# The effect of out-of-plane deformation on ligament surface strain measurements

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**ABSTRACT**

*The characterization of biological tissues depends on accurate measurements of deformation and strain, but less attention has been given to the role of out-of-plane deformation in ligament strain. The objective of this study was to investigate the influence of out-of-plane deformation on surface strain measurements in healthy and damaged ligaments. Tensile tests on five porcine posterior cruciate ligaments (PCL) were performed before and after damage using the femur-PCL-tibia construct. Damage was simulated by loading the ligament to its maximum force capacity. Digitized surface dots were tracked using an optical motion capture system. The transverse strain ($\varepsilon_{xx}$), longitudinal strain ($\varepsilon_{yy}$), and shear strain ($\gamma_{xy}$) distributions on the ligament surface were obtained for the control and damaged states using two-dimensional (2d) strain and three-dimensional (3d) strain measurements. There was no significant difference between the 2d and 3d strains in the control state for all three strains. However, the value and location of the peak strain values (tensile and compressive) in ligament surfaces did change. The 2d peak tensile strain was both over and under-estimated, compared to 3d strain, when out of plane deformation was included for $\varepsilon_{xx}$ and $\varepsilon_{yy}$; but consistently overestimated for positive $\gamma_{xy}$. The percentage of damaged regions, quantified as a loss in tensile strength, after damage was overpredicted by 2d strain for $\varepsilon_{yy}$. Care should be taken when using 2d surface strain as peak values and local damage is sensitive to out-of-plane deformation.*

**Keywords:** Posterior cruciate ligament; Out-of-plane deformation; 2d strain; 3d strain.

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## 1 Introduction

Injuries to ligaments are a common occurrence specifically among the athletes and more physically active populations. Posterior cruciate ligament (PCL) rupture occurs in 5-20% of all acute ligament knee injuries and causes pain, swelling, instability, and functional disability of the knee joint [1, 2]. The accurate measurement of displacement and strain is critical to characterize biological tissues, organs, and their interactions with biomedical devices [3]. In the case of ligaments, as well as several other musculoskeletal tissues, this characterization is challenging due to their inhomogeneous and anisotropic nature. A precise full field measurement of ligament strain is necessary to help identify local strain concentrations and regions susceptible to damage [3]. This information can then be used to evaluate structure-strength relationships at different length scales and inform the development of engineered materials designed to replace damaged ligaments.

Several methods have been used to measure the ligament and capsule strain distribution such as photoelastic coating, high speed films, dye lines, marker bead etc [4–8]. In most cases, the strain measurement is based on in-plane deformation; neglecting the out-of-plane deformation and reports of strain is limited to the axis of loading [9]. Digital image correlation (DIC) is a technique that can measure both two-dimensional (2d) and three-dimensional (3d) surface strain [9] but care is needed to optimize the surface preparation, hardware, and software settings to obtain accurate and precise measurement of strain [3]. However, from the existing literature, it is not clear if the inclusion or exclusion of out-of-plane deformation has any effect on the ligament surface strain calculations and no comparisons have been made to determine the accuracy of a 2d approximation.

Therefore, the goal of this study was to investigate the contribution of out-of-plane deformation on the measurement of PCL surface strains. We sought to identify if the out-of-plane deformation affects the surface strain calculations and assessment of local damage. A simple and non-invasive digitized surface dot marker method was used to measure the transverse, longitudinal, and shear strains on the ligament surface with and without out-of-plane deformation for both the control and damaged states.

## 2 Materials and methods

### 2.1 Specimen preparation

Porcine knee specimens (n=5, six months old) were collected from the Meat Science Laboratory at the University of Illinois and stored at –20°C. Specimens were thawed at room temperature overnight before dissection. All soft tissues were carefully dissected without disturbing any part of the PCL or its bony insertion sites leaving a bone (femur) – ligament (PCL) – bone (tibia) construct (Fig. 1A). The PCL was moistened with phosphate-buffered saline (PBS) solution during the dissection, specimen preparation, and mechanical testing to prevent dehydration.

### 2.2 Experimental setup

Biomechanical testing was performed using a materials test machine (Instron Model 5967, Instron Corporation, Norwood, MA, USA). A custom fixture was developed to mount the femur–PCL–tibia construct in the test machine. The femur and tibia were aligned as close to full extension as possible and embedded with a fast curing epoxy (Fig. 1B). Twenty-one surface dots were marked in a grid using permanent ink along the ligament surface (Fig. 1C). The dots were digitized using an optical motion capture system with an accuracy of 0.1 mm (Optotrak Certus, Northern Digital Inc., Waterloo, Canada) to record the three-dimensional coordinates ($x$, $y$, and $z$). The repeatability of digitizing landmarks was 0.147 mm; therefore displacements below 0.15 mm were excluded.

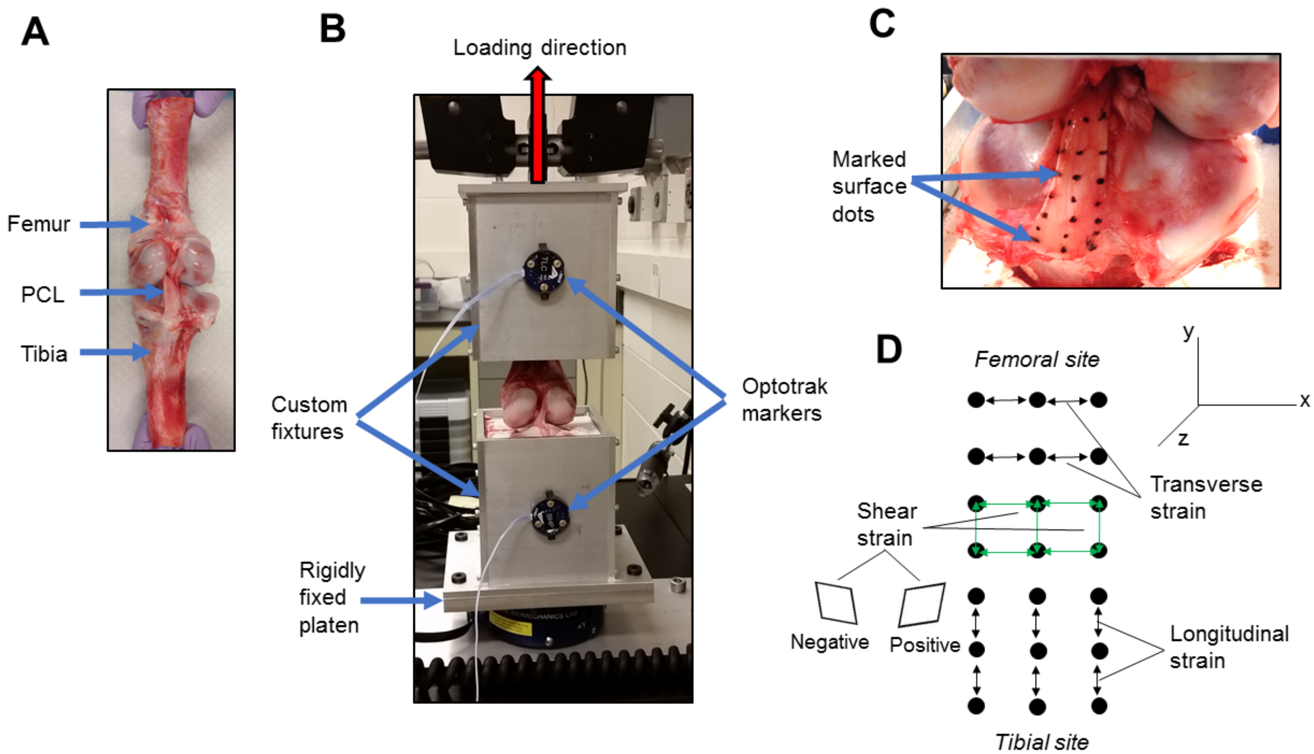


**Fig. 1: (A) The posterior view of the knee joint after dissecting all soft tissues except the PCL and leaving a bone (femur) - ligament (PCL) - bone (tibia) construct, (B) experimental testing setup with potted knee specimen including the Optotrak markers to measure the strains, (C) twenty-one dots marked on the ligament surface to measure the local strain and then strain distribution maps, seven rows in the transverse direction and three columns in the longitudinal direction along the PCL, and (D) transverse and longitudinal local strains were calculated between the markers along the transverse and longitudinal directions as shown by black arrows. Local shear strain was calculated by the angular deformation of the plane formed by four adjacent surface dots from the longitudinal and transverse directions as shown by green arrows.**

### 2.3 Biomechanical testing

Testing for each specimen was performed in three steps: (1) pre-damage strain, (2) damage simulation, and (3) post-damage strain. The initial position of the construct was defined as the reference position, and all three steps were started from this reference position. First, the PCL insertion sites and surface dots of the pre-damage ligament (herein referred to as the control state) were digitized prior to testing. Specimens were preconditioned with 5 loading-unloading cycles of displacements from 0 to 1.5 mm at an extension rate of 50 mm/min. Next, the specimen was loaded to 100 N at 50 mm/min ensuring that the ligament stiffness remained in the elastic region. Immediately once the specimen reached 100 N, the PCL insertion sites and surface dots were digitized again to obtain the final positions. The specimen was then returned to the reference position.

During the second step, we permanently deformed the ligament to induce damage. The specimen was again preconditioned and the construct was loaded at 50 mm/min until it reached the maximum load. The load-deformation curve was monitored during testing and the test was stopped as soon as the load began to decrease from maximum load. Finally, the damaged ligament was loaded again from the reference position using the same protocol as in the first step (loaded to 100 N). The PCL insertion sites and surface dots were re-digitized at the reference and loaded position.

## 2.4 Strain distribution map

We calculated the transverse strain ($\varepsilon_{xx}$), longitudinal strain ($\varepsilon_{yy}$), and shear strain ($\gamma_{xy}$) before and after simulated damage. The local transverse strain was calculated as the change in length between two surface dots in the transverse direction divided by their initial length (Fig. 1D). Transverse strain among all surface dots was calculated and a distribution map was obtained by interpolating the strain over the surface of the ligament using custom software (Matlab R2017, Mathworks Inc., Natick, MA, USA). Similarly, the longitudinal strain map was obtained between two surface dots along the longitudinal direction (Fig. 1D). In the case of shear strain, two direction vectors were identified using four adjacent surface dots from the longitudinal and transverse to form a plane (Fig. 1D). Local shear strain was calculated from the angular deformation of the plane and finally the shear strain distribution map was obtained.

For all three types of strains (transverse, longitudinal, and shear), strain distribution maps were obtained for 2d strain and 3d strain for both control and damaged states. For 2d strain, the local strain between two surface dots was based on the '*x*' and '*y*' coordinates and the out-of-plane coordinate '*z*' was omitted thus representing only in-plane deformation. The '*z*' coordinate was included for 3d strain calculations between the two surface dots. A paired-sample t-test was used to determine differences between the 2d strain and 3d strain in control state for all three types of strains ($\varepsilon_{xx}$, $\varepsilon_{yy}$, $\gamma_{xy}$) (OriginPro 2018, OriginLab Corporation, Northampton, MA, USA). Significance was set at $p < 0.05$ and trends at $p < 0.1$.

## 2.5 Changes in peak strain and identification of damaged regions

To assess the sensitivity of peak strain to the inclusion of out-of-plane deformation we calculated the percent change of peak strain values from 2d strain to 3d strain in the control state. Only the tensile peak strain was considered for transverse and longitudinal strains. However, for peak shear strain, we calculated percentage changes for both positive and negative shear. To determine whether the assessment of damage varies when using 2d or 3d strain measurements, we compared the percentage of damaged regions in each ligament for longitudinal strain. Damage was defined as regions with a loss in tensile strength; that is those areas initially in tension but observed to be in compression, indicating that those regions are no longer taking tensile loads. The percentage of damaged regions was calculated as the ratio of the number of these damaged regions to the original number of tensile regions in the control state.

# 3 Results

There was no significant difference between the 2d and 3d strains in the control state for all three strains. However, two out of five specimens showed an increasing trend for $\varepsilon_{xx}$ (specimen 3, $p = 0.06$ and specimen 4, $p = 0.072$) whereas one specimen had increasing trend for $\varepsilon_{yy}$ (specimen 5, $p = 0.098$) when using 3d strain measurements.

Overall the strain distribution maps (between 2d and 3d control; between 2d and 3d damaged) were similar except the values and locations of peak strains varied (Fig. 2). Change in peak location was more common for compressive strain compared to tensile strain. When out of plane deformation was included, the peak transverse tensile strain ($\varepsilon_{xx}$) increased in three specimens (mean increase = 71.17%) (Fig. 3A). For longitudinal strain ($\varepsilon_{yy}$), only one specimen resulted in increased strain (64%) (Fig. 3B). However, the peak positive shear ($\gamma_{xy}$) increased for all five specimens and peak negative shear decreased (Fig. 3C, 3D). In terms of damage, the 2d longitudinal strain measurements overestimated the percentage of damaged regions in four specimens and one specimen was underestimated (Fig. 4).

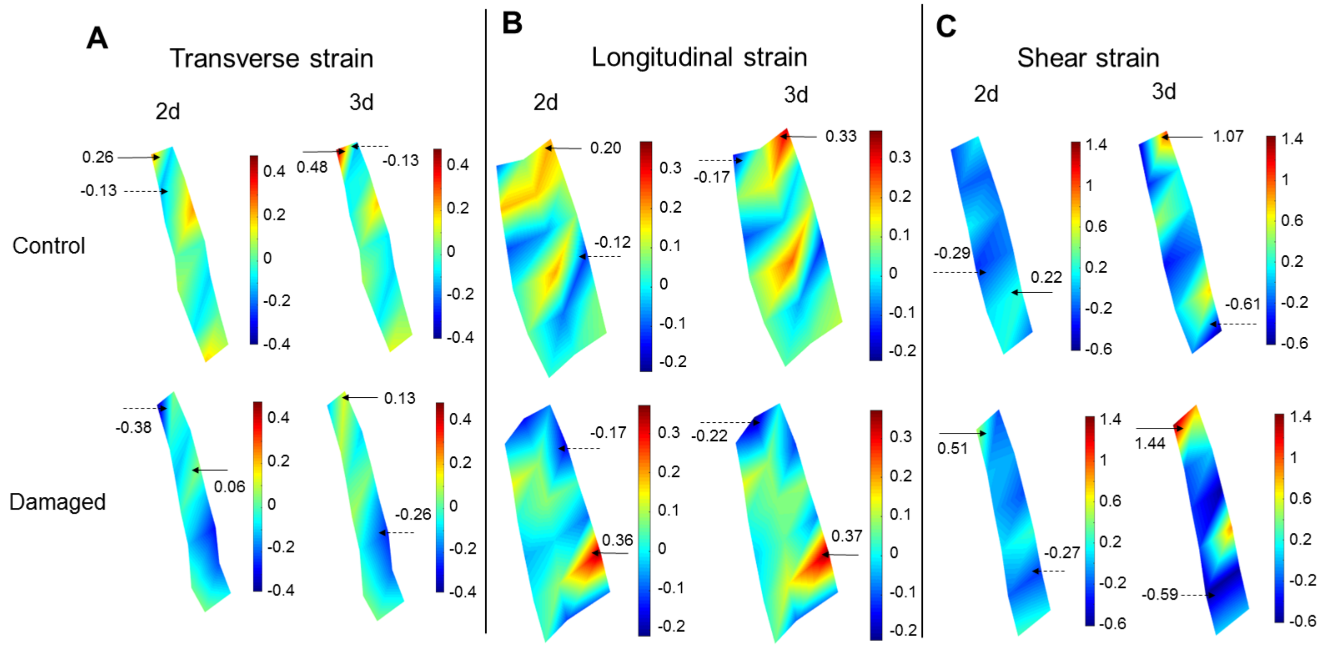


**Fig. 2: (A) Transverse, (B)longitudinal, and (C) shear strain distirbution maps on the ligament surface of specimen 2 for 2d and 3d strains in both control and damaged stages. The location of the tensile and compressive peak for transverse and longitudinal strains was represented by solid arrow and dash arrow with magnitudes respectively. For shear strain, solid arrow and dash arrow represent the peak location for positive and negative strains respectively.**

## 4 Discussion

The aim of this work was to understand the effect of out-of-plane deformation on ligament surface strain. While several methods exist to measure the surface strain of biological tissues, we utilized a simple and non-invasive digitized dot marker with an optical motion capture system to assess the 2d and 3d strains on ligament surface.

Our results show that statistically there was no significant difference between the 2d and 3d strains in control states, but the value and position of the tensile and compressive peak strains changed. For shear strain, positive peak increased more than 300% for three specimens whereas negative peak decreased more than 100% for four specimens. Although the average strain distributions across the surfaces was not significantly different between 2d and 3d measurements, the change in peak values may increase in certain specimens causing higher local strain concentrations.

Previous studies have shown that the shoulder and knee ligaments are often ruptured near the insertion sites [10–13]; typically, the common regions where the higher strain occurs in the ligaments compared to mid-substance [5, 6, 8, 11, 14]. Therefore, neglecting the out-of-plane deformation may mask the actual strain value and earlier failure may occur than expected based on 2d strain. Furthermore, all five specimens for $\varepsilon_{yy}$ showed different percentages of damaged regions when compared between the 2d and 3d strains; indicating that the 2d strain may not accurately predict whether the local regions are in tension or compression before and after damage.

The strain distribution maps suggest that transverse, longitudinal, and shear strains are nonuniformly distributed on the ligament surface. Most previous studies only report the longitudinal or transverse strain [9] and our results show that shear strain maps are similarly nonuniform. Although ligament shear strain receives less attention in literature, the shear deformation of the ligament surface was sensitive to damage; four out of five specimens had a four-fold increase in either positive/negative peak shear from control to injured states (for 3d shear strain) indicating angular deformation occurs on the ligament

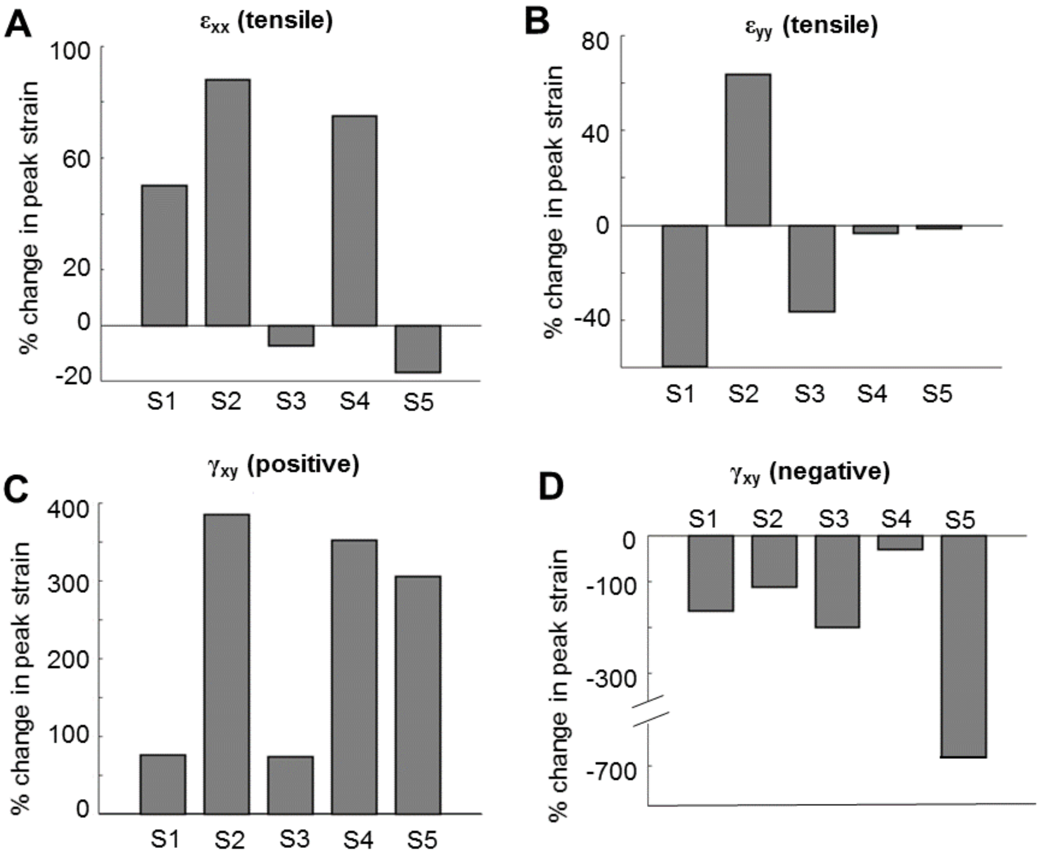


**Fig. 3: The percentage change in peak strain values from 2d strain to 3d strain in control states for (A) tensile peak for transverse strain, (B) tensile peak for longitudinal strain, (C) positive peak for shear strain, and (D) negative peak for shear strain. S1 to S5 represent the five specimens. The percentage change in tensile peak strain for transverse and longitudinal strains may increase or decrease from specimen to specimen; but positive peak in all five specimens for shear strain increased and negative peak decreased.**

surface during damage.

Since ligament strain is heterogeneous with some regions stronger than others, care should be taken during the development of the ligament reconstruction grafts or even during the ligament repair so that the ligament can sustain the non-uniform load including non-tensile loading directions. These local mechanics are likely linked to more locally intrinsic micro-structural or compositional properties of ligaments. This variation may be due to differences in collagen fiber distribution, alignment, and cross-linking [15–18]. The variation in strain may also be a result of the compositional contributions of water, collagen, and glycosaminoglycan (GAG) [5, 19]. Further research to measure the local mechanical response and micro-structural analysis would be useful to explain the inhomogeneity and microstructure-function relationships.

The current study has several limitations. First, we chose animal ligament (porcine PCL) for this biomechanical testing with a nominal sample size. We did not test the ligament at different flexion angles. Biomechanically, during flexion, the PCL experiences a different set of forces than those imposed by this study and likely results in a different inhomogeneous force distribution. Furthermore, the method used to simulate damage is different than hypothesized physiological injury conditions. Future studies on ligaments with full volumetric displacement measurement and physiological boundary conditions are necessary to understand the through thickness surface strain distribution as it relates to specific mechanisms of ligament rupture.

In conclusion, we have investigated the sensitivity of out-of-plane deformation on surface strain

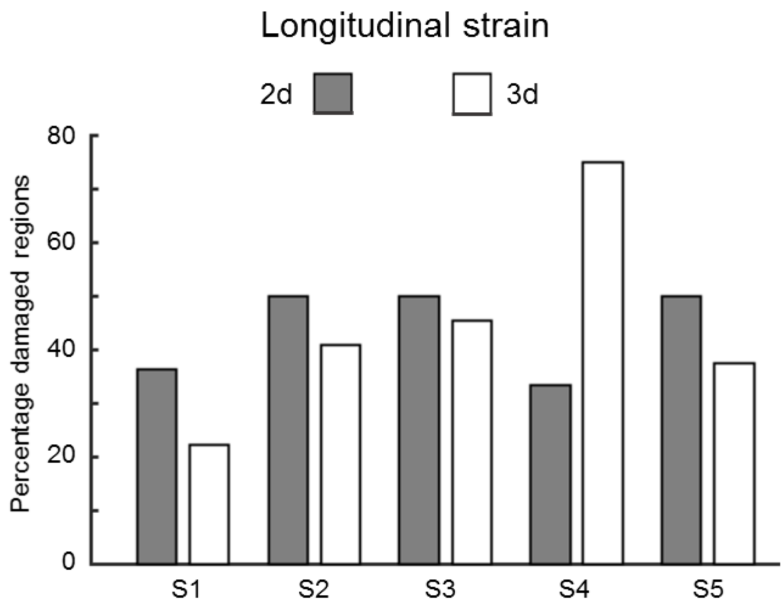


**Fig. 4: The percentage damaged regions from control to damaged states for longitudinal strain. S1 to S5 represent the five specimens. The grey bar represents the 2d strain whereas the white bar represents the 3d strain. The 2d strain overpredicts the percentage damaged regions in four specimens.**

measurement. The use of 2d surface measurements is likely sufficient for elastic testing as evidenced by the similarity in the strain maps prior to damage. However, in some cases the peak strain may change and mask higher localized strain due to the omission of out-of-plane deformation. 2d strain in local regions also could be misleading while analyzing ligament damage.

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