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.

Keywords: Cruciate Ligament; ACL; PCL; Smart Compression;

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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).

| 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                  |
The MVIC was used as a means of normalising the force in the muscle with respect to both systems of measurement. The tests were designed to selectively load either one of the cruciate ligaments maximally; test 1 loaded only the ACL at maximal extension, tests 2 & 3b the PCL at full flexion and 90 degrees (respectively), and test 3a loading of neither cruciate ligaments (provided no hamstring co-contraction occurred) at a 90 degree flexion angle. A summary of the expected results of the testing can be seen in Table 1.

2.2. Calculating Knee Ligament Loading

The calculation of cruciate ligament forces was achieved by extending Fuss' [9] inverse-dynamic method to a forward dynamic one. Through the measurement of KFA, several others parameters could be derived to determine critical soft tissue conditions within the knee joint. Measured KFA values allowed for the average angles (relative to the normal of the tibial plateau) of the ACL (\(\theta_{ACL}\)), PCL (\(\theta_{PCL}\)), patellar ligament (\(\theta_{PL}\)) and average hamstring tendons (\(\theta_{HT}\)) could be calculated. Furthermore, the KFA was utilised to determine the mechanical advantage created by the patella (\(MA_P\)), and the moment arms of the patellar ligament (\(L_{PL}\)) and hamstring tendons (\(L_{HT}\)).

Table 2. Determined soft tissue parameters based upon knee flexion angle [9]

| Parameter                        | 5°      | 90°     | 138°    |
|----------------------------------|---------|---------|---------|
| ACL angle                        | \(\theta_{ACL}\) | 59.5°   | 40.9°   | 34.1°   |
| PCL angle                        | \(\theta_{PCL}\) | 51.5°   | 61.9°   | 69.7°   |
| Patellar ligament angle          | \(\theta_{PL}\) | 23.5°   | -1.8°   | -10.0°  |
| Hamstring tendon angle           | \(\theta_{HT}\) | -9.9°   | -82.7°  | -130.4° |
| Mechanical Advantage of Patella  | \(MA_P\) | 1.37    | 0.61    | 1.03    |
| Patellar ligament moment arm     | \(L_{PL}\) | 49 mm   | 37 mm   | 36 mm   |
| Hamstring tendon moment arm      | \(L_{HT}\) | 32 mm   | 46 mm   | 31 mm   |

Combining the \(MA_P\) and the quadriceps force, allows for the determination of resultant force (\(F_{PL}\)) within the patellar ligament. This permits calculation of the moment about the knee instant centre produced by the quadriceps (\(M_{PL}\)).

\[
F_{PL} = F_Q \times MA_P \tag{1}
\]

\[
M_{PL} = F_{PL} \times L_{PL} \tag{2}
\]

The hamstring force (\(F_H\)) also produces a resultant moment about the knee instant center (\(M_{HT}\)) that when coupled with \(M_{PL}\), determines the overall knee moment \(M_K\) (balanced by the external moment). The sign of which will dictate whether extension (positive) or flexion (negative) of the knee is occurring.

\[
M_{HT} = F_H \times L_{HT} \tag{3}
\]

\[
M_K = M_{PL} + M_{HT} \tag{4}
\]

As \(M_K\) is a product of the muscles balancing the \(F_{GRF}\), the horizontal external force is calculated based upon the relative moment arm of the knee instant center to the ground. For this the body height (BH) of the subject is considered where the relative shank (28.8% BH), and foot height (3.9% BH) are calculated [10] or measured.
\[ F_{\text{GRF}} = \frac{M_K}{BH(0.285+0.039)} \]  

(5)

The horizontal (\(x\)) component of both \(F_H\) and \(F_{PL}\) along with the \(F_{GRF}\) is summed for the net horizontal shank force to be compensated by the cruciate ligaments. A forward (positive) result for \(F_{x\text{-net}}\) is compensated by the ACL, and a backward (negative) result by the PCL.

\[ F_{x\text{-net}} = [F_{PL} \sin(\theta_{PL})] + [F_{HT} \sin(\theta_{HT})] + F_{GRF} \]  

(6)

Finally through the angles of the cruciate ligaments based on the current KFA, the cruciate ligament forces can be determined. As the ligaments do not provide support under compression, a negative result is zeroed and only the positive result deemed relevant to the loading conditions.

\[ F_{ACL} = \frac{F_{x\text{-net}}}{\cos(\theta_{ACL})} \]  

(7)

\[ F_{PCL} = -\frac{F_{x\text{-net}}}{\cos(\theta_{PCL})} \]  

(8)

3. Results and Discussion

3.1. Static Cruciate Loading Tests

The sampled data for the cruciate loading tests was compared across all tests, with specific focus placed on matching calculated loading conditions (shown within Table 1) with that of outputs from the SCG. The outcomes for all four tests, for both Pressure and EMG measurements, were processed through the presented mathematical model and the relationship of each system inferred from the muscle activity to the resultant ligament loads (Figure 1).

Figure 1. Normalised cruciate ligament loading of EMG and Pressure sensors (a) Test 1; (b) Test 2; (c) Test 3a; (d) Test 3b
Results for all the tests (1, 2, 3a, & 3b) showed strong correlations ($R^2$) values of 0.7812, 0.8129, 0.8422, 0.8722 respectively between both pressure and EMG signals for each test, further confirming evidence that muscle electrical activity correlates to that of surface pressure changes of the active muscle group. Tests 1 and 2 evaluated the forces produced as a result of the quadriceps extending the knee at both full extension and full flexion angles. As calculated, the tests selectively stress the cruciate ligaments during the activity; where the resultant $F_{x-net}$ is compensated in test 1 by the ACL (Figure 1a), and test 2 the PCL (Figure 1b).

As when the knee is flexed at 90 degrees the patella ligament is closely aligned with the normal to the tibial plateau ($\theta_{PL} = -1.8^\circ$), there exists only a small resultant horizontal force produced by the quadriceps. Thus horizontal net force largely occurs through the activation of the hamstrings muscles, resulting in a posterior force to the tibial plateau; stressing the PCL. This is evident in the results of Test 3a where the PCL is minimally stressed through inadvertent hamstring co-contraction activity whilst the quadriceps is used maximally to extend the knee. When the hamstring muscles are activated to further flex the knee during Test 3b, the PCL is maximally stressed. This relationship is clearly shown in Figure 1c and 1d.

3.2. Cruciate Loading: Walking

Additional to the static tests, the muscle surface pressures and KFA were measured whilst a participant walked at constant pace (4 kph) on a treadmill over 29 individual strides. The averaged SCG pressure data was converted to the estimated muscle force in the quadriceps and hamstrings [8], where the resultant cruciate ligament forces were derived and compared to the loading during stance phase of the gait cycle (Figure 2).

![Figure 2](image-url)
A lack of centre of mass acceleration of the body, as experienced during traditional walking, is present when walking on a treadmill. As a consequence both muscle and ligament loading differ from standard activation patterns of walking over solid ground. The results however clearly show that the ACL and PCL are alternatively loaded during the stance phase of the gait, where during low knee flexion angles with significant quadriceps loading the ACL is loaded, and during high Hamstring activity with increasing KFA the PCL.

Figure 2b displays four key components of the cruciate ligament loading during the stance phase of Figure 2a. At the initial contact of heel-strike (1), ligament loading is minimal as a result of low muscular exertion. As the bodyweight is transferred onto the foot the quadriceps engage for stability (2), at low KFA this increases the loading of the ACL aligning with the results found in Test 1. As the foot is further loaded the hamstrings drive the body forward, straightening the leg just prior to heel-raise (3). At this condition $F_{x\text{-net}}$ is balanced and neither cruciate ligament loaded. As the heel is raised, hamstring force continues to increase as the ball of the foot is loaded. This action along with increases in KFA loads the PCL for the remainder of the stance phase, reaching a maximum just prior to toe-off (4).

4. Conclusions

A smart compression garment is a new approach at creating a wearable system capable of assessing active muscle loading, knee ligament strain and co-contraction of paired muscles in a real-time capacity during physical activity. The mathematical approach presented allows for the calculation of cruciate ligaments loads through the knowledge of the forces in the lower leg, and the respective angle of the knee. Continued development of not only the garment but also the associated information processing and calculation methods allows for the real-time monitoring of an individual’s cruciate ligament loading forces, providing metrics for improved exercise performance and safety. Preliminary research shows that the selective loading of the cruciate ligaments by both varied muscle activation and knee flexion angle can be calculated by measuring both the electrical activity within the muscle as it contracts, and the subsequent surface pressure variations under a compression garment as the muscle contracts to apply a force.

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