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Estimation of cruciate ligament forces via smart compression garments

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Abstract

Muscle and ligament injuries are among the most common sports injuries with Anterior Cruciate Ligament (ACL) injuries commonplace in many sporting codes. Several studies have been performed in an effort to quantify the loading of the cruciate ligaments during activity. However these ultimately rely on data obtained through static machines performing isokinetic movements. Smart Compression Garments (SCG), functioning as a wearable muscle and ligament management system, were developed to understand the loading of the ligaments whilst providing an additional means to mitigate the risk of overload and strain. Forces were determined through a new method of calculating the cruciate ligament forces utilising the forward dynamic calculation of the SCG determined muscle forces and knee angle. Four controlled scenarios were performed to evaluate the ligament loading conditions involving maximal contraction of the hamstrings or quadriceps at several knee flexion angles. The loading of the cruciate ligaments was demonstrated during walking on a treadmill, where the both the ACL and PCL were significantly stressed alternatively once per stride. The application of an SCG allows for the associated information processing of soft tissue data through a wearable system capable of assessing active muscle load, cruciate ligament forces, and co-contraction of paired muscles in real-time, providing metrics for improved performance and safety.

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1. Introduction

Soft tissue injuries (both acute and chronic overuse syndromes) are among the most prevalent sports injuries. In numerous sporting codes, from the amateur to the elite, every season is plagued by injuries that prevent many participants from full participation. Of key concern is the increasing predominance of ligament injuries in the lower limbs, specifically the Anterior and Posterior Cruciate Ligaments (ACL, PCL). Several studies have been performed in an effort to quantify the loading of the cruciate ligaments when in use, but ultimately measurement systems rely on data commonly obtained through static machines performing either isometric or isokinetic movement.

In the design of the knee joint, it is the cruciate ligaments that function as restraining elements to anterior and posterior movement of the tibial plateau with relation to the distal head of the femur. Only one ligament is ever loaded to compensate for the net horizontal force from the ground reaction force and subsequent supportive muscular activity, where the resultant load on the ligament is highly dependent of the flexion angle of the knee. Although significant research has been done into the failure of the cruciate ligaments under various loading conditions [1,2,3], and the prevalence of injury during due to muscle activity [4], gender [5] or sport [6], quantifying the real-time loading forces of the cruciate ligaments within the sporting environment has been limited. This research explores the continued development of a Smart Compression Garment (SCG) [7, 8], a wearable muscle and soft tissue management system capable of estimation of muscle activity, inferring loading conditions and providing an additional avenue to mitigate injury risk through overload and straining of soft tissues. This paper purposely introduces a new technique in the estimation of cruciate ligament loading conditions previously developed by the research team with the use of a SCG as a means to quantify cruciate forces during controlled loading tests and locomotion.

2. Methodology

2.1. Experimental Methodology

The elements responsible for cruciate ligament loading involve the ground reaction force (F_{GRF}), muscular force from the quadriceps (F_Q) and hamstrings (F_H), along with the knee flexion angle (*KFA*), all of which were determining through the measurements from the SCG. The prototype apparel system contains multiple pressure and flexion sensing nodes integrated within a commercially available compression garment. Muscular forces were determined through the initial calibration of the smart apparel data to that of set leg flexion and extension exercises, where inverse-dynamic calculations were used to correlate muscle pressure to the expected muscle load [8, 9]. Additional to the pressure sensors, wireless EMG sensors (*Zero-wire Cometa Systems, Italy*) were utilised to confirm the muscular activity during the tests. Placement of the EMG electrodes was dictated by a previously performed 5-point signal analysis [8], where the measurement signal was optimised for correct siting with relation to the muscle belly centre.

To evaluate the loading of the cruciate ligaments static tests were performed which alternatively strained either the ACL or PCL ligaments. In total, four tests were conducted where the KFA was held constant and the muscles of the Quadriceps and/or Hamstrings were activated to extend or flex the knee against a stationary anchor at maximal voluntary isometric contraction (*MVIC*).

Table 1. Ligament load testing conditions

Test	Knee Flexion Angle (degrees)	Muscular Action	Target Cruciate Ligament Load
1	5	Maximal Extension with Quadriceps	Maximal ACL
2	138	Maximal Extension with Quadriceps	Maximal PCL
3a	90	Maximal Extension with Quadriceps	Neither
3b	90	Maximal Flexion with Hamstrings	Maximal PCL