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Short communication

Novel technique for evaluation of knee function continuously through the range of flexion

Kevin M. Bell [a,b], Fabio V. Arilla [a,b], Ata A. Rahnemai-Azar [a,b], Freddie H. Fu [b], Volker Musahl [a,b], Richard E. Debski [a,c,*]

[a] Orthopaedic Robotics Laboratory, Department of Orthopaedic Surgery, Department of Bioengineering, University of Pittsburgh, PA 15219, USA
[b] Department of Orthopaedic Surgery, University of Pittsburgh, Kaufman Building Suite 1011, 3471 Fifth Avenue, Pittsburgh, PA 15213, USA
[c] Department of Bioengineering, University of Pittsburgh, 302 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15260, USA

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ABSTRACT

Previous research has utilized robots to examine joint kinematics and in situ forces in response to loads applied at discrete flexion angles (static method). Recently, studies have applied loads continuously throughout flexion (continuous flexion method). However, the joint kinematics resulting from each of these methods have not been directly compared. Therefore, the objective of this study was to utilize a robotic testing system to compare kinematics and in situ forces of porcine knees in response to 89 N of anterior tibial load and 4 Nm of internal tibial torque between the static method (loads applied at 30°, 45°, 60°, and 75° of flexion) and the continuous flexion method (measured continuously from 30–75° of flexion) for both the anterior cruciate ligament (ACL) intact and ACL deficient (ACLD) knees. When anterior tibial load was applied the average differences in anterior tibial translation between the two methods for the intact state was 0.5 ± 0.0 mm and for the ACLD state was 0.3 ± 0.2 mm. The difference in the in situ forces in the ACL was 1.6 ± 0.9 N. When internal tibial torque was applied the average differences in the resultant internal tibial rotation for the intact state was 0.9 ± 0.4° and for the ACLD state was 1.0 ± 0.5°. The difference in the in situ forces in the ACL was 3.3 ± 2.0 N. Both methods are equally efficient in detecting significant differences ($p < 0.05$) between intact and ACL deficient knee states. The continuous flexion method was also shown to be more efficient than the static method and provides continuous data on knee function throughout the range of motion.

1. Introduction

During the last few decades, industrial robots have been utilized to investigate diarthrodial joint biomechanics by applying loads and recording the resulting motion. These systems have also quantified the forces in anatomic structures by repeating the recorded motions and measuring the change in forces after cutting the structure (Fujie et al., 1995; Rudy et al., 1996; Woo et al., 1999). The loading conditions typically simulate clinical examinations performed at discrete flexion angles ("static tests" such as Lachman or Anterior Drawer Test) (Kanamori et al., 2000; Livesay et al., 1995, 1997; Ma et al., 2000) or discrete angle simulations of "dynamic tests" which apply loads continuously throughout a range of flexion (Pivot Shift Test) (Kanamori et al., 2000).

Although the static method has direct clinical applicability, it narrows the quantity of data obtained which could negatively affect the interpretation of the results. There is also an ongoing debate regarding the clinical utility of static tests versus dynamic tests (Musahl et al., 2012). Therefore, efforts have been made to analyze in vitro knee kinematics and in situ forces continuously throughout the range of flexion (Markolf et al., 2014). Determination of the in situ forces in the previous continuous loading studies required instrumentation of the ACL (Markolf et al., 2010, 2014; Sena et al., 2013), however in-situ forces can also been calculated non-invasively using the principle of superposition (Fujie et al., 1995).

In this study, a novel robotic testing system was utilized to determine knee kinematics continuously throughout the range of flexion (continuous flexion method) in the intact and ACL deficient knee. The ACL has been widely studied and has been shown to be the primary stabilizer of anterior translation and a secondary stabilizer of internal rotation (Butler et al., 1980; Nielsen and Helmig, 1985; Shaw and Murray, 1974). The objective of this study was to compare the continuous flexion method with the static

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[*] Corresponding author at: Orthopaedic Robotics Laboratory, Department of Orthopaedic Surgery, Department of Bioengineering, University of Pittsburgh, 408 Center for Bioengineering, 300 Technology Drive, Pittsburgh, PA 15219, USA. Tel.: +1 412 648 1638; fax: +1 412 383 8788.
E-mail address: genesis1@pitt.edu (R.E. Debski).

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method during application of an anterior tibial load and internal tibial torque. The resultant joint kinematics and in situ forces in the anterior cruciate ligament (ACL) were quantified. It was hypothesized that the resultant kinematics and in situ forces determined using the continuous flexion method and static method would have a strong positive correlation. Since the static method and the continuous method apply the same loads in a different sequence, this hypothesis assumes that loading is sequence independent for the knee joint. To validate the continuous methodology, the kinematics of the intact and anterior cruciate ligament deficient (ACLD) knees were compared. It was hypothesized that the continuous flexion method would be able to show a difference in anterior tibial translation and internal tibial rotation between the intact and ACLD knee states as has been demonstrated previously with the static method (Ishibashi et al., 1997; Kanamori et al., 2000).

2. Materials and methods

Eight fresh-frozen skeletally mature porcine knees were used in this study (Boguszewski et al., 2011; Fuss, 1991; Kiapour et al., 2015; Xerogeanes et al., 1998). Each specimen was screened for bony abnormalities and osteoarthritis using a Fluoroscan Insight 2 mini-C-arm (Hologic Inc., Bedford, MA). Specimens were stored in airtight plastic bags at −20 °C until 24 h before testing, at which time they were thawed at room temperature (Woo et al., 1986). The femur and tibia were each secured within custom-made aluminum clamps by using an epoxy compound (Bondo, Atlanta, GA). The specimen was then mounted in a robotic testing system.

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 6-degree-of-freedom universal force/moment sensor (UFS, ATI Delta IP60 (SI-660-60), Apex, NC) (Fig. 1). The UFS 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 1% of full scale.

Knee kinematics were defined with respect to the knee joint coordinate system (KJCS) (Grood and Suntay, 1983). The orthogonal femoral and tibial coordinate systems and the neutral position of the knee were defined as previously described (Fujie et al., 2004). The path of passive flexion–extension of the intact knee was then determined from 30° to 75° of flexion while the forces and moments were continuously minimized using the hybrid velocity impedance control algorithm programmed in an open-access LABVIEW program (Fujie et al., 2004). The passive path was repeated 10 times to precondition the knee prior to mechanical loading.

The robotic testing system then utilized the continuous flexion method and static method to apply two loading conditions to the knee and recorded the resulting knee kinematics (Table 1). For the continuous flexion method, the loads were applied to the knee at 30° of flexion and then the load was actively maintained while the knee was flexed from 30° to 75° at a flexion rate of approximately 1°/s. For the static method, the loads were applied at 30°, 45°, 60°, and 75° of flexion. The following external loading conditions were applied to the tibia: (1) an 89 N anterior tibial load and (2) 4-Nm internal tibial torque (Loh et al., 2003; Yagi et al., 2002). To determine the test–retest repeatability of the robotic testing system, 89 N of anterior tibial load and 4 N-m of internal tibial torque were reapplied to the same specimen three times after completely removing the specimen from the robotic testing system, letting it rest for 30 min and remounting the specimen in the system between tests. The test–retest repeatability of the system is ±0.21 mm and ±2.45° under the described loading conditions using a porcine model, which has been previously shown to exhibit high individual variability for internal–external rotation (Zaffagnini et al., 2000).

Table 1
Outline of the experimental testing protocol and data that were acquired.

Protocol	**Data acquired**	
	Kinematics	**In-situ force**
I. Intact knee		
A. Path of passive flexion–extension	Passive path	
B. 89 N anterior tibial load	Anterior tibial translation	
-Continuously 30–75°		
-Statically 30°, 45°, 60° and 75°		
C. 4 Nm Internal tibial rotation torque	Internal tibial rotation	
-Continuously 30–75°		
-Statically 30°, 45°, 60° and 75°		
II. ACLD knee		
A. Repeat intact anterior tibial translation (I–B)		Anterior tibial load
B. Repeat intact internal tibial rotation (I–C)		Internal tibial torque
C. Reapply I–A loading	Passive path	
D. Reapply I–B loading	Anterior tibial Translation	
E. Reapply I–C loading	Internal tibial rotation	

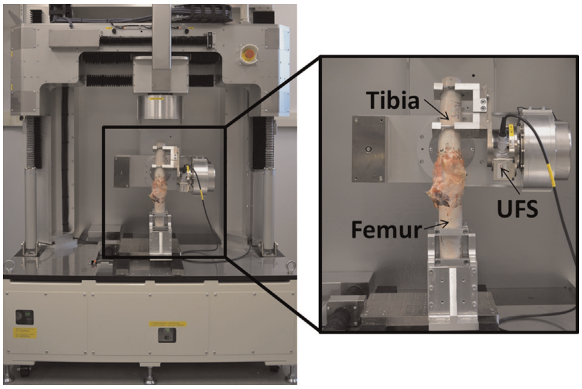

Fig. 1. Image of the robotic testing system with a porcine knee mounted during the experimental protocol.

The in situ force in the ACL was determined by first carefully transecting the ACL through a medial mini-arthrotomy (Loh et al., 2003). Then, the kinematics of the intact knee were repeated by the robotic testing system in position-control mode while the UFS measured the new forces and moments. Based on the principle of superposition, the difference in the force vectors measured for the intact and the ACLD knee states represents the in situ force in the ACL (Fujie et al., 1995; Rudy et al., 1996). The repeatability of recording the in situ forces in the robotic testing system is ±2.25 N, which was determined by replaying the recorded kinematics three separate times while letting the specimen rest for 30 min between trials.

To assess changes in knee kinematics associated with ACL deficiency, the same external loading conditions previously applied to the intact knee were again applied to the ACLD knee, and the resulting kinematics were determined. The anterior tibial translation and internal tibial rotation of the intact and ACLD knees, as well as the in situ force of the ACL were compared using interclass correlation coefficients ($\text{ICC} > 0.75 = \text{strong}$, $0.5 - 0.75 = \text{moderate}$, and $< 0.5 = \text{poor}$) to assess absolute differences between the continuous flexion method and the static method. Paired *t*-tests were also used to detect differences in anterior tibial translation and internal tibial rotation at 30°, 45°, 60°, and 75° between intact and ACLD knees. Significance was set at $p < 0.05$.

3. Results

Small differences were observed between the continuous flexion method and the static method when an anterior tibial load was applied and the continuous flexion method was able to detect a significant change in translation as a result of cutting the ACL. Application of 89 N of anterior tibial load resulted in average differences between the two methods for the intact state of 0.5 ± 0.0 mm (11.0 ± 0.5%) and for the ACLD state of 0.3 ± 0.2 mm (1.3 ± 0.7%), corresponding to an interclass correlation coefficient of 0.99 for all flexion angles (Table 2). When comparing the anterior tibial translation resulting from the application of 89 N of anterior tibial load between the intact and ACLD knee, an average difference of 19.0 ± 0.7 mm for the continuous method and 19.2 ± 0.8 mm for the static method (Fig. 2) was observed and these differences were statistically significant ($p < 0.05$).

Similarly, small differences were observed between the continuous flexion method and the static method when 4 Nm of