Key Challenges Confronting Biomechanist Aiming to Predict ACL Injury Mechanisms

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ABSTRACT

Even though everyone is predisposed to anterior cruciate ligament (ACL) injuries, the highest incidences of non-contact ACL injuries are seen among athletes. There is a significant amount of *in-vivo* and *in-vitro* studies, musculoskeletal and computational modeling studies, as well as other related study approaches aimed at improving our understanding of ACL injury mechanisms. Despite all these efforts, there is still no clear understanding of non-contact ACL injury mechanisms. Consequently, there is no clear consensus that identified risk factors implicated to cause ACL injuries. The objective of this study is to provide insights as to why the mechanisms of ACL injury during non-contact events remain unknown. This study has found several key challenges which, among many, include the lack of material properties of some of the human tissues, shortcomings in problem definition, wide inter- and intra-subject variability, and also limitations of the existing study approaches. In addition, the lack of test standards and specifications in the field of biomechanics continues to hinder constructive dialogue among researchers. In order to predict the ACL injury mechanisms, new approaches or coupled approaches, as well as, benchmarks are needed. Until this can be done, our ability to identify, develop, and improve prevention and training strategies to mitigate the risk of ACL injuries, is limited.

INTRODUCTION

Increased participation in athletic activities, especially among females, and greater intensity of play has resulted in more ACL injuries. Approximately 100,000 to 175,000 ACL-related surgeries are conducted in the United States each year with associated costs exceeding $2 billion [1, 2]. Among athletes, female's ACL injuries are 2-8 times more frequent than in males [3]. Approximately 70% of ACL injuries occur as a result of a non contact event which amounts to a cost of almost one billion dollars in the United states alone [4]. This does not account for the 31% of patients who require revision surgery approximately five years after ACL reconstruction [5]. The high number of non contact ACL injuries and frequent need for surgical treatment, thus, warrants greater research into enhancing our understanding of ACL injury mechanisms.

A non contact event is one in which there are no externally applied forces to the body except the body's interaction with the environment. Most research in the scholarly literature on ACL injury look at this area in the context of knee mechanics before and after ACL failure or reconstruction and surgical treatment. Hence, precise knowledge of how and why ACL injuries occur is unknown.

Better understanding of non-contact ACL injury mechanisms will enable the identification and categorization of risk factors according to their order of criticality. It will help to provide pre-screening tools, tailor preventative and exercise regimens, and aid in the design of better intervention devices. In addition, better understanding can aid in ACL reconstruction techniques and become a starting point for engineering artificial tissues which ultimately can improve the quality of life.

The central tenet of this paper is to provide a comprehensive assessment of the challenges that hinder understanding of non-contact ACL injury mechanism. This is important because the literature is replete with discrepancies, a lack of consensus, coherence, and confusion. Understanding these challenges is a necessary first step towards designing studies to predict ACL injury.

METHODOLOGY

This article reviewed the relevant literature on ACL injury mechanisms in the PubMed electronic database using MEDLINE from 1966 until 2007, Applied and Complementary Medicine Database (AMED) on Ovid from 1985 until Sept. 2007, as well as a comprehensive search of other articles in the literature between 1966 and 2007. Keywords used in our search included “anterior cruciate ligament”, “injury mechanisms”, and “non-contact injuries”. The most relevant full text English articles pertaining to ACL non-contact injuries, risk factors for ACL injuries, and study approaches to understand ACL mechanics were analyzed for this article. Studies that captured the association of ACL and non-contact injuries and ACL with a specific study approach were also included. Our search was supplemented by reviewing the bibliographies of retrieved articles, as well as hand searching scholarly journals outside of the bio-fields related to this topic.

RESULTS AND DISCUSSION

The vast majority of studies on ACL injuries are in the context of reconstruction and surgical treatment, but not on the very important aspect of ACL injury mechanism. The following subsections briefly underscores key challenges confronting Biomechanists aiming to enhance their understanding of ACL injury mechanisms. These challenges are presented in no order of importance.

General Inherent Challenges incurred when studying ACL injury mechanisms

For ethical reasons, measurement of ACL forces to failure using human subjects cannot be undertaken. Hence, experimentally non-contact ACL injury cannot be replicated in the laboratory environment. It is also difficult to conduct identical tests and obtain repeatable results when utilizing experiments involving biological tissues. As well, relationships between internal muscle forces, external loading, and ACL loads are mostly unknown due to the difficulties of measuring ligament and muscle forces *in-vivo*. Moreover, maximum kinematic changes of knee, for example, anterior tibial translation (ATT) may not necessarily correspond to maximum force in the ACL due to the concurrent interaction of multiple tissues. The difficulties encountered when attempting to obtain material property data for human tissues also create some limitations. The ACL is an intra articular ligament and obtaining data on its geometry is difficult. Finally, ACL injury is a non-life threatening disorder and, so, obtaining financial support to undertake research of this nature can be tricky.

Challenges in ACL Problem Definition

Some studies do not include the muscles in their problem definition. A study that does not include muscles cannot adequately predict mechanisms of ACL injury. Omitting the muscles leads to inaccuracies since the forces transmitted to the ligaments and bones are dominated by the muscle forces [6]. In addition, the majority of studies do not address the effects of hip and ankle kinematics and kinetics on ACL loads. Moreover, a majority of studies in the literature do not account for the effects of whole body movement on ACL loads. As well, some studies do not capture external loading. Externally applied forces have also been implicated as a risk factor to non-contact ACL injuries. The relationship between external forces and the force seen on the ACL have been studied primarily through *in-vitro* studies using cadavers [7]. In these cadaveric studies, the effects of ground impact forces and moments on ACL load were not captured. Some other studies do not accurately capture articular surface geometries. However, it is known that the geometry of the articular surfaces, for example, femoral notch [8] can be seen as a risk factor for ACL injury. The geometry of the hard tissues aids in knee joint stability. For instance, it was demonstrated that, irrespective of muscular activity, the ACL is subjected to inherent increase in strain as the knee extends owing to the geometry of the articular surfaces of the knee [9]. As well, accurate geometries of soft tissues are difficult to extract especially those that are intra articular like the ACL. Given this, it is clear that the mechanisms of ACL injury is multifaceted and, most likely, a whole body phenomenon. The simultaneous inclusion of the muscles, hip, knee and ankle articulations, external forces, and accurate 3D tissue geometry appears to be crucial study prerequisites. Without an objective view of these factors in problem definition, a comprehensive understanding of ACL injury mechanisms may remain elusive.

Some Shortcomings in the Field of Biomechanics

Combining and comparing results from separate studies that use different approaches can be valuable, but differences in specimen type, methodology, and data acquisition methods may prevent drawing solid conclusions. It is difficult to compare the results from one study to another due to the tremendous heterogeneity between different studies. The challenge is that these differences exist possibly due to the lack of standards and specifications in the biomechanics field. The dearth of standards and specifications may also hinder dialogue among different research groups working in this field. A few examples of standardization that have led to tremendous benefits in the research community include the Visible Human Project[10], VAKHUM[11], and the standardized femur[12], all serving as benchmark for many study approaches.

Shortcomings in the current Study Approaches

Experiments, athlete interviews, clinical studies, video analyses, musculoskeletal and computational modeling are all different study approaches that have contributed to our understanding of ACL mechanics. A brief outline of the challenges encountered with each of these study approach is provided below. Clinical studies, interviews with athletes, and video analyses provide mostly qualitative data and as a result are not adequate for obtaining a comprehensive understanding of injury mechanisms to the ACL. Knowing this fact, these three methods will not be discussed further in detail.

In-vivo experiment

There has been a considerable interest in quantifying the ACL loading *in-vivo* during activity [13]. But, a significant challenge with *in-vivo* testing is that it is invasive. Moreover, some researchers have argued that strain gauge and other similar type transducers require instrumentation and contact with the ligament that alters the ligament length and subsequently ligament force [14]. In many cases, the measurements are taken at discrete locations rather than continuously over the entire surface of the ligament. It is known that because of the fibrous and bundle nature of the ACL, its deformation patterns are not uniform and vary according to where the localized measurement is taken [15]. Thus, a complicating factor with *in-vivo* techniques is the fact that specific bands of the ACL are tensioned at different portions of the loading cycle. As a result, a localized measurement of ligament linear strain may not correlate directly with total ligament strain.

In addition, because of the size of the sensor employed and the location of the ACL, *in-vivo* studies to-date can only measure strain on the anteromedial bundle of the ACL for movements confined to sagittal plane [16]. Moreover, the measurement is confined to linear displacement at discrete locations and at knee flexion angles approximately greater than 15 degrees [13]. This is particularly important given the fact that non-contact ACL injuries have been implicated to occur at low knee flexion angles where *in-vivo* testing cannot be performed. There are also difficulties recruiting patients to conduct *in-vivo* testing. There is also very large amount of variability with *in- vivo* data likely due to different muscle strength and mental concentration of subjects [23]. Nonetheless, *in-vivo* testing is perhaps one of the most accurate methods of obtaining force response on human tissue.

In-vitro experiment

In-vitro testing is conducted outside of the body typically with human subjects or post mortem human subjects (PMHS)/ cadavers. The vast majority of studies investigating ACL injury mechanisms are *in-vitro* [14]. The major challenge with *in-vitro* studies using cadavers is the inability to include muscle activation and the challenges of obtaining repeatable results. Recently some research groups simulate muscle response by attaching tendon grips and cabling to tendons through a pulley system [24]. However, the magnitude of the load applied to cabling is very limited due to fear of tendon yielding or bone avulsion occurring. A popular *in-vitro* method is to employ a universal force moment sensor (UFS) with robotic manipulator. A cadaveric knee is attached to this device for conducting the study [14]. There are other studies that rely on cadavers with soft tissues sectioned expect the tissue of interest to conduct studies in custom made fixtures similar to UFS [17].

Replicating an isolated ACL injury *in-vitro* is difficult, and has been achieved with only limited success [18]. Many of these studies may not accurately describe ligament function *in-vivo* since loading applied to the cadavers during experiment are different from that applied by the muscles during activity. In addition, load sharing among the ligaments in *in-vitro* experiments may be significantly different from that induced by the muscles *in-vivo*. *In-vitro* studies using cadavers have been shown to lack repeatability due to the absence of muscles [18].

A prevalent *in-vitro* study method using human subjects is gait analysis that employs skin markers. The use of skin markers with gait studies have been shown to induce significant errors in predicting *in-vivo* ligament behavior [19]. As well, many gait studies are conducted in the laboratory setting, and the question of how well laboratory experiments replicate true human motion still remains unanswered. In addition, *in-vitro* studies using human subjects also show variability with single subjects and, of course, even greater variability when comparing between subjects.

Computational Modeling

There are mainly two different approaches to computational modeling in the current literature: mathematical and finite element (FE) modeling. Even though mathematical models have aided our understanding of the mechanics of the knee, the gross approximations and assumptions can readily be answered with technology and information available today. One such technology is finite element (FE) modeling. It is clear that finite element approach will continue to be significantly used compared to mathematical models simply because of the improved capabilities of the finite element software today, and the computing power available nowadays. The literature indicates that only a small number of FE models are used to study ACL mechanics, and none has focused on ACL injury mechanisms [20]. Lack of accurate tissue geometries, in-homogeneity and anisotropy of human hard and soft tissues, and also lack of accurate constitutive equations and material properties of biological tissues will continue to limit progress in using FE modeling for reinforcing our understanding of ACL injury mechanisms. Another challenge of employing FE modeling includes the dependence on empirical data for validation. Moreover, since some FE models are not verified and/or validated in the literature and that only general trend in the strains or stresses match, they can only be used qualitatively and are not usually useful for clinical applications.

Musculoskeletal Modeling

Musculoskeletal modeling is based on research aimed at developing a dynamic model for balancing muscle and ligament forces with externally applied forces to produce motion [21]. Musculoskeletal models cannot provide detailed information about the stresses and strains distribution within tissues. Musculoskeletal modeling requires extremely long computational time to converge to a solution and in some cases requires parallel computing [22]. To the best of our knowledge, no commercially available and user friendly software package has been validated to date for the estimation of muscle forces based on kinematic data.

SUMMARY AND CONCLUSIONS

This paper presented challenges confronting our understanding of non-contact ACL injury mechanisms. Despite substantial research, there are still many open questions and conflicting views about the risk factors and forces implicated to cause injury. It seems apparent that new and/or improved study approaches are required. Today our ability to improve current prevention programs, training regimes, and rehabilitation programs is limited by an incomplete understanding of the causes of ACL injuries. Addressing many of the challenges presented can bring us one step closer to enhancing our understanding of ACL injury mechanisms. Perhaps finding a technique to simultaneously and concurrently address all existing challenges would be more fruitful. The information garnered from this paper can facilitate advancements in this research field as it aids in identifying gaps in knowledge.

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