ALTERATIONS IN THE RELATIVE SURFACE VELOCITY OF JOINT FOLLOWING ANTERIOR CRUCIATE LIGAMENT INJURY IN A SHEEP MODEL

S. M. M. Shekarforoush, K. Barton, M. Atarod, B. J. Heard, J. Sevick, D. A. Hart, N. G. Shrive
McCaig Institute for Bone and Joint Health, Cumming School of Medicine, University of Calgary

INTRODUCTION

Osteoarthritis (OA) is the most common type of musculoskeletal disorder in the world. OA is a disabling, chronic, degenerative disease of joints characterized by pain, swelling, and loss of joint function, with progressive and irreversible loss of articular cartilage [1]. OA is the most common form of arthritis in Canada with around 4.4 million Canadians (13%) having clinically diagnosed OA [1-2]. The total (direct and indirect) cost of OA to the Canadian economy was estimated to be $27.5 billion in 2010, rising substantially in the future as the demographic bulge of the "baby-boomers" reaches old age [3]. There are various risk factors for the initiation and development of OA, including systemic factors such as age and gender and intrinsic factors such as bone malalignment, muscle weakness and previous injuries [1]. Among all these risk factors, joint injuries have been considered as the most well defined factor in the initiation and progression of a subset of OA [4-6]. This sub-type of OA that develops as a direct result of an injury to a joint is also called secondary or post-traumatic osteoarthritis (PTOA). Whereas OA is most commonly diagnosed in individuals over 50, PTOA is frequently diagnosed in people of any ages 5-15 years post injury [6-9]. Specific to the knee joint, a large and growing body of literature with respect to both human and animal models has revealed that damage to knee joint ligaments, especially the cruciate ligaments, and/or the menisci often results in the development of OA in the long term [10]. For example in one follow-up study, it was reported that 51% of females exhibited radiographic evidence of OA several years after rupture of the ACL [11]. It has also been reported that 50-80% of individuals with an ACL injury go on to develop PTOA as early as 5-10 years after the injury [7, 9]. The exact mechanisms that initiate articular cartilage degradation in PTOA are unknown but there is a general consensus that biomechanical factors are significantly important to the development of OA after joint injuries. The details of the mechanical alterations that initiate or cause progression of OA processes remain unknown. Recently, it has been suggested that changes in the relative velocity of the cartilage surfaces may correlate more consistently with cartilage damage after joint injury than other measures of kinematic change [12-13].

The major purpose of this study was to investigate the change in the relative linear and angular velocity vectors of the tibiofemoral component of a knee joint in the ACL transection sheep model of PTOA. The major rationale for this objective is that the direction of the shear (tangential) stresses, as a major factor in the wear of superficial cartilage, are related to the direction of the relative velocity vector at points in the contact area on the articular surfaces. We hypothesize that the directions of the relative velocity vectors change after ACL transection, and damage to the cartilage surface first develops where the new direction of shear has the greatest misalignment with the direction of the fibres in the cartilage surface layer.

METHOD

An Instrumented Spatial Linkage (ISL) was used to measure the kinematics of ovine stifle

(knee) joints. An ISL is a measuring device in which series of rigid links connect to each other through rotational transducers. The details of the kinematic experiment are explained in Atarod et al. [14]. Briefly, one skeletally mature female Suffolk-cross sheep was trained to walk on a standard treadmill. Four weeks prior to kinematic testing stainless steel bone plates were implanted onto the proximomedial aspect of the tibia and the distolateral aspect of the femur by using 3 stainless steel screws on each plate. The ISL was attached to the tibia and the femur by using these plates and the kinematics of the intact joint measured (Figure 1). Arthroscopic surgery was performed on the stifle joint to transect only the anteromedial (AM) band of the ACL. Finally, the kinematics of the joint were measured again 22 weeks and 40 weeks after the ACL transection. Finally, an analytical technique was developed to calculate the relative linear and angular velocity vectors of the tibiofemoral component of the joint by defining appropriate coordinate systems.

value of the strides (n=100) and the shaded areas represent ± 1 standard deviation (SD) for all strides. The gait cycle has two major segments: the stance phase from 0% to 66±2% of the gait cycle, starting with hoof strike (HS) and finishing with hoof off (HO) and the swing phase of the gait cycle that is the non-weight-bearing part of the gait cycle. As may be seen in Figure 2, at the beginning of the stance phase (from 0% to 10%), the components of both relative linear and angular velocity fluctuate slightly. Following that, for most of the remaining part of the stance phase (10% to 50%) there is very little relative motion, which is predictable as the bones move very little with respect to each other during this time period. Just before hoof off, the bones begin to move one relative to the other in preparation for the swing phase. In the swing phase of the gait cycle, the components of the relative velocities have sinusoidal shapes, which are compatible with the periodic type of motion during that phase of the gait cycle.

Figure 1: The application of the ISL in measuring sheep joint kinematics during gait

RESULTS

The six components of the relative angular and linear velocity vectors of the femoral coordinate system with respect to the tibial coordinate system are plotted in Figure 2. The relative linear velocity vector is measured for the point of the attachment of the ACL to the femoral condyle. Solid lines represent the mean
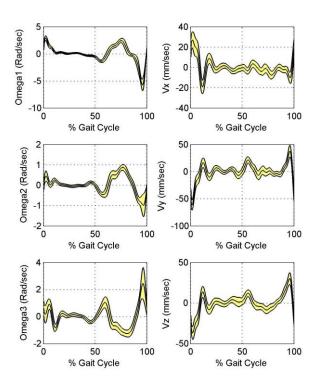

Figure 2: The six components of the relative angular and linear velocity vector of the femur with respect to the tibia at the intact time point.

The next step is to investigate the change of the relative velocity vector after ACL transection. The mean values of the components of the relative linear and angular velocities of the femur with respect to the tibia at the intact time point (before injury) and at 22 and 40 weeks after ACL transection are presented in Figure 3. It is apparent that the magnitude of the velocity components decreased at many points during the gait cycle. Interestingly, these results also show that there were changes in the timing of the phases of the gait cycle between the intact and follow-up time points after ACL transection. Such changes are suggestive of changes in the direction of the relative surface velocity. The change in phase of the motion is particularly apparent from 0% to 10% of the gait cycle in the second and third components of the relative angular velocity vector (ω_2 and ω_3) and the first component of the linear velocity vector V_x.
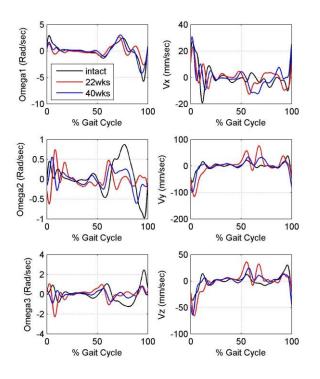

Figure 3: Mean value of in vivo relative linear and angular velocity components for one subject at the intact time point and 22 and 40 weeks after ACL-injury

CONCLUSIONS

The purpose of the current study was to investigate the change of relative velocity of the stifle joint after ACL transection. The results suggest that ACL transection results in a major abnormality in relative joint velocity. The angular velocity is shown vectorially in 3 dimensional space in Figure 4 for the three experimental time points (before injury and 22 and 40 weeks after ACL transection) at 4 distinct points in the stance phase of gait: hoof strike (HS), loading response (LR), mid stance (MS) and hoof off (HO). As may be seen, the spatial direction of the angular velocity vector changed over time after injury, which supports our hypothesis that ACL injury changes the relative motion of the surfaces of the joint.

Interestingly, although the patterns of the motions before and after injury are moderately similar, the change of direction of the motion at some points is highly significant - almost opposite to the direction of that before injury- (see Figure 4(B) and (D)). The main reason is that there is a phase change in the relative velocity vector where even a slight shift of the extremums (peaks and valleys) of the motion can result in a significant change in the direction of the velocity vector.

Although we were primarily interested in the change of the direction of the cartilage surface relative velocity vector because of our hypothesis that the direction of the relative velocity defines the direction of shear forces on cartilage surfaces, the major decrease of the magnitude of the components of the relative velocity vector during many points of the gait cycle are unexpected. One explanation is that there might be muscle weakness after surgery and this might also be considered as an important biomechanical factor.

Finally, the major conclusion that can be drawn from the present study is that velocity analysis can be complementary to kinematics analysis to provide more information about joint motion, as it considers the effect of time.
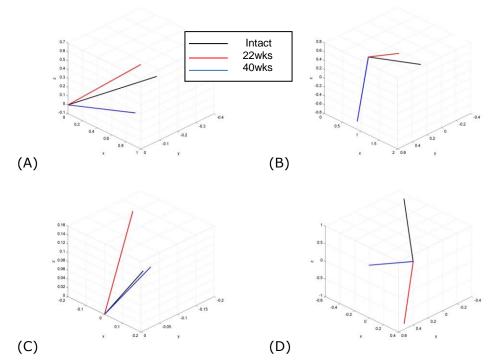
Figure 4: The 3-Dimensional orientation of the mean values of an in vivo relative angular velocity vector for one subject at 4 distinct points in the stance phase at intact time point and 22 and 40 weeks after ACL-injury

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