Evaluation of Kinematics of Anterior Cruciate Ligament-Deficient Knees with Use of Advanced Imaging Techniques, Three-Dimensional Modeling Techniques, and Robotics

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Measuring knee biomechanics in six degrees of freedom with acceptable accuracy has been proven to be technically challenging. At our bioengineering laboratory, we have employed both an in vitro robotic testing system and an in vivo combined dual fluoroscopic and magnetic resonance imaging technique to analyze the impact of anterior cruciate ligament rupture on the knee joint.

When measuring the tibiofemoral kinematics of nine cadavers with the robotic testing system, we found that anterior cruciate ligament deficiency not only altered anterior translation and axial rotation of the tibia, but it also increased the medial translation of the tibia as well. The in vivo dual fluoroscopic imaging analysis of tibiofemoral kinematics in ten anterior cruciate ligament-deficient patients revealed analogous findings: an increased medial translation of the tibia of approximately 1 mm between 15° and 90° of flexion was found in anterior cruciate ligament-deficient knees, in addition to an increased anterior translation (approximately 3 mm) and internal rotation (approximately 2°) of the tibia at low flexion angles. In a subsequent study of tibiofemoral cartilage contact, we found that the cartilage contact points shifted posteriorly—as was expected on the basis of the increased anterior tibial translation—as well as laterally on the surface of the tibial plateau.

The data demonstrate how rupture of the anterior cruciate ligament initiates a cascade of events that eventually results in abnormal tibiofemoral cartilage contact in both the anteroposterior and mediolateral directions. If the restoration of normal knee homeostasis is the ultimate goal of ligament reconstruction, the normal function of the anterior cruciate ligament should be restored as closely as possible in all degrees of freedom.

Injuries to the anterior cruciate ligament are very common. In the United States alone, approximately 80,000 individuals per year sustain a rupture to the anterior cruciate ligament¹. Furthermore, this injury is sustained primarily by young and active individuals. It has been calculated that anterior cruciate ligament deficiency could affect one of every 1750 persons in the fifteen-to-forty-five-year-old age group annually². The results of anterior cruciate ligament deficiency can be devastating. Acute rupture is often associated with meniscal tears, chondral damage, and injury to the medial collateral ligament³⁻⁸. As the anterior cruciate ligament injury becomes chronic, an increasing prevalence of joint swelling, instability, and meniscal tears is found, eventually resulting in progressive osteoarthritis^{3,9-11}. Because of these detrimental clinical findings, it is

understandable why there has been a tremendous amount of study of the knee joint with regard to anterior cruciate ligament deficiency.

Some authors have hypothesized that the abnormal kinematics seen in anterior cruciate ligament-deficient knees would alter the stress distributions in the articular cartilage and thus predispose the knee to degenerative changes¹²⁻¹⁴. At our laboratory, we have employed both an in vitro robotic testing system^{15,16} and an in vivo combined dual fluoroscopic and magnetic resonance imaging technique¹⁷ to analyze the impact of anterior cruciate ligament rupture on the knee joint. In this article, we present our previously published in vitro and in vivo data on the effect of anterior cruciate ligament deficiency on six-degrees-of-freedom knee kinematics^{16,18-23}.

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Fig. 1

The robotic testing system with pulleys for the application of muscle loads.

Methodology

Robotic Testing System

The robotic testing system applies various external loads on a human cadaver knee and measures the corresponding changes in knee kinematics as well as in situ forces in the native anterior cruciate ligament and anterior cruciate ligament graft^{15,24}. The robotic manipulator is a device that controls the position of the knee in six degrees of freedom in space. Under the force-control mode, the robotic manipulator can also apply an external load to a knee specimen through the attached universal force-moment sensor (Fig. 1). These two features provide the test system with the capability of both position and force-control modes. A pulley system is mounted on the femoral clamp to allow application of muscle loads (the quadriceps, semitendinosus, semimembranosus, and biceps femoris) to simulate isometric flexion and extension of the knee. With use of the principle of superposition²⁵, the in situ force of the native anterior cruciate ligament and the anterior cruciate ligament graft can be obtained by calculating the differences between the forces measured before and after anterior cruciate ligament transection and reconstruction, respectively. The robotic manipulator can learn and reproduce the complex motion of the

knee joint. One limitation of the robotic testing system, however, is in the simulation of physiological loading conditions. The robotic system simulates isometric flexion and/or extension of the knee by applying quadriceps and hamstring loads by means of hanging weights. Knee-joint loads during weight-bearing activities are much more complex than those simulated in this system. Furthermore, due to the in vitro nature of the robotic testing system, graft-healing and postrehabilitation effects on graft biomechanics cannot be addressed.

Combined Dual Fluoroscopic and Magnetic Resonance Imaging Technique

To overcome the limitations of the in vitro studies, our laboratory has developed a combined dual fluoroscopic and magnetic resonance imaging technique to analyze the impact of anterior cruciate ligament rupture on the knee joint in vivo¹⁷.

Three-dimensional knee models are created from a series of sagittal magnetic resonance images of the knee, and the motion of the subject's knee is recorded with use of two fluoroscopes¹⁸. The three-dimensional knee model and the fluoroscopic images are then imported into a solid modeling software program (RhinoCeros; Robert McNeel and Associates, Seattle,

Fig. 2

The overall procedure used to reproduce in vivo knee kinematics with use of the combined dual fluoroscopic and magnetic resonance imaging technique. Each subject's (A) magnetic resonance imaging (MRI) scans (B) are used to construct a three-dimensional (3D) anatomic knee model (C). Each subject's knees are then imaged from two directions during in vivo activities (D). The knee model is manipulated in six degrees of freedom to reproduce the knee positions (E-G).

Fig. 3-A

Fig. 3-B

Fig. 3-C

Anteroposterior (AP) translation (Fig. 3-A), internal-external (IE) rotation (Fig. 3-B), and mediolateral (ML) translation (Fig. 3-C) of the tibia relative to the femur for the intact and anterior cruciate ligament (ACL)-deficient knees. Asterisk denotes p value < 0.05 , with use of a repeated-measures analysis of variance. (Reproduced, with permission, from: DeFrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, Li G. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. *Am J Sports Med.* 2006;34:1243.)

Washington) to construct a virtual dual fluoroscopic system. To determine the in vivo position of the knee, the three-dimensional knee models are viewed from two directions corresponding to the x-ray sources of the fluoroscopes. The models are manipulated in six degrees of freedom until their projections match the outlines of the knee on the two fluoroscopic images. These models are used to measure the in vivo position and orientation of the knee (Fig. 2). The accuracy of this methodology in measuring translation and rotation has been rigorously validated for both quasistatic and dynamic motion^{17,18,26}.

Study Results

Normal Anterior Cruciate Ligament Function

In order to fully comprehend the effect of anterior cruciate ligament rupture on the knee joint, investigation of the healthy anterior cruciate ligament was first necessary.

The in situ forces in the anterior cruciate ligament and posterior cruciate ligament were measured with use of the robotic testing system²³. When the cadaver knees were subjected to combined quadriceps and hamstring loads, the force in the anterior cruciate ligament peaked at 30°, whereas the force in the posterior cruciate ligament peaked at 90°²³. These findings can be qualitatively related to the in vivo elongation pattern of the individual bundles of the cruciate ligaments as studied in the healthy knee with use of the combined dual fluoroscopic and magnetic resonance imaging technique. The anterior cruciate ligament bundles were longest in low flexion angles, whereas the posterior cruciate ligament had increased length during flexion²¹. Of interest, the data illustrated that a reciprocal function exists between the posterior cruciate ligament and the anterior cruciate ligament during flexion but that a reciprocal function does *not* exist between the anteromedial and posterolateral bundles of the anterior cruciate ligament—a

Fig. 4

Illustration showing the motion of the three-dimensional tibiofemoral contact points for the intact (contralateral) and anterior cruciate ligament (ACL)-deficient knees at full extension and at 15°, 30°, 60°, and 90° of flexion, averaged across the nine patients. (Reproduced from: Li G, Moses JM, Papannagari R, Pathare NP, DeFrate LE, Gill TJ. Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. *J Bone Joint Surg Am.* 2006;88:1830.)

traditional concept based on cadaver studies in which the anteromedial and posterolateral bundles were believed to be taut at high and low flexion angles, respectively²⁷. Instead, with in vivo flexion, both bundles of the anterior cruciate ligament are parallel and maximally elongated at low flexion angles¹⁹.

Most biomechanical research of the anterior cruciate ligament has modeled the cruciate ligament as a straight line and limited the measurements to the elongation of this line²⁸⁻³⁰. However, the anterior cruciate ligament is a continuum of fibers, with a clear three-dimensional structure. During weight-bearing knee flexion, the twist of the anterior cruciate ligament increases with increasing flexion. At low flexion angles, the anterior cruciate ligament is oriented more vertically (approximately 60°) and slightly laterally (approximately 10°), once more indicating that the anterior cruciate ligament plays a more important role at lower flexion angles than at higher flexion angles during weight-bearing flexion²⁰. With these insights into the function of the anterior cruciate ligament, we can now more clearly explain the changes in kine-

matICS that are observed in anterior cruciate ligament-deficient knees.

Normal Tibiofemoral Joint Kinematics

When the passive flexion path of cadaver knees was investigated with the robotic manipulator, the tibia moved anteriorly as the flexion angle increased. The tibia also internally rotated during passive flexion¹⁶. When studying the tibiofemoral kinematics based on the osseous geometry of the femur and tibia of the healthy weight-bearing subjects with use of our combined dual fluoroscopic and magnetic resonance imaging technique, we found a similar anterior translation of the tibia with increasing flexion. At full extension, the tibia of the intact knee was -3.2 ± 3.0 mm (positive values denote anterior position, while negative values denote posterior position) from the center of the femur. At 90° of flexion, the tibia was 14.1 ± 3.9 mm from the center of the femur. Analogous to the in vitro passive flexion path, the tibia rotated internally with increasing in vivo flexion of the knee. At full extension, the healthy knee was rotated by $-4.9^\circ \pm 7.2^\circ$ relative to the femur (positive

values denote internal tibial rotation, while negative values denote external rotation). At 30° of flexion, the tibia rotated internally to $3.6^\circ \pm 4.7^\circ$. Thereafter, the tibia rotated slightly, reaching a maximum of $8.0^\circ \pm 4.5^\circ$ at 90° of flexion¹⁸.

Disturbed Tibiofemoral Joint Kinematics

With use of the robotic testing system, we measured the kinematics in nine cadaver tibiofemoral joints, from full extension to 90° of flexion both before and after anterior cruciate ligament resection, and found that anterior cruciate ligament deficiency not only altered anterior translation and axial rotation of the tibia (findings that have been documented extensively in the in vitro and in vivo literature³¹⁻³⁶) but also increased the medial translation of the tibia³⁷. Our in vivo dual fluoroscopic imaging analysis of the tibiofemoral kinematics in ten patients with acute anterior cruciate ligament deficiency revealed analogous findings: an increased anterior translation (approximately 3 mm, Fig. 3-A) and internal rotation (approximately 2°, Fig. 3-B) of the tibia at low flexion angles¹⁸, as well as a medial translation of the tibia of approximately 1 mm between 15° and 90° of flexion (Fig. 3-C)¹⁸. This medial shift of the tibia relative to the femur can be explained by the relative lateral orientation of the native anterior cruciate ligament, as described above²⁰. The tibial insertion of the anterior cruciate ligament remains medial to the femoral insertion as the knee flexes, possibly providing resistance to the medial translation of the tibia in the healthy knee.

Normal Cartilage Contact Characteristics

One of the most common long-term complications of anterior cruciate ligament deficiency is the development of osteoarthritis of the knee. Therefore, it was important to include the description of the cartilage contact characteristics in the investigation of the tibiofemoral joint in limbs with anterior cruciate ligament deficiency. With use of cartilage contact models of the healthy knee, the medial femoral condyle was shown to remain within the central portion of the tibial plateau from 0° to 90° of flexion during weight-bearing flexion. The lateral articular contact point was 4 mm anterior to the centerline of the tibial plateau at 0°, and it consistently moved posteriorly with flexion³⁸. Both the medial and lateral tibiofemoral contact points were located on the inner portions of the tibial plateau and femoral condyles (close to the tibial spine), indicating that the tibial spine may play an important role in knee stability³⁹. An interesting finding was that, in normal knees, the cartilage was thicker in regions where cartilage-to-cartilage contact was present^{14,40}. This further supports the hypothesis that injuries that alter knee kinematics might load regions of the joint where cartilage is thinner and thereby alter the stress distributions within the cartilage.

Disturbed Cartilage Contact Characteristics

The changes in the tibiofemoral kinematics after anterior cruciate ligament injury were expected to lead to changes in the tibiofemoral cartilage contact characteristics. Specifically, the medial shift of the tibia after anterior cruciate ligament deficiency

would alter the contact stress distributions in the tibiofemoral cartilage near the medial tibial spine. Indeed, in the presence of anterior cruciate ligament injury, the cartilage contact points not only shifted posteriorly—as was expected on the basis of the increased anterior tibial translation—but also laterally on the surface of the tibial plateau²² (Fig. 4). In the medial compartment, the contact points shift toward the medial tibial spine, a region where degeneration is observed in patients with chronic anterior cruciate ligament injuries. For example, Fairclough et al.⁴¹ noted that patients with chronic anterior cruciate ligament deficiency often had osteophytes on both the femur and the tibia, near the medial tibial spine. These data underscore the concept that, if the tibiofemoral cartilage is to be protected, the ideal reconstruction of the anterior cruciate ligament should aim to restore the motion of the three-dimensional tibiofemoral cartilage contact points, not only in the anteroposterior but also in the mediolateral direction.

Conclusions

Our research in biomechanics of the knee joint has evolved from an in vitro experimental design to full in vivo imaging measurements. The advantage of the in vitro method is the quantitative nature, that is, the possibility to directly measure the effects of anterior cruciate ligament deficiency and reconstruction on knee joint kinematics with use of the same specimen, thus minimizing the interspecimen variation. Furthermore, the in vitro test also provides quantitative data on the in situ forces of the anterior cruciate ligament and the anterior cruciate ligament graft under controlled loading conditions. On the other hand, the in vivo combined dual fluoroscopic and magnetic resonance imaging technique that was developed in our laboratory provides an easy and powerful tool for accurately determining six-degrees-of-freedom positions of healthy, injured, and surgically treated knees in three-dimensional space. Our data demonstrate how rupture of the anterior cruciate ligament initiates a cascade of events that eventually results in abnormal tibiofemoral cartilage contact in both the anteroposterior and mediolateral directions. If the restoration of normal knee homeostasis is the ultimate goal of ligament reconstruction, then normal function of the anterior cruciate ligament should be restored as closely as possible in all degrees of freedom. ■

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