INTRODUCTION

Anterior cruciate ligament (ACL) injury is a common occurrence in many sports, with up to 135,000 ACL injuries leading to over 95,000 reconstructions per year in the United States\(^1\). The ACL is a two-bundle ligament that stabilizes against anterior displacement (AD) and internal rotation (IR) of the tibia. Currently, the manual ‘pivot shift’ test is the most specific knee stability examination for diagnosis of ACL injuries\(^2\). It is performed by applying internal and valgus torque along with an axial load to the joint. A positive ‘pivot’ (consisting of tibial AD and IR followed by a rapid reduction, or ‘clunk’) is a strong predictor of osteoarthritis risk, patient-reported instability, and poor long-term patient outcome\(^3\), \(^4\). Unfortunately, the test is semi-quantitative and difficult to perform reproducibly.

We have developed a novel device that mimics the clinical pivot shift test through the application of standardized dynamic loads by a constant-tension spring. It reliably induces the characteristic ‘pivot’ event in an ACL-deficient knee. In this work, we compare the 3D rotational and translational kinematics of tibiofemoral motion during manual and mechanized pivot shift tests for both intact and ACL-deficient knees. We hypothesized that the mechanical pivot shift device (MPSD) allows for more sensitive detection of deficiencies in rotational knee stability in comparison to a manual test.

METHODS

Fresh-frozen full lower limb specimens (n=2) were sectioned, potted, and mounted on a hinged testing base. To replicate iliotibial (IT) band tension, a 4.5 kg weight was suspended from cord sutured to the isolated IT band. Kinematic trajectories were recorded using the Optotrak® navigation system (<1° and <1mm resolution). Coordinate frames for the femur and tibia rigid bodies were defined using anatomical landmarks. Carbon fiber rods were attached separately to the lateral side of the tibia and femur using a surgical external fixation system. Finally, a constant-tension (48N) spring was attached between the rods. For each mechanized test the examiner gently supported the distal tibia from underneath, raised it, and then lowered it into flexion. Throughout knee flexion the MPSD applies the axial load and internal/valgus torque needed to replicate a manual pivot shift test.

For each specimen, manual and mechanized pivot shift tests (with and without IT tension) were performed in triplicate by an experienced knee surgeon. Manual and MPSD tests were performed in intact, followed by ACL-deficient knee states. For each test, knee joint configuration was recorded using the Optotrak system and represented in MATLAB (as a function of flexion angle \(\theta\)) by a set of tibial translations \(T(\theta)=[T_x, T_y, T_z]\) and rotations \(R(\theta)=[R_\psi, R_\phi]\) of the tibia relative to a full-extension reference configuration. Maximum internal tibial rotation (IR\(_{\text{max}}\)), maximum anterior displacement (AD\(_{\text{max}}\)), and posterior tibial velocity (PTV) were employed as joint stability metrics.

RESULTS AND DISCUSSION

The MPSD was successful in mimicking the IR, AD, and PTV trajectories of a manual pivot shift maneuver performed by an experienced clinician (Fig. 1). In ACL-deficient knees, the tibia first became subluxed (AD and IR) at a knee flexion angle of 17±1º. At an angle of 35±2º the tibia was then rapidly reduced, exhibiting peak posterior tibial (PTV) near 70 mm/s. Intact knees became only slightly subluxed, and did not exhibit rapid tibial reduction. Although IT tension was needed to
generate a positive pivot in ACL-deficient knees using the manual tests, such tension was not a requirement when using the MPSD.

**Figure 1:** Intact (- -) and ACL deficient ( — ) pivot shift trajectories for the MPSD (n=3, left) and manual test (n=5, right) for a single knee. IR (top), AD (bottom), and PTV (inset), versus knee flexion angle. A clunking ‘pivot’ occurred at ~35° (~).

Both the manual and MPSD tests demonstrated increased IR$_{\text{max}}$, AD$_{\text{max}}$, and PTV following ACL transection (Fig. 2), however the coefficient of variation ($c_v=\sigma/\mu$) was significantly less for the MPSD metrics (mean $c_v=0.028$) in comparison to the manual metrics (mean $c_v=0.16$). When comparing matched right and left knees using the device, IR$_{\text{max}}$ and AD$_{\text{max}}$ differed by less than 1.5° and 2 mm in either the intact or ACL-deficient state. These results demonstrate the capacity of the MPSD to produce a realistic pivot shift in an unstable knee with a high degree of reproducibility.

**Figure 2:** IR$_{\text{max}}$, AD$_{\text{max}}$, and PTV values from MPSD tests (top), and manual maneuvers (bottom), for both intact (□) and ACL-deficient (■) knees. Error bars represent 99% confidence intervals.

Logistic regression procedures (JMP; version 7.0) were used to relate the categorical knee state (intact or ACL deficient) to continuous measurements (IR$_{\text{max}}$, AD$_{\text{max}}$, PTV; n=5 tests each from 2 knees) made during the mechanical pivot shift test. Univariate analysis demonstrated that IR$_{\text{max}}$ was the most predictive of ACL condition and explained 40% of the variance ($R^2=0.41$, $p=0.0001$). The knee state was predicted with complete accuracy when the logistic regression included two variables, IR$_{\text{max}}$ and PTV ($R^2=1$, $p=0.0001$). These data suggest that measurements made using the MPSD are sensitive to ACL condition and provide valuable clinical information.

**CONCLUSIONS**

The purpose of this study was to evaluate a novel mechanized pivot shift apparatus and analysis system for quantitative assessment of rotational knee stability under controlled laboratory conditions. The testing apparatus facilitated reproducible application of dynamic forces and moments to the knee during a simulated pivot shift, while the data-acquisition system recorded 3D tibiofemoral motion. Our results support the hypothesis that the MPSD allows for more sensitive detection of deficiencies in rotational knee stability in comparison to the manual test.

Development of a standardized rotational knee stability evaluation will be vital in determining the consequences of graded soft tissue defects of the knee joint, or the effects of different ACL reconstruction techniques, on rotational stability. Diagnostic kinematic signatures specific to certain injuries will enhance our current understanding of knee biomechanics, and may ultimately help improve clinical outcomes through in vitro optimization of surgical techniques.

**REFERENCES**