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The effect of an impulsive knee valgus moment on *in vitro* relative ACL strain during a simulated jump landing

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Abstract

Background. We tested the hypothesis that impulsive compression, flexion and valgus knee moment loading during a simulated one-footed jump landing will significantly increase the peak relative strain in the anteromedial region of the anterior cruciate ligament compared with loading without the valgus moment.

Methods. Ten cadaveric knees [mean (SD) age: 67.9 (7.6) years; 5 males; 5 females] were mounted into a custom fixture to simulate a lower extremity impact loading of approximately 1600 N. Triaxial load cells monitored the 3D tibial and femoral impulsive force and moments at 2000 Hz, while 3D tibiofemoral kinematics were measured at 400 Hz. Pre-impact quadriceps, hamstring and gastrocnemius muscle forces were simulated using pretensioned steel cables. A differential variable reluctance transducer measured the relative strain in the anteromedial aspect of the anterior cruciate ligament. With the knee initially in 25° flexion, 10 trials were conducted with the impulsive force directed 4 cm posterior to the knee joint center in the sagittal plane (“neutral” loading) to cause a flexion moment, 10 trials were conducted under a similar loading, but with the force directed 15° lateral to the knee sagittal plane (“valgus” loading), and the 10 neutral loading trials were then repeated. A non-parametric Wilcoxon signed rank test was used to test the hypothesis using a $P < 0.05$ significance level.

Findings. The peak normalized anterior cruciate ligament strain was 30% larger for the impulsive compression loading in valgus and flexion compared with an impulsive compression loading in isolated flexion ($P < 0.05$).

Interpretation. Minimizing the abduction loading of the knee during a jump landing should help reduce anterior cruciate ligament strain during that maneuver.

Keywords: Knee; Anterior cruciate ligament; Strain; Valgus moment; *In vitro*

1. Introduction

The majority of anterior cruciate ligament (ACL) injuries do not involve direct physical contact between athletes at the time of injury (Arendt and Dick, 1999; Delfico and Garrett, 1998; Ferretti et al., 1992; Griffin et al., 2000). For example, *post hoc* video analyses have shown that the maneuvers most likely to cause ACL ruptures include an axial impulsive loading of the knee joint combined with a valgus knee moment, often combined with internal or external tibial rotation, occurring during a plant-and-cut maneuver or single leg landing with a fully extended knee (Boden et al., 2000; Krosshaug and Bahr, 2005; Olsen et al., 2004; Teitz, 2001).

These findings are supported by *in vivo* jump landing studies of female athletes that demonstrate increased apparent valgus angulations at the knee upon landing,

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turning, and cutting (Besier et al., 2001; Ford et al., 2003, 2005; Hewett et al., 2004, 2005; Malinzak et al., 2001). In addition, a computer modeling study suggests that "increased knee valgus" in females may contribute to the higher risk of ACL injury (McLean et al., 2004).

Experimental studies conducted *in vivo* by Fleming et al. (2001) using a differential variable reluctance transducer (DVRT) to measure the strain in the anteromedial region of the ACL *in situ* also showed that a valgus knee moment increased ACL strain relative to that at the start of the experiment. They found that the application of valgus knee moments during weightbearing increased relative ACL strain. However, when the valgus knee moment was applied in a non-weightbearing condition, relative ACL strain did not increase.

Earlier *in vitro* studies have also examined a valgus knee moment as an injury mechanism (Berns et al., 1992; Dürselen et al., 1995; Markolf et al., 1995). For example, Markolf et al. (1995) examined valgus knee moment loading as well as combinations of other forces and moments in cadaveric knees at static knee flexion angles. A quasistatic valgus knee moment loading of 10 N m was found to increase ACL strain in the flexed knee. Conversely, Berns et al. reported that an isolated valgus knee moment of 26 N m had no significant effect on ACL strain under fixed knee flexion angles of 0°, 15° and 30° without muscle (Berns et al., 1992). However, the combination of a 26 N m valgus knee moment and a 106 N anterior force did produce significantly higher ACL strains. Dürselen et al. (1995) suggested that external tibial rotation plus a valgus lower extremity alignment strains the ACL through the entire flexion range of the knee. While these early studies gave useful insights, they were limited by muscle forces, loading rates and magnitudes that were too low to physiologically represent *in vivo* impact loads acting during jump landings. Until the mechanical and physical risk factors for ACL injury are better identified, preventative measures continue to be based on empirical understanding.

The objective of the present study, therefore, was to compare the magnitude of *in vitro* anteromedial ACL strain under sagittally symmetric impulsive axial loading with, and without, a valgus knee moment, simulating a jump landing or sudden stop executed with pre-activated knee muscle forces. We tested the hypothesis that an impulsive valgus knee moment would significantly increase anteromedial ACL relative strain compared with a corresponding sagittal plane ("neutral") loading without the valgus knee moment.

2. Methods

2.1. Specimen procurement and preparation

Ten cadaveric specimens [mean (SD) age: 67.9 (7.6) years; 5 males; 5 females] were acquired from the University's Anatomical Donations Department and fresh frozen at −20 °C until 24 h prior to testing. All specimens were visually checked for scars and other indications of surgery, mal-alignments or radiographic deformities prior to procurement. Specimens were dissected to the capsule level leaving the knee ligaments intact, but removing the muscle tissue on the quadriceps tendon, the medial and lateral hamstrings and the medial and lateral gastrocnemius tendons. Specimens were cut both 15 cm proximal and distal to the knee joint and potted in 10 cm-diameter polyvinyl chloride (PVC) cylinders using polymethylmethacrylate.

2.2. Knee testing apparatus

A custom 2.5 m-high loading frame was built to maintain the specimen with an initial knee flexion angle that simulates the position of a single extremity as it initially strikes the ground while landing on one leg from a jump landing maneuver (Fig. 1). It is well known that the knee extensor and flexor muscles are co-activated to stiffen the knee just prior to ground impact when landing from a jump (for example, Mortiz and Farley, 2004). Therefore, in our set-up pre-impact quadriceps, hamstring and gastrocnemius tensions were set to 180 N for the quadriceps, and 70 N each for the other four muscles groups. Each muscle-tendon unit tension had an independent tensioning mechanism allowing its initial pre-tension to be set separately without altering the initial knee flexion angle.

Aircraft cable (diameter 3 mm; tensile stiffness 7 kN/cm, McMaster-Carr, Aurora, OH, USA) was used to mimic representative *in vivo* dynamic resistance of the quadriceps,

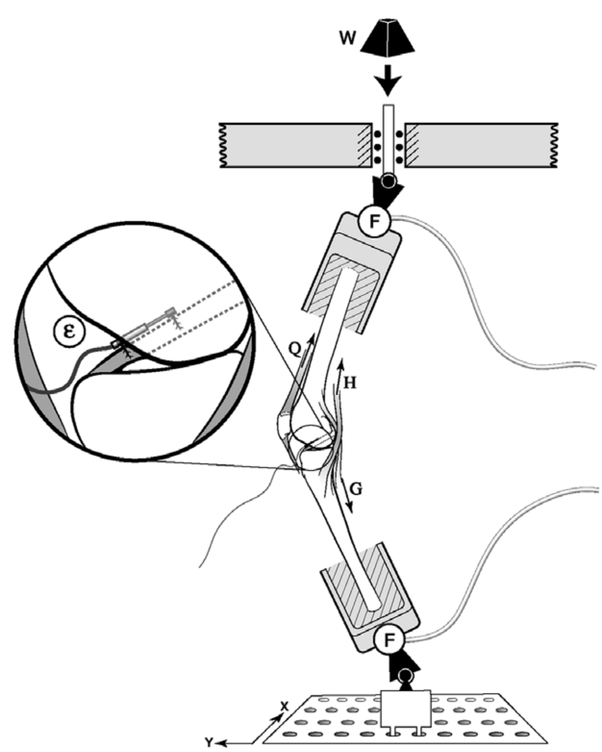

Fig. 1. Schematic of test set-up in the neutral configuration.