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Biomechanical evaluation of knee endpoint during anterior tibial loading: Implication for physical exams

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ABSTRACT

Background: Physical exams that apply anterior tibial loads are typically used to evaluate knees with anterior cruciate ligament (ACL) injuries. The amount of anterior tibial translation that occurs during these exams can be difficult to assess due to a "soft" endpoint. Therefore, the objective of this study is to determine the biomechanical characteristics of the endpoint for the intact and ACL deficient knee using quantitative criteria.

Methods: Eight porcine knees were tested using a robotic testing system. An 89 N anterior tibial load was applied to the intact and ACL deficient knee at 30°, 45°, 60° and 75° of flexion. The stiffness of the toe and linear regions was determined from the load–translation curve. The width of the transition region was defined by the distance between the points where the best-fit lines used to define the stiffness of the toe and linear regions diverged from the load–translation curve.

Results: Stiffness of the toe and linear regions significantly decreased after transecting the ACL at all flexion angles (71–85% and 38–62%, respectively). Width of the transition region was significantly increased in the ACL deficient knee at all flexion angles (approximately four to five times and four to nine times, respectively).

Conclusions: The novel quantitative criteria developed in this study have the potential to be deployed in clinical practice by coupling them with data from knee arthrometers that are commonly used in clinical practice. Thus, additional information from the load–translation curve can be provided to improve the diagnosis of ACL injury.

1. Introduction

Primary diagnostic evaluation of anterior cruciate ligament (ACL) injury includes taking history and performing physical exams like the Lachman test, anterior drawer test and pivot shift test [1,2]. Proper interpretation of physical exams by clinicians can help reduce unnecessary referrals for further diagnostic studies and related financial expenses [3].

During physical exams that apply anterior tibial loads, the amount of anterior tibial translation together at the knee endpoint contributes to the examiner's impression of the ACL state [4,5]. The endpoint of the intact knee is typically defined by a significant

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increase in knee stiffness due to the engagement of the ACL (firm endpoint). However, increased anterior tibial translation together with a "soft" endpoint indicates ACL disruption. In addition, a soft endpoint makes the amount of anterior tibial translation difficult to quantify and can complicate the information provided to the physician.

Analysis of the load–translation curve from knee arthrometers (i.e. KT1000 and KT2000, MEDmetric Corp, San Diego, CA, USA) for an improved assessment of the knee endpoint may help physicians to better understand the diagnostic value of these tests. In general, the load–translation curve obtained from these devices can be divided into the toe region (defined as the initial low stiffness, non-linear region of the curve) and linear region (defined as the high stiffness, linear region of the curve). The intermediate region is then defined as the transition region. Different methods have been employed for regional analysis of the load–translation curve to calculate stiffness of ACL intact and ACL deficient (ACLD) knees during both in vitro [6,7] and in vivo studies [8,9]. However these methods are difficult to interpret or are not commonly used in clinical practice. Previous studies that attempted to quantify the knee endpoint analyzed limited regions of the load–translation curve (toe region and/or linear region), which ignores the information in the transition region. This could be one of the reasons that these methods are not currently being applied in clinical practice. Thus, a new comprehensive quantitative criteria to be used with arthrometers are needed to assist with interpretation of the quantitative information and to distinguish between different injury patterns. Thus, new quantitative criteria that can be used with arthrometers are needed to assist with interpretation of the quantitative information and to distinguish between different injury patterns.

The aim of this study was to determine the characteristics of the endpoint in intact and ACLD knees in response to an anterior tibial load at four flexion angles using a porcine model in terms of: 1) stiffness and 2) width of transition region — a novel quantitative parameter used to describe the amount of translation required between the low and high stiffness regions of the load–translation curve. It was hypothesized that the ACLD knee will a have "softer endpoint" compared to the intact knee as shown by: 1) decreased stiffness of the toe and linear regions, and 2) increased width of the transition region.

2. Methods

Study approval was obtained from institutional review board. Eight fresh frozen skeletally mature porcine knees were used in the study. The porcine model was shown to be suitable for the simulation of the human knee characteristics and provides a convenient platform to test our hypotheses [10,11]. Specimens were stored at −20 °C and thawed at room temperature for 24 h before testing. Each specimen was evaluated by physical exam and plain X-ray and thereby any evidence of bone deformation, cartilage defect or ligamentous injury was ruled out. The tibia and femur were transected mid shaft and were potted with epoxy putty (Bondo, Atlanta, GA). The femur and tibia were then cut approximately 15 cm from the joint line. The surrounding skin and muscles more than 10 cm away from the joint line were removed so that the bones were exposed. The fibula was rigidly fixed to the tibia with a cortical screw to maintain its anatomical position. Throughout the experiment, the specimens were kept moist with 0.9% saline solution. The femur and tibia were each secured within custom-made aluminum clamps using an epoxy compound (Bondo, Atlanta, GA). The specimen was then mounted in a robotic testing system [12].

The femur was rigidly fixed relative to the lower plate of the robotic testing system (Technology Service Ltd., Model FRS2010, Chino, Japan). The position and orientation repeatability of the robotic manipulator was less than ±0.015 mm and ±0.01°. The tibia was attached to the upper end effector of the robotic manipulator through a six-degree-of-freedom universal force/moment sensor (UFS, ATI Delta IP60 (SI-660-60), Apex, NC) (Figure 1). The UFS can measure three forces and three moments along a Cartesian coordinate system and has a full-scale capacity of 660 N for fx/fy, 1980 N for fz and 60 Nm for mx/my/mz. The measurement uncertainty of the UFS is approximately one percent of full scale.

After mounting in the robotic testing system, the insertion sites of the medial collateral ligament and lateral collateral ligament were mechanically digitized relative to the robot and UFS coordinate system. The line passing through the insertion sites forms

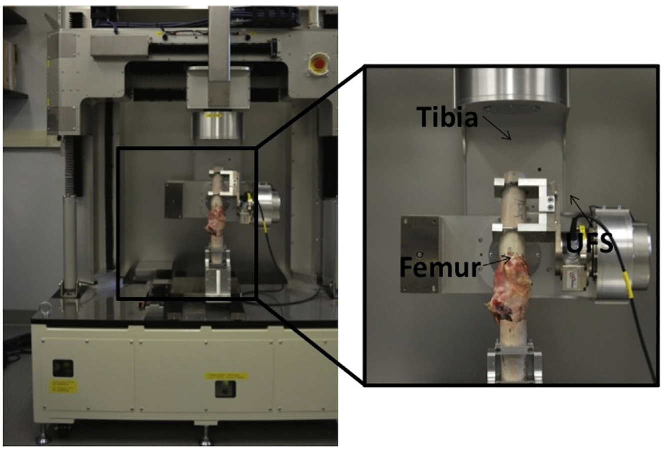

Figure 1. Image of the robotic testing system with a porcine knee during the experimental protocol.