Evaluation of Knee Stability with Use of a Robotic System

By Savio L-Y. Woo, PhD, DSc(Hon), and Matthew B. Fisher, BS

In our research center, we have developed and utilized a novel robotic/universal force-moment sensor testing system to gain quantitative data on multiple-degree-of-freedom kinematics of the knee simultaneously with data on the in situ forces in normal and repaired soft tissues. In particular, we have investigated the complex interaction of the anteromedial and posterolateral bundles of the anterior cruciate ligament as well as several key biomechanical variables in anterior cruciate ligament reconstruction, such as graft selection and femoral tunnel placement (both of which impact knee stability). For example, both the bone-patellar tendon-bone and quadrupled hamstrings tendon autografts restored anterior stability but were insufficient in gaining rotatory stability. In a follow-up study, we have shown that a more laterally placed graft was beneficial and could improve these outcomes. Such findings led to additional investigation in which the biomechanical advantages of double-bundle anterior cruciate ligament reconstruction were demonstrated. However, a more laterally placed autograft at the femoral insertion of the posterolateral bundle also worked well, especially when the knee was nearly at full extension (a position in which the anterior cruciate ligament is needed most). At present, we are moving forward by obtaining in vivo kinematics data and then repeating those kinematics exactly to obtain new data with use of the robotic/universal force-moment sensor testing system in order to gain further insight regarding the function of the anterior cruciate ligament and anterior cruciate ligament replacement grafts in vivo. In parallel, we are developing a mathematical model of the knee and validating the computational model with experimental data. The combined approach will yield new and relevant information, including the stress and strain distribution in the anterior cruciate ligament and anterior cruciate ligament grafts. This will facilitate a better understanding of the function of the anterior cruciate ligament and a scientifically based design of surgical procedures and postoperative rehabilitation protocols that will lead to better patient outcomes.

The need to know the function of various soft tissues in and around diarthrodial joints has led to the design and development of a number of biomechanical devices to study multiple-degree-of-freedom joint kinematics as well as the in situ forces in these tissues and their contribution to joint stability. Since 1993, our research center has been developing a unique robotic/universal force-moment sensor testing system that consists of a six-degrees-of-freedom robotic manipulator capable of recording and reproducing positions in three-dimensional space with an accuracy of <0.2 mm and 0.2° (Fig. 1). In combination with the universal force-moment sensor mounted to the end effector, the testing system can operate in position control, force control, or hybrid mode. To date, use of this technology has been reported in more than eighty published studies on the knee, shoulder, and other joints¹⁻⁶, and, over the years, more than a dozen other laboratories have adopted this system^{7,8}.

The robotic/universal force-moment sensor testing system offers a number of distinct advantages. First, a reference

position for a joint can be established and used as a common starting position for all experimental conditions. This allows direct one-to-one comparisons of multiple experimental conditions in the same cadaver knee specimen (e.g., the knee in which the anterior cruciate ligament is intact compared with the same knee following anterior cruciate ligament reconstruction). Furthermore, this reduces the effect of interspecimen variation and greatly increases the statistical power of the data. Second, the robotic/universal force-moment sensor testing system can operate in both force-control and position-control modes. In force-control mode, the robot applies an external load to the specimen and the corresponding kinematics can be obtained. Alternatively, the robotic/universal force-moment sensor testing system can operate under position-control mode by moving the specimen exactly along a previously recorded motion path so that the universal force-moment sensor can record a new set of force and moment data. As such, the in situ force in a specific tissue can be calculated in a noncontact manner by determining

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Fig. 1

Schematic drawing illustrating the robotic/universal force-moment sensor (UFS) testing system and the six degrees of freedom (DOF) of motion of the human knee joint: anterior-posterior (AP), medial-lateral (ML), and proximal-distal (PD) translations; flexion-extension (FE), internal-external (IE), and varus-valgus (VV) rotations. (Reproduced, with permission, from: Allen CR, Livesay GA, Wong EK, Woo SL-Y. Injury and reconstruction of the anterior cruciate ligament and knee osteoarthritis. *Osteoarthritis Cartilage*. 1999;7:117.)

the changes in measured forces for a given set of kinematics before and after removing that tissue (for example, cutting the anterior cruciate ligament), on the basis of the principle of superposition⁵. With these advantages, this technology has been applied to study the anterior cruciate ligament and anterior cruciate ligament grafts, in particular, as well as the medial collateral ligament and the meniscus of the knee, the glenohumeral capsule of the shoulder, the flexor tendons of the hand, and other structures.

The anterior cruciate ligament is one of the most often injured knee ligaments, and its loss of function frequently leads to instability of the knee in multiple directions. Since the anterior cruciate ligament has a limited healing potential, it is commonly surgically replaced with tissue autografts⁹. The two most popular grafts are the bone-patellar tendon-bone and the hamstrings tendon autograft. Both were found to be effective at restoring initial stability of the knee¹⁰⁻¹⁵. Complications occur with the passage of time, however¹⁶⁻²⁷, and long-term results indicate that 20% to 25% of patients have less than satisfactory results, with osteoarthritis developing in a large number²⁸⁻³⁴. Indeed, anterior cruciate ligament reconstruction remains a clinical dilemma; over 3300 papers have been published on this topic in the last ten years. As a result, our research center has focused on making use of robotics technology to gain a better understanding of the complex function of the anterior cruciate ligament and to acquire new and quantitative data on knee kinematics and in situ force of the anterior cruciate ligament in an effort to improve

ligament reconstruction procedures. Specifically, we will describe several key factors that have been found to affect the outcomes, such as graft choice and femoral tunnel placement. These studies led to investigations of the biomechanical advantages of anatomic double-bundle anterior cruciate ligament reconstruction.

With all of the knowledge gained from in vitro experiments, we are ready to advance to the collection of in vivo kinematics data, which can be repeated on the robotic/universal force-moment sensor testing system so that the in situ forces in the anterior cruciate ligament during in vivo activities of daily living can be elucidated. Concomitantly, mathematical models of the knee are being built and validated with the findings from these experiments. Once completed, these models will provide data with regard to the normal stress and strain distribution in the anterior cruciate ligament and anterior cruciate ligament grafts, plus data with regard to more complex loading conditions. This activity will help us to gain a fundamental understanding of the function of the anterior cruciate ligament and will facilitate a scientifically based design of surgical procedures and postoperative rehabilitation protocols, thus leading to better patient outcome.

Applications of Robotic Technology: Evaluation of Anterior Cruciate Ligament Function and Reconstruction *Complex Anatomy and Function*

In the human knee, the anterior cruciate ligament consists of two bundles: the anteromedial bundle and the posterolateral

bundle. The anatomic division of these bundles is based on the gross tensioning pattern of the anterior cruciate ligament during passive flexion-extension of the knee, with the anteromedial bundle being tauter in flexion and the posterolateral bundle tauter in extension. With use of the robotic/universal force-moment sensor testing system, we found that the two anatomical bundles of the anterior cruciate ligament have different functions, even under the simplest external loading conditions⁴. For example, we found that under an anterior tibial load, the posterolateral bundle carries a higher load than the anteromedial bundle with the knee near extension, and the anteromedial bundle carries a higher load with a knee flexion angle $>30^\circ$. We also found that when the knee was under combined rotatory loads of valgus and internal tibial torques, the anteromedial and posterolateral bundles almost evenly shared the load at 15° of knee flexion. Thus, it is clear that the small posterolateral bundle plays an appreciable role in controlling rotatory stability due to its more lateral femoral position.

We have also demonstrated the role of the anterior cruciate ligament in relation to other tissue structures in the knee. For example, the anterior cruciate ligament primarily resists anterior tibial translation in the knee, especially when the knee is near full extension. However, its role decreases in deeper flexion, as other tissue structures (such as the medial collateral ligament) increase their contribution to anterior stability of the knee³⁵. Additionally, an anterior cruciate ligament deficiency would increase the load-sharing by other tissues (i.e., the meniscus and the articular cartilage)^{36,37}.

Evaluation of Selected Surgical Variables in Anterior Cruciate Ligament Reconstruction

Graft Choice

As most autografts for anterior cruciate ligament reconstruction procedures are either bone-patellar tendon-bone or hamstrings tendon autografts, it is necessary to critically compare the biomechanical effectiveness of these two types of grafts with regard to the restoration of knee stability. To accomplish this goal, the robotic/universal force-moment sensor testing system was used to simulate clinical examinations, such as the Lachman and pivot-shift tests, by applying the appropriate external loads to the knee (a 134-N anterior tibial load, or a combined 10 N-m of valgus torque and 5 N-m of internal and external tibial torques, respectively) while measuring the resulting kinematics. When an anterior tibial load is applied, both the bone-patellar tendon-bone or hamstrings tendon autograft reconstructions were found to be successful in limiting anterior tibial translation³⁸, and the in situ forces in the grafts were near those measured in the intact anterior cruciate ligament from full extension to 90° of flexion (Fig. 2). However, when combined rotatory loads are applied, both reconstructions were insufficient to reduce coupled anterior tibial translation. This insufficiency was further revealed by the significantly lower mean in situ forces in the grafts, which ranged from 45% to 65% of that in the intact anterior cruciate ligament ($p < 0.05$, Fig. 2). Thus, our data clearly suggest that femoral tunnel

Fig. 2

In situ force in the hamstrings and patellar tendon grafts (mean $\pm$ standard deviation), normalized with respect to the intact anterior cruciate ligament in response to an anterior tibial load and a combined rotational load with the knee in 15° of flexion. An asterisk indicates a significant difference ($p < 0.05$). (Reproduced, from: Woo SL-Y, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. A cadaveric study comparing anterior tibial and rotational loads. *J Bone Joint Surg Am.* 2002;84:913.)

placement of the graft to more closely approximate the anatomy of the anterior cruciate ligament may be needed.

Femoral Tunnel Placement

First, we studied how well a bone-patellar tendon-bone autograft placed at the posterolateral or anteromedial insertion site in the femur (equivalent to the 10 and 11 o'clock positions in the frontal view) could restore knee function³⁹. In response to an anterior tibial load, both the single posterolateral-bundle and single anteromedial-bundle reconstructions were able to restore anterior tibial translation to a level similar to that of the intact knee, except at deep knee flexion angles for the single posterolateral-bundle reconstruction. Under combined rotatory loads, however, the single posterolateral-bundle reconstruction could better restore the coupled anterior tibial translation and in situ force in the graft to those of the intact knee at 15° and 30° of knee flexion, compared with the single anteromedial-bundle reconstruction. Thus, although the grafts placed at the anteromedial-bundle or posterolateral-bundle femoral insertions are similarly effective under an anterior tibial load, the more laterally placed single posterolateral-bundle reconstruction can more effectively resist rotatory loads, particularly when the knee is near full extension.

Fig. 3

Anterior tibial translation (mean $\pm$ standard deviation) in the intact, anterior cruciate ligament (ACL)-deficient, and anatomic double-bundle and single posterolateral (PL)-bundle anterior cruciate ligament-reconstructed (ACL-R) knees in response to an anterior tibial load and combined rotatory load at 15° of knee flexion. An asterisk indicates a significant difference ($p < 0.05$). (Reproduced, with permission, from: Yamamoto Y, Hsu WH, Woo SL-Y, Van Scyoc AH, Takakura Y, Debski RE. Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. *Am J Sports Med.* 2004;32:1830.)

Single-Bundle Compared with Double-Bundle Anterior Cruciate Ligament Reconstruction

To further investigate the issue of rotatory instability following anterior cruciate ligament reconstruction, we evaluated the potential of an anatomic double-bundle anterior cruciate ligament reconstruction to restore normal knee kinematics and in situ force of the anterior cruciate ligament and compared the data with those from single-bundle reconstructions placed either at the anteromedial or posterolateral femoral insertions^{38,40,41}. It was found that an anatomic double-bundle reconstruction could restore knee kinematics and in situ force of the anterior cruciate ligament under anterior tibial loading, and also under combined rotatory loads. Furthermore, the results were superior to a single anteromedial-bundle reconstruction. For example, under combined rotatory loads at 30° of flexion, the in situ forces of the anatomic double-bundle reconstruction grafts and single anteromedial-bundle grafts, normalized to the normal anterior cruciate ligament, were $91\% \pm 35\%$ and $66\% \pm 40\%$, respectively (mean and standard deviation).

A similar study was also done to compare the anatomic double-bundle reconstruction to a more laterally placed single posterolateral-bundle reconstruction⁴². In this case, in response to anterior tibial and combined rotatory loads, both reconstructions were able to restore anterior tibial translation and in

situ force in the anterior cruciate ligament graft to a level similar to that of the intact knee at flexion angles close to full extension (Fig. 3). Moreover, there were no significant differences between the two reconstruction procedures at 15° and 30° of knee flexion under either loading condition. For example, under the combined rotatory loads at 15° of flexion, the coupled anterior tibial translation was 4.8 ± 2.4 mm for the anatomic double-bundle reconstruction compared with 4.8 ± 3.0 mm for the single posterolateral-bundle reconstruction. Thus, to reproduce the complex function of the anterior cruciate ligament throughout the range of knee flexion, replacing both bundles of the anterior cruciate ligament may have some biomechanical advantages. On the other hand, a more laterally placed reconstruction, such as the single posterolateral-bundle reconstruction, may also work well, especially when the knee is nearly at full extension, a position in which the function of the anterior cruciate ligament is most critical.

Future Directions: Advancing from in Vitro to in Vivo Studies

Significant advances have been made in characterizing the contribution of ligaments to joint kinematics and function on the basis of in vitro testing; however, it is time to focus on in vivo conditions in order to identify mechanisms of anterior

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Fig. 4

Flowchart showing the utilization of in vivo kinematic data to drive experimental and computational methodologies leading to improved patient outcome. UFS = universal force-moment sensor, Δ = multiple iteration, mech = mechanism, proc = procedure. (Reproduced, with permission, from: Woo SL-Y, Debski RE, Wong EK, Yagi M, Tarinelli D. Use of robotic technology for diarthrodial joint research. *J Sci Med Sport*. 1999;2:294.)

cruciate and other ligament injuries, to improve reconstruction procedures, and to optimize rehabilitation protocols. In the end, the new information should provide patients with better long-term outcomes.

With the advent of a biplanar fluoroscopy system, it has become possible to measure in vivo knee kinematics with an accuracy of <0.2 mm and 0.3° for knee motions⁴³. These accurate data can then be reproduced on cadaver knees, utilizing the robotic/universal force-moment sensor testing system in order to determine in situ forces in the anterior cruciate ligament during these in vivo activities (Fig. 4). We have found that the accuracy of kinematics data on the order of 0.1 mm and 0.1° could predict the in situ forces on the order of 15 N (unpublished data). Major efforts have also been made in our research center with our collaborators, Dr. Michael Torry and Dr. Richard Steadman from the Steadman Hawkins Research Foundation, to determine the necessary criteria to match cadaver knees to knees of human subjects in order to obtain accurate data on the in situ force of the anterior cruciate ligament. A new high-payload robotic/universal force-moment sensor testing system designed to determine the in situ forces

in the anterior cruciate ligament and anterior cruciate ligament grafts can be utilized on the basis of this novel approach.

Moreover, in vivo kinematics are being integrated into three-dimensional finite-element models of the knee, which incorporate the complex anatomy of the anterior cruciate ligament, such as multiple bundles, variable cross-sectional area, and fiber twist. This model is being validated with experimental data. In the future, it will be possible to calculate stress and strain distributions in the anterior cruciate ligament and replacement grafts as well as apply the validated model to study more complex external loading conditions, such as those encountered during in vivo activities. With such a combined experimental and computational approach, it will be possible to develop a database of the in situ forces, stresses, and strains in ligaments for patients of different age, sex, and size. We believe that such a biomechanics-based approach will provide clinicians with valuable scientific information. Likewise, this technology can be further extended to study problems in total joint replacement in order to evaluate the changes in kinematics as well as the forces experienced by the implants. ■

Savio L-Y. Woo, PhD, DSc(Hon)
Matthew B. Fisher, BS
Musculoskeletal Research Center, Swanson School of Engineering,

Department of Bioengineering, 405 Center for Bioengineering,
300 Technology Drive, Pittsburgh, PA 15219.
E-mail address for S.L-Y. Woo: ddecenzo@pitt.edu

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