rotation at high flexion angles.[21] Nakagawa and coworkers and Li and coworkers reported a sharp increase in tibial internal rotation occurring beyond 120° flexion.[21,22] The change in convexity to concavity in articular geometry beyond the posterior condyles and the impingement of the shallower superior surface of the lateral condyle on the lateral side of the knee results in this increased tibial internal rotation.[22]

Tibiofemoral Kinematics During Gait

Tibiofemoral motion during normal gait requires 0° to 60° of sagittal flexion. At heel contact, the knee is flexed about 5° and continues to flex up to 15 to 20°. It then reaches nearly full extension until heel off. At this point, the knee starts to flex reaching 35° at toe off. The maximum knee flexion of 60° occurs at the beginning of mid-swing phase for toe clearance. During mid to terminal swing, the knee extends again before heel contact.[23]

Understanding normal rotation in the frontal and transverse planes during gait is even more important due to the goals of anatomical reconstruction in restoring preinjury tibiofemoral kinematics. Using intracortical pins, Lafortune and coworkers measured secondary tibiofemoral motions during gait.[24] The authors reported 1.2° valgus and 2°-3° external rotations of the tibia at heel contact up to 5° valgus and 5° internal rotation throughout the gait phase. Reinschmidt and coworkers reported similar kinematic pattern throughout gait with greater total range of motion of 5°-10° for both abduction/adduction and internal/external rotations.[25]

Tibiofemoral Kinematics in the ACL-Deficient Patient

Tibiofemoral Kinematics in 6 DOF in the ACL-Deficient Knee

Recent open MRI studies demonstrate medial and lateral compartmental shifts in the tibiofemoral contact points with ACL injury.[26-29] Compared with the contralateral healthy knee, Scarvell and coworkers reported a 1-mm posterior shift in the medial compartment at 0° and 15° knee flexion and 1.5 mm posterior shift in the lateral compartment throughout range of motion in the ACL-deficient knee.[26] Similarly, von Eisenhart-Rothe and coworkers reported a 1.3-mm posterior shift of the medial compartment in the ACL-deficient knee.[30] Logan and his colleagues conducted a study to assess tibiofemoral kinematics in ACL-reconstructed knees and reported that the amount of excursion between the tibial and femoral joint surfaces was similar; however, the lateral compartment was displaced 5 mm posteriorly throughout the flexion arc of 0° to 90°.[28]

Based on kinematic analysis of cadaveric ACL-deficient knees, Mannel and coworkers reported that ACL disruption led to greater than 10 mm of medial translation of the axis of motion of the femur.[31] This is in agreement with previous research that located the longitudinal axis of the normal knee in the medial compartment whereas the axis of the pivot shift was localized more medially at the medial collateral ligament in ACL disruption.[19,20,32] However, to our knowledge, no

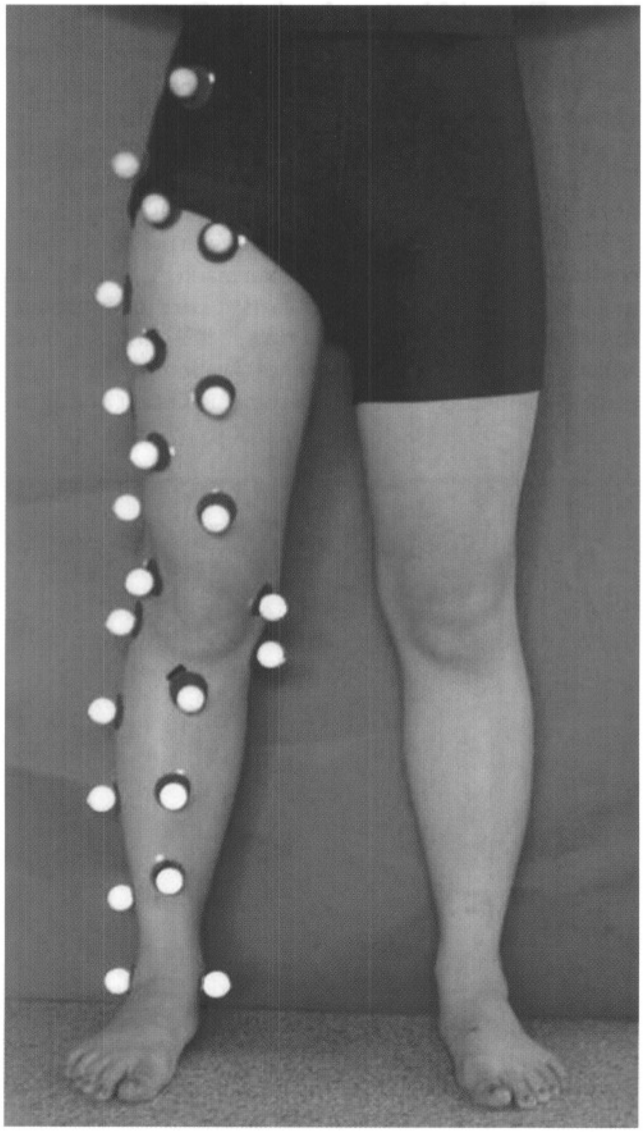

Figure 1 Retroreflective Marker positions for point cluster technique.

study has attempted to investigate the effect of ACL-reconstruction in restoring the longitudinal axis of knee rotation.

Tibiofemoral Kinematics in the ACL-Deficient Patient During Gait

Very few studies have attempted to accurately identify tibiofemoral kinematics of the ACL-deficient knee in 6 DOF during gait. Previous gait analysis of ACL-deficient patients demonstrated various adaptations in kinematics. The ACL-deficient patients are further categorized into 2 groups: copers who can still participate in any type of sports without any episode of giving way and noncopers who cannot do these. Previous studies have reported that copers walked with similar or increased knee flexion while noncopers walked with decreased flexion and slower speeds.[33-35]

Other studies investigated 6 DOF during gait and reported that ACL-deficient patients walked with increased external rotation and abduction of the tibia to compensate for the loss of ACL.[36,37] Conversely, Georgoulis and colleagues reported increased internal rotation of the tibia preoperatively after acute ACL injuries and similar rotation postoperatively, compared with those in ACL-intact knees.[38] Significant increase in standard deviations and variability in these studies suggest difficulty and inconsistency in recording internal/external and abduction/adduction rotations of the tibia during gait. Therefore, the effects of ACL reconstruction for restoring preinjury 6 DOF during gait are not fully understood.

Kinematics of Clinical Tests in the ACL-Deficient Knee

The Lachman and pivot shift tests have long been used to elicit abnormal knee kinematics following ACL injury but only recently, a significant increase in lateral compartment motion (ie, tibial internal rotation) in ACL-deficient knees was demonstrated on MRI.[8] Matsumoto had described an abnormal internal tibial rotation during the pivot shift in cadaveric knees using biplanar photography and located its axis at the medial collateral ligament.[32] More recently, Bull and coworkers defined both a rotational and translational component of the pivot shift. The reduction of the anteriorly subluxed tibia was found to occur at 56° flexion with a tibial external rotation of 17°.[39]

The role of the ACL in restraining increased internal tibial rotation has been emphasized by Kanamori and coworkers who demonstrated increased internal tibial rotation in the ACL-deficient knee during a simulated pivot shift test.[40] They also went on to demonstrate that an internal tibial torque (as applied during the pivot shift) caused greater increase in coupled anterior tibial translation of up to 10.2 mm in the ACL-deficient knee.[41]

Measurement of Tibiofemoral Kinematics

In vitro techniques have contributed much to our current knowledge of knee kinematics as described in the previous

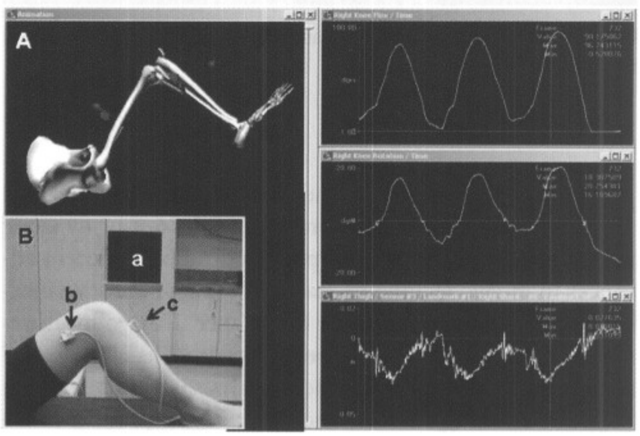

Figure 2 Electromagnetic tracking of the knee joint. (A) The animation of the 3-dimensional knee position. (B) Electromagnetic receiver sites of attachment. (a) Long Range Transmitter. (b) Femoral sensor. (c) Tibial sensor.

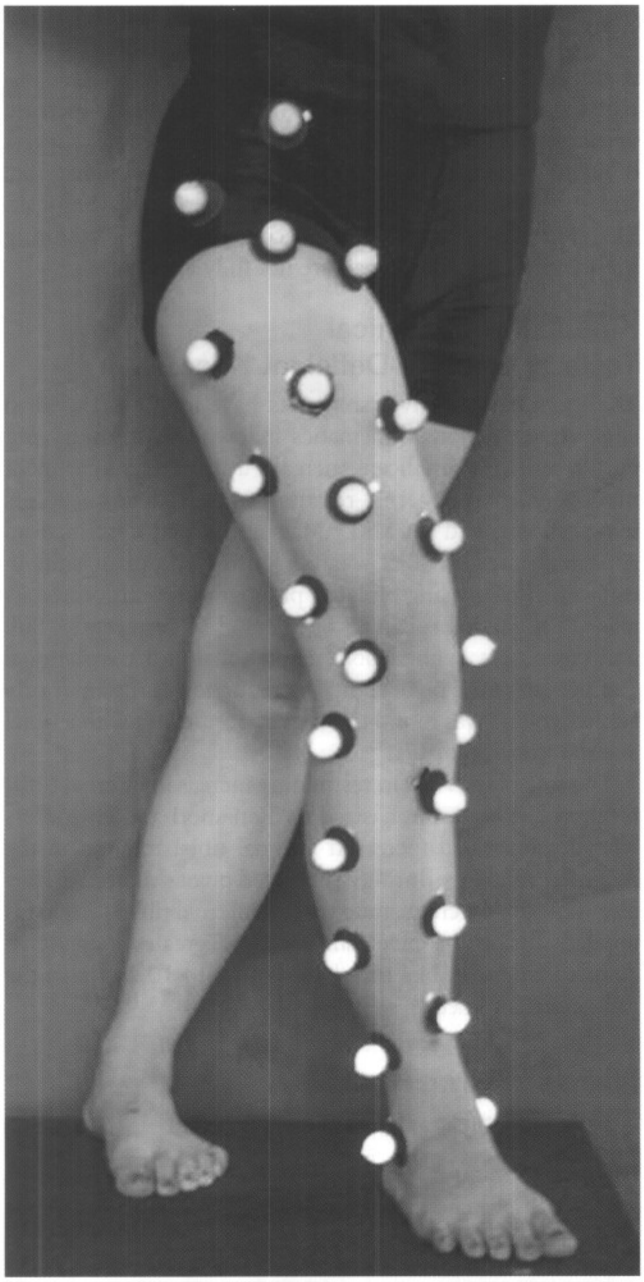

Figure 3 Standing pivot-shift test assessment using the video-based motion analysis system.

paragraphs. Many scientists and clinicians are also interested in examining in vivo tibiofemoral kinematics during dynamic movements, such as gait, jumping, and running. Recent advances in in vivo techniques have led to more accurate measurement of kinematics in the living knee. In vivo measurement methods can largely be categorized as radiological techniques, video-based motion analysis systems, electromagnetic tracking devices, and more recently, ultrasound-based systems.[42,43] In the following section, we will discuss the video-based and electromagnetic motion analysis systems, 2 commonly used systems in the sports medicine laboratory.

Video-Based Motion Analysis System

In orthopaedic and biomechanics literature, video-based motion analysis systems have been widely used to study the tibiofemoral joint kinematics because it is noninvasive, easy to operate, and able to assess various movements such as gait, landing, jumping, and cutting.[44-48] However, because of soft-tissue movement artifacts (mainly from skin), it has limited applications, even in research. According to previous studies comparing bone pin markers and skin markers, there were as much as 10 mm of soft tissue artifacts at knee joint markers, and 8° of associated rotational errors.[25,49-51] Although these artifacts may be acceptable in knee rotation in the sagittal plane (flexion/extension), they become significant during in-

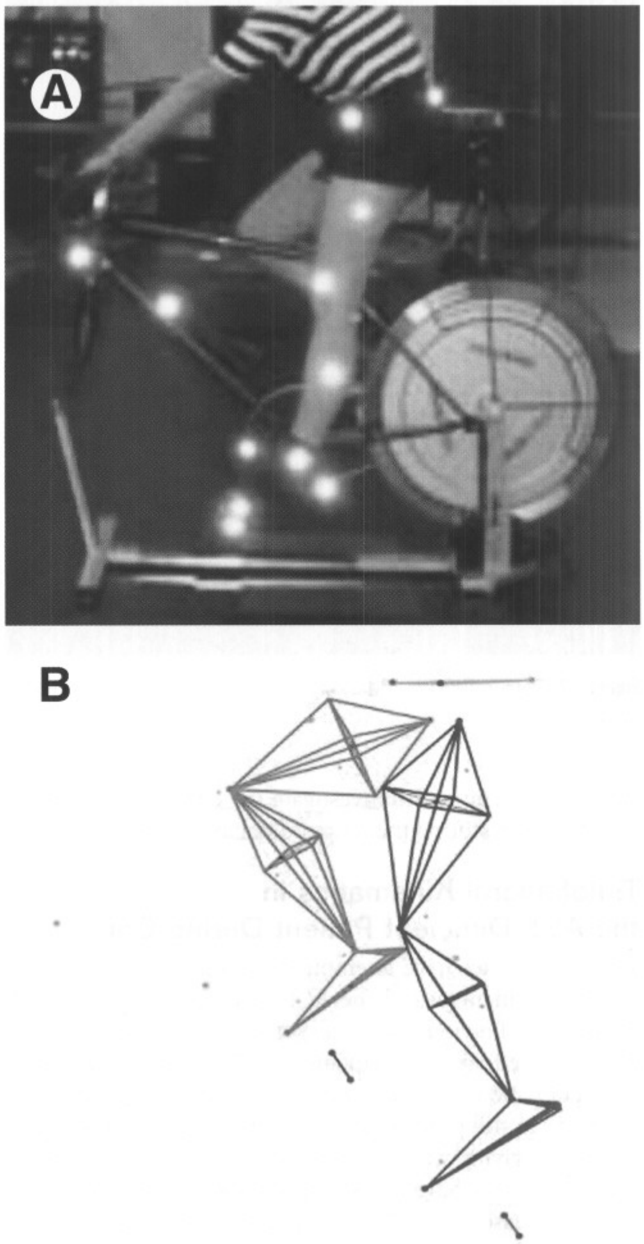

Figure 4 Pedaled cycling assessment using the video-based motion analysis system. (A) Retroreflective Marker positions. (B) Stick figure.

ternal/external and abduction/adduction rotations because of their limited total range of motion.[49,50,52] Therefore, the data collected from a video-based motion analysis system should be interpreted carefully.

Researchers have developed several methodologies to minimize errors associated with soft-tissue artifacts.[53-55] Andriacchi and colleagues have combined the "point cluster technique" (Fig. 1), in which clusters of skin markers were placed on each segment, with the "interval deformation technique," which uses a model of skin deformation during daily activity to minimize skin artifacts.[53,56] Their methodology has been compared with a previous study using the Ilizarov external fixation device and satisfactorily minimized the errors up to 0.25 mm in location and 0.37° in orientation.[57]

Electromagnetic Tracking Device (ETD)

ETD has been employed by various researchers to track the tibiofemoral kinematics both in vitro and in vivo.[39,58,59] This system (Fig. 2) allows for in vivo tracking of knee kinematics in 6 DOF simultaneously and can operate up to a radius of 0.7 mm from the transmitter, with an accuracy of ±0.5 mm in translation and ±1° in rotation, collecting data at 100 Hz.[60] Another advantage of ETD is the capability to assign any anatomical points to obtain 6 DOF data.

Although ETD can collect surface points noninvasively with a high frequency, the main drawback lies in their poor precision (mainly due to skin artifacts) and lack of methods to compensate for this inaccuracy. The root mean square (RMS) error was previously reported to be 1.5 mm or worse, but van Ruijven and coworkers recently evaluated a method to improve accuracy in modeling articular surfaces up to a RMS of 0.07 to 0.18 mm.[30]

Future Directions

Improved appreciation of knee kinematics throughout functional ranges of sagittal knee motion will continue to evolve from noninvasive in vivo studies of the living knee with greater accuracy from newer technologies. This may lead to revised definitions and classifications of posttraumatic knee derangements especially in ACL injuries. The need to reproduce preinjury knee kinematics and rotational stability necessarily demands changes in post injury rehabilitation protocols and a more anatomic reproduction of the ACL during surgical reconstruction. Attempts to achieve the latter include a more horizontally oriented femoral tunnel or double-bundle ACL reconstruction.[61,62]

With the evolution of surgical management of ACL injuries, including anatomic reconstructions, in vivo techniques will hopefully be available to assess and compare clinical and functional outcomes. Although radiographic images have promising accuracy, development of quantitative measures of rotational stability in vivo during human movements is a very important future step in outcome assessment. However, a standardized accurate measurement technique, which is functional, noninvasive, and easy to use for many subjects, has yet to be determined. Possible in vivo clinical assessment tests such as the "standing pivot-shift test" (Fig. 3) or "internal pedaled cycling" (Fig. 4) may allow us to report internal/external rotations of the tibia quantitatively and accurately.

Currently in our laboratory, dynamic instability in the ACL-deficient knee is being measured during stationary cycling using a video-based motion analysis system. This allows simultaneous capture of hip, knee and ankle motions in 6 DOF during cycling, which has similar knee kinematics to walking and is commonly utilized during rehabilitation after ACL injuries and reconstruction. Comparison of secondary internal/external rotation between the normal and ACL deficient knee may provide a means for assessing dynamic rotational stability.

Quantification of the pivot shift and dynamic rotational instability on the ETD is also being evaluated for accuracy and minimization of skin movement artifacts. Both these devices may provide objective measures of rotational stability after different treatment protocols.

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