Contact Stress Patterns across the Tibial Plateau during Gait: Effect of Anterior Cruciate Ligament Injury
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INTRODUCTION:
The magnitude and direction of external dynamic forces acting across human knees has been well characterized for a range of daily activities [1,2]. However, the loading profiles acting directly on the articular cartilage of the knee have not been established. This lack of information negatively impacts our ability to understand the mechanical consequences of soft tissue injury; and limits our ability to understand the mechanical pathways that drive the development of post-traumatic osteoarthritis.

The objectives of this study were to: (i) quantify the loading patterns across the tibial plateau surface of intact human cadaveric knees (ii) quantify how those patterns change as a function of anterior cruciate ligament (ACL) rupture. We hypothesized that changes in the characteristic loading patterns between intact and ACL ruptured knees will be most prevalent in the posterior aspect of the plateau, damage to which has been clinically associated with ACL rupture [3].

METHODS:
**Pressure Measurements Across the Tibial Plateau:** 9 human cadaveric knees were stripped of soft tissue, except for the capsule, collateral and cruciate ligaments, and menisci. All knees were pinned through the epicondylar axis and aligned with the flexion-extension axis of a load-controlled Stanmore Knee Simulator. The simulator was programmed to apply axial force, rotational torque and flexion-extension dynamic load profiles to mimic gait; while a pressure sensor (4010N, Tekscan Inc, MA) inserted under the menisci and attached to the surface of the tibial plateau was used to record normal contact force data at a frequency of 10 Hz [4]. Knees were tested intact for 20 cycles. The ACL from each knee was resected and testing was repeated.

**Characteristic Loading Patterns of Intact Knees:** Using a custom in-house developed Matlab program (Mathworks Inc, MA), the loading patterns for each of the 209 sensing elements (sensels) across the sensor were isolated and mapped as a function of percent of the gait cycle. To establish if characteristic loading patterns existed across the tibial plateau, the load profile from each sensel was used as a template and compared to the patterns as recorded by the remaining sensels of the sensor using a normalized cross-correlation (NCC) algorithm (eq. 1).

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NCC = \frac{\sum_{t=1}^{N} (f(t)-\bar{f})(\bar{r}(t-u)-\bar{r})}{\sqrt{\sum_{t=1}^{N} (f(t)-\bar{f})^2 \sum_{t=1}^{N} (r(t-u)-\bar{r})^2}}
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where \( t \) is the time (seconds), \( u \) is the time for one full gait cycle (2 seconds), \( N \) is the current time shift, \( f \) is the function describing the pattern of interest, \( \bar{f} \) is the mean of the current time window, \( r \) is the template function, \( \bar{r} \) is the mean of the current template function. Sensels with NCC values greater than 0.96 were considered as similar patterns and grouped. The grouped patterns were averaged and compared between knees using the same NCC algorithm.

**Characteristic Loading Patterns of Intact vs. ACL Ruptured Knees:** The NCC value of the loading pattern at each individual sensel was calculated on a knee-by-knee basis between each intact and its respective ACL ruptured condition. The maximum value of the calculated NCC was subtracted from 1, and used as a metric of pressure pattern difference at each sensel; where a score of 1 = maximum difference and 0 = minimum difference. The procedure was applied to all sensels on the medial tibial plateau.

RESULTS:
**Intact Knees:** Three reoccurring loading patterns which occurred in consistent locations were found in the intact knees. The first pattern (Type I) consisted of two peaks, the timing of which corresponded to that of the peak externally applied axial forces at 14% and 45% of gait (Fig. 1A). This loading pattern was located centrally on the medial tibial plateau with a peak pressure magnitude ranging from 0.9 to 2.5 MPa. The second pattern (Type II) contained a single prominent single peak which occurred at 25 to 30% of gait with peak pressure values ranging from 0.5 to 1.5 MPa (Fig 1B) and was located along the anterior and posterior edges of the tibial plateau. The final loading pattern (Type III) consisted of a prominent single peak during the stance phase of gait followed by a series of diminishing peaks during the swing phase of gait (Fig 1C), which was located in the posterior peripheral region of the tibial plateau with a peak pressure magnitude ranging from 0.3-2.0 MPa. 

**Intact vs. ACL ruptured knees:** For the ACL ruptured knees, the pressure distribution during the gait cycle was similar in Type I (Fig 1D) and Type II (Fig 1E) characteristic patterns while there was a 50% decrease in magnitude in the Type III profile. (Fig 1F).

To understand the local changes in loading pattern between intact and ACL ruptured knees, the change in pattern seen at each sensel of the pressure sensel was quantified (Fig 2). The mean normalized cross-correlation variation between intact and ACL ruptured knees was 0.151 +/- 0.073 suggesting that there is, on average, a 15% difference in loading patterns from intact to ACL ruptured knees. These local changes occurred in the anterior central, posterior central and posterior lateral aspects of the tibial plateau (Fig 2A). 2 of the 9 knees exhibited little change to local loading patterns (~0.02 to 0.08) (Fig 2B).

DISCUSSION:
We have demonstrated that distinct loading patterns consistently occur on the medial compartment of the tibial plateau of intact knees, during simulated gait. While similar loading patterns were found in the pooled ACL resected knees, when examined on a knee-by-knee basis, distinct local variations in loading patterns were apparent. 70% of knees demonstrated pronounced variations in loading patterns in the posterior central and posterior lateral aspects of the medial plateau; supporting our hypothesis that changes would be most prevalent in that region. The direct association between the changes in load profile and the damage seen clinically [3], has yet to be made. However, the ability to quantify the contact stress patterns to which the surface of articular cartilage is subjected to during gait, will allow for this link to be further explored.

SIGNIFICANCE: The regional variation in contact load distribution and magnitude profile on the tibial plateau during simulated gait in intact and ACL ruptured injured knees has been quantified. This unique data has identified distinct characteristic loading profiles in intact knees; and consistent changes in loading patterns localized to regions that are clinically pre-disposed to damage following ACL injury. It is envisaged that our data will help to elucidate the mechanical pathways that drive the development of post-traumatic osteoarthritis.


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