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# Correlation between translational and rotational kinematic abnormalities and osteoarthritis-like damage in two *in vivo* sheep injury models

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ABSTRACT

The relations between kinematic abnormalities and post traumatic osteoarthritis have not yet been clearly elucidated. This study was conducted to determine the finite helical axes parameters and the tibiofemoral translation vector in the knee joints of two surgically induced injury sheep models: anterior cruciate ligament and medial collateral ligament transection (ACL/MCL Tx) ($n = 5$) and lateral meniscectomy ($n = 5$). We hypothesized that morphological damage in the experimental joints would be correlated to alterations in these kinematic variables. There was no strong evidence that morphological damage to the joints 20 weeks post ACL/MCL transection or meniscectomy was correlated with alterations in the finite helical axes variables. Nevertheless, significant correlations were found between the morphological damage to the joints and the magnitude of the change in the translation vectors after ACL/MCL transection (significant correlations ($p = 0.005$) during stance and trends ($p < 0.1$) at all points analyzed during swing). It can be concluded that: (1) osteoarthritic-like morphological damage after ACL/MCL transection is more critically correlated to the absolute tibiofemoral translational change and (2) alterations in analyzed kinematic variables cannot solely define osteoarthritis risk after meniscal injuries. From a clinical perspective, our results suggest that the magnitude of the change in the translation vector, which is independent of the coordinate system and combines the effects of the three translational degrees of freedom, i.e. medial–lateral, anterior-posterior and inferior-superior, would be an osteoarthritis risk factor after ligament injury, and requires validation in humans.



## 1. Introduction

Major joint injury, such as ligament and meniscal tears, dramatically increases the risk of osteoarthritis (OA) developing in that joint (Buckwalter and Brown, 2004). There is consensus that alterations to joint biomechanics, such as joint kinematics, are key factors in the evolution of osteoarthritis after joint injury, which is also called post-traumatic osteoarthritis (PTOA).

The three-dimensional (3D) motion of the knee joint is usually described by three rotational and three translational (i.e. 6) degrees of freedom (DOF), detailing the relative motion of the tibia and femur with respect to each other. In clinical terms, these rotational and translational DOFs are reported as flexion–extension (FE), adduction-abduction (AA) and internal-external (IE) rotations and medial–lateral (ML), anterior-posterior (AP) and inferior-superior (IS) translations. Previous human and animal studies in combined ACL and MCL injury (Frank et al., 2012; Tapper et al., 2008; Zaffagnini et al., 2007) and meniscectomy (Beveridge et al., 2011; Bulgheroni et al., 2007; Sturnieks et al., 2008) show different degrees of alteration for each translational and rotational DOF. Although kinematic alterations after joint injury have been generally established, the relation between the abnormalities in these 6 DOF and long-term clinical outcomes in terms of PTOA develop-

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ment in the subjects have not been clearly established (Barton et al., 2016). Therefore, other comprehensive kinematic parameters such as the finite helical axis (FHA) might be useful to assess kinematic changes after joint injury and their correlation with PTOA development.

The 3D motion of the knee joint can be described as an instantaneous rotation about an axis called the axis of rotation or helical axis, and the translation along that axis (Spoor and Veldpaus, 1980). This methodology has been used less commonly than decomposition of the motion into 6 components, but has been used in various joints such as the knee (Grip and Häger, 2013; Mannel et al., 2004a, 2004b; Sheehan et al., 2007). The major advantage of using the FHA is that the motion (rotation about and translation along the FHA) description is independent of coordinate systems (Blankevoort et al., 1990). Moreover, the knee joint has a complex motion and the flexion–extension, adduction-abduction, and internal-external rotational degrees are not independent of one another; thus, geometrical combinations of these rotational degrees can strengthen the statistical analysis compared to analysis of rotational kinematic degrees of freedom independently (Titchenal et al., 2017).

In addition to the FHA variables, the translation vector from the origin of an anatomical coordinate system defined on the tibia to the origin of a femur-based anatomical coordinate system was measured from the FHA variables. The (tibiofemoral) absolute translational change, which is the magnitude of the change of the translation vector after injury is another kinematic variable used in this study. The value of this kinematic variable is independent of coordinate system and has the advantage that the combined effects of three translational DOFs, i.e. medial–lateral, anterior-posterior and inferior-superior, aggregate into one variable.

Combined ligament transection such as ACL/MCL Tx and meniscectomy (Mx) are severe knee injuries with risk of PTOA onset and development that need clinical attention (Morelli et al., 2013; Neuman et al., 2008). From a mechanical standpoint, these injuries would have different mechanisms of PTOA induction because of different functions of ligaments and menisci in the knee. Therefore, the first objective of the present study was to define the alterations in the FHA variables, translation vectors and the absolute tibiofemoral translational changes of the knee joint after anterior cruciate ligament (ACL) and medial collateral ligament (MCL) transection (ACL/MCL Tx) or lateral meniscectomy (Mx) in the sheep. The second objective was to investigate the correlations between these kinematic parameters and the gross morphological damage (signs of potential initiation and development of PTOA) in the joints after injury. We hypothesized that: (1) both types of injury would alter the location and orientation of FHA and the tibiofemoral translation vector during gait; and (2) that there would be a correlation between the severity of PTOA-like damage and changes of the kinematic variables after injuries.

## 2. Materials and methods

### 2.1. Animal models and in vivo kinematic data collection

Ten skeletally mature, 3 to 5-year-old female Suffolk-cross sheep were separated into ACL/MCL Tx (n = 5) and Mx (n = 5). The animals were trained to walk on a treadmill at 2 mph for data recording. The stifle joint kinematics were recorded at 120 Hz using video-based motion analysis (accuracy: 0.4 ± 0.4 mm, 0.4 ± 0.4°). A detailed description of the video-based system is provided in Tapper et al. (2004). Two stainless steel modified bone fracture plates were surgically implanted on the femur and tibia. These plates were used to attach a post, and removable markers, rigidly to the bones for the camera-based motion analysis system. In addition, another marker was placed over the lateral aspect of the right hoof to detect hoof-strike and hoof-off. The positions of all markers were recorded in the motion capture global coordinate system (Motion Analysis, Santa Rosa, CA). After the intact (baseline) kinematics of the joints had been defined, surgical interventions were performed on the animals. The kinematics of the joints was measured again at 4 weeks and 20 weeks after injury.

### 2.2. Surgical interventions

All procedures were approved by the University of Calgary Animal Care Committee and complied with the guidelines of the Canadian Council on Animal Care. For the combined ACL/MCL Tx group, the MCL was first transected in its mid-substance perpendicular to the long axis: then, by performing an anterolateral arthrotomy, the ACL was fully transected at its mid-substance. For the Mx group, a lateral meniscectomy was performed. The meniscal horns and the meniscofemoral ligament were transected and the lateral meniscus was removed while the lateral collateral ligament was left intact.

### 2.3. Tissue harvest and gross morphological grading

At 20 weeks, all animals were euthanized, and their hind limbs were disarticulated. Both the right (surgical) and left (nonsurgical) joints were graded morphologically at the patella, femoral groove, femoral condyles, and tibial plateau for gross cartilage score (GCS) (Drez et al., 1991) and gross osteophyte score (GOS) (Cummings et al., 2002). The sum of GCS and GOS was defined as joint gross score (GS). The experimental scores were expressed as the difference from the contralateral scores, i.e. ΔGCS, ΔGOS and ΔGS.

### 2.4. Kinematic data analysis

As described previously (Tapper et al., 2004), the joints were digitized using a portable coordinate measuring machine (FaroArm Platinum, accuracy 0.025 mm) to define anatomical coordinate systems on the femur (the femoral coordinate system, or FCS) and the tibia (the tibial coordinate system, or TCS). The origins of the femoral and tibial anatomical coordinate systems coincided with the ACL origin and insertion, respectively. The anatomical z-axes were directed proximally and parallel to the long shaft of each bone; the x-axes were directed along the line between the insertions of the MCL and LCL on the bones; the y-axis was determined using the cross product of the z- and x-axes. The raw marker coordinate data in the motion capture global coordinate system were smoothed using a cubic spline with a 6 Hz low-pass cut-off frequency (Woltring, 1986). the period between successive hoof-strikes was determined from the hoof marker data based on maximum and minimum excursions in the direction of travel (Tapper et al., 2004), and the marker data were normalized between successive hoof-strikes (0–100% gait cycle). At each percent of gait, the transformation matrix between the global coordinate system and each anatomical coordinate system was determined via singular value decomposition (Söderkvist and Wedin, 1993) and finally the transformation matrix between the tibial and femoral coordinate systems was determined as

$$T_{Femur/Tibia} = T^{T}_{Tibia/Global} \times T_{Femur/Global} \quad (1)$$

The helical axis parameters were extracted from the rotation matrix ($\boldsymbol{R}$) and the translation vector between the TCS to the FCS ($\boldsymbol{v}$) as previously described by Spoor and Veldpaus (1980):

$$\varphi = \arccos\left(\frac{R_{11} + R_{22} + R_{33} - 1}{2}\right) \quad (2)$$