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Novel mechanical impact simulator designed to generate clinically relevant anterior cruciate ligament ruptures

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ABSTRACT

Background: Over 250,000 anterior cruciate ligament ruptures occur each year; therefore, it is important to understand the underlying mechanisms of these injuries. The objective of the current investigation was to develop and analyze an impact test device that consistently produces anterior cruciate ligament failure in a clinically relevant manner.
Method: A mechanical impact simulator was developed to simulate the ground reaction force impulse generated from landing in a physiologic and clinically relevant manner. External knee abduction moment, anterior shear, and internal tibial rotation loads were applied to the specimen *via* pneumatic actuators. The magnitudes of applied loads were determined *in vivo* from a cohort of healthy athletes. Loads were systematically increased until specimen failure was induced. Three cadaveric lower extremity specimens were tested and clinically assessed for failure. Knee specimens were physically and arthroscopically examined at baseline and at post-injury by a board certified orthopedic surgeon.
Findings: All three specimens experienced failure at either the midsubstance or the femoral insertion site. The mean peak strain prior to failure was 18.8 (6.2)%, while the mean peak medial collateral ligament strain was 7.9 (5.9)%.
Interpretation: A board certified orthopedic surgeon confirmed observed rupture patterns were representative of clinical cases. Peak strains were consistent with literature. The novel mechanical impact simulator will allow researchers to assess clinically relevant patterns of rupture and the data generated will inform clinician decisions. This novel machine presents the ability to assess healthy specimens as well as differences in the function of deficient and reconstructed knees.

1. Introduction

An overwhelming majority of anterior cruciate ligament (ACL) ruptures occur in non-contact scenarios, typically the result of an impulse force within the first 50 msec of initial ground contact that originate from a rapid deceleration or change of direction (Agel et al., 2005; Boden et al., 2000; Krosshaug et al., 2006; Mcnair et al., 1990). Several studies have described various combinations of external knee loads that are involved in ACL injuries (Boden et al., 2000; Boden et al., 2010; Hewett et al., 2006). In particular, studies have utilized impact-driven mechanical simulators designed to investigate knee biomechanics during simulated jump landings (Bates et al., 2015a; Hashemi et al., 2010; Levine et al., 2013; Oh et al., 2011; Oh et al., 2012a; Oh et al., 2012b; Quatman et al., 2014; Withrow et al., 2006a, 2006b). These impact simulators have examined the agonist and antagonist roles of the hamstrings and quadriceps musculature relative to ACL strain (Bates et al., 2015a). In addition, these simulators have been used to assess the relative influence of induced knee abduction moment (KAM) and internal tibial rotation (ITR) on ligament strain.(Bates et al., 2015a) However, these particular simulators failed to consistently reproduce ACL tears within their cadaveric specimens.(Hashemi et al., 2010; Oh et al., 2011; Oh et al., 2012a; Oh et al., 2012b; Withrow et al., 2006a, 2006b)

A drop-stand mechanical impactor developed by our group was the first impulse simulator to successfully and reliably induce ACL failure on cadaveric specimens (Kiapour et al., 2012; Levine et al., 2013; Quatman et al., 2014). Of the 17 specimens tested on this machine, 15 sustained an ACL disruption (Levine et al., 2013). While previous impact

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simulators demonstrated both ITR and KAM contributed to increased peak ACL strain, the first generation drop-stand impactor showed that only knee abduction moment (KAM) significantly contributed to calculated ACL strain at failure (Levine et al., 2013). However, despite its success in the creation of ACL injuries, the first generation drop-stand impactor had limitations. Bony injury severity was often greater than that observed in the operating room, which may indicate that greater magnitudes of loading were applied to the impactor specimens than *in vivo* (Levine et al., 2013). Also, tibial avulsion failures, which are more common in cadaveric tissue than *in vivo* cases, were observed in 4 of 15 cases, while tears at the tibial insertion were observed in an additional 5 of 15 cases (Levine et al., 2013). Thus, although ACL ruptures occurred in the cadaveric specimens, they failed to reproduce the physical distribution of ACL rupture location within the ligament structure that is typically observed in the clinical setting. Therefore, augmentation of the current simulator design to produce more clinically relevant injury patterns may provide further insight into injury ACL mechanisms (Meyer et al., 2008).

The objective of the current investigation was to develop and analyze an impact test device that produces ACL ruptures on cadaveric specimens in a manner that reproduces the patterns of failure seen in the clinical environment. It was hypothesized that the design modifications made to the external load and muscle force application from the previous generation impactor device would lead to ACL ruptures that are more consistent with the clinically observed patterns of ACL injury.

2. Methods

2.1. Mechanical design

The mechanical impact simulator is a gravity-driven mechanical testing apparatus designed to generate impulse forces at the knee on lower extremity joints that are representative of the *in vivo* loading induced when landing from a jump. It was designed around the utilization of two weight sleds on a minimal-friction, slide-rail track system to deliver an impact load to the foot of an inverted lower extremity specimen (Fig. 1). The inferiorly positioned weight sled served as the ground, resting on the base of a specimen's foot, while the superiorly positioned sled was suspended by electromagnets 31 cm above the ground sled. Modifications unique to the presented impactor include an electrical trigger that was used to release the drop sled from the electromagnets, allowing it to fall along the slide-rail track solely with gravitational force and impact the prepared specimen in alignment to the tibial shaft. Additionally, apart from the impact load, external forces and torques associated with ACL loading were applied about the knee with pneumatic actuators to simulate various degrees of relative injury risk loading on each specimen. Investigational methods were approved by the Institutional Review Board at Mayo Clinic.

2.2. Specimen preparation

Three (3) cadaveric full lower extremity specimens from unique donors (age = 33.0 (13.1) years [min = 24, max = 48]; mass = 90.1 (28.1) kg) were obtained from an anatomical donations program (Anatomy Gifts Registry, Hanover, MD) to validate our methodology. Specimens over 50 years of age and those with previous history of knee trauma or knee surgery were excluded from this investigation. The specimens were kept frozen at −20 °C until 24 h prior to use. After thawing, specimens were prepared to be mounted into the mechanical impact simulator. The skin 5 cm proximal to the superior aspect of the patella was resected and thigh musculature was individually isolated. The quadriceps, biceps femoris, semitendinosus, semimembranosus, and gracilis tendons were identified and rasped to remove muscle tissue leaving the tendinous tissue intact. All other musculature was resected. The femur was then resected 20 cm proximal to the superior patella and the distal end of the femur was potted with Bondo® aligned with the long axis of the bone in a 2-inch inner diameter cylinder. The quadriceps tendon was then aligned with and placed into a cable clamp and secured with a U-bolt such that tension could be applied along the loading axis of the tendon. This process was similarly completed two additional times with the semimembranosus, semitendinosus, and gracilis groups

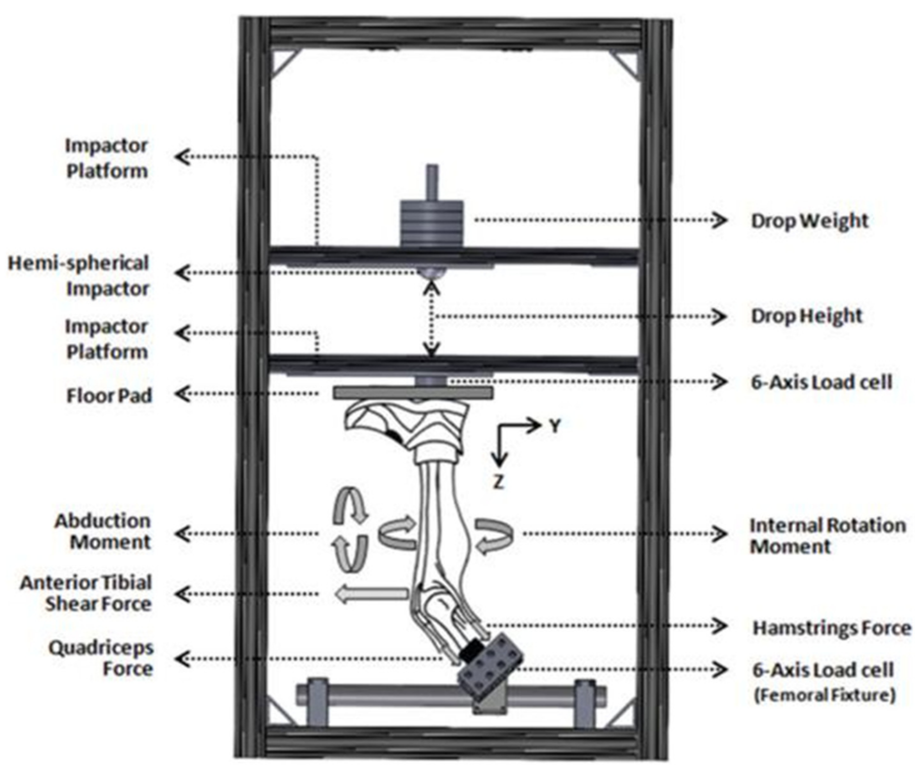

Fig. 1. Custom designed landing impact test apparatus. Image reproduced with permission from Quatman et al., *Am J Sports Med*, 2014, 42(1):177–186.