Viscous Damping in a Loaded Joint Articular Pendulum May Explain Articular Degeneration in an ACL Transection Injury Model

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Introduction: Articular pendulums where the joint acts as the pendulum fulcrum are frequently employed to study joint friction and cartilage damage. Stanton's equation (µ = ΔΩ/L(r)), where ΔΩ is the change in swing amplitude, L is the length of the pendulum, and r is the bearing radius) is traditionally used to calculate the coefficient of friction (µ). It assumes linear decay in the amplitude of the pendulum and energy loss through friction. However, curvilinear decay indicates a velocity dependent energy loss (viscous damping) in addition to frictional losses. Curvilinear decay is often recorded experimentally but its relevance and how it may change with cartilage damage has not been established. Our objective was to apply both modeling strategies to evaluate the µ of joints taken from ACL-intact and ACL-transected (ACL T) joints 9-months after injury. We hypothesize that µ and constant coefficient of viscous damping (VC) will increase in the ACL T joints when compared to ACL-intact joints.

Materials and Methods: 10 Hartley guinea pigs were used in this study following IACUC approval. Animals underwent ACL T surgery in the right leg at 3-months of age. Animals were allowed to recover and underwent euthanasia at 12-months of age. The hind limbs were harvested, dissected down to the joint capsule, and stored at -80°C until testing. We have shown that cartilage damage is much greater in the ACL T knee when compared to the contralateral ACL intact knee with this model [3]. A pendulum system was used to measure the ex vivo energy loss [2,3]. The tibia mounted to the pendulum was swung relative to the fixed femur at approximately 1Hz while a joint compressive load of 300g (+/−1/2 body-weight) was applied. Pendulum motion was measured using an optical tracking system (Optotrak: Northern Digital, Ontario), and was initiated by rotating the pendulum 17° about the flexion-extension axis of the joint. The changes in peak amplitudes of the pendulum were fit with linear and exponential models of decay [2]. Each model assumed the joint pendulum behaves as a damped lumped-parameter system. In the linear model, peak amplitudes were assumed to decay linearly with cycle number, and damping was defined as a constant µ. The exponential model assumed exponential decay with cycle number. In addition to a constant µ, the exponential model included a constant coefficient of viscous damping (VC) that was dependent on rotational velocity. A paired Student’s t test was used to determine differences in µ and VC between the ACL T knee and the contralateral control knee using the linear and exponential decay models.

Results: The rotation of the ACL T articular pendulum reached equilibrium in less cycles than that of the control joints (62±13 cycles vs. 78±11 cycles; p<0.02). The linear model predicted that the µ was significantly increased (p=0.03) in the ACL T as compared with the control knee (Fig. 2A). In contrast, the exponential model predicted that there was no significant difference (p=0.54) in µ between the ACL T and control knees. However, the VC was predicted by the exponential model and demonstrated a significant increase (p=0.03) with ACL T (Fig. 2B). The exponential model provided a better fit to the decaying peak amplitudes than the linear model with RMSEs of 0.08° and 0.9°, respectively (Fig. 1).

Discussion: This study demonstrated that the damping of an articular pendulum is better predicted when decay is assumed proportional to the rotational velocity (viscous damping), rather than frictional damping. The linear decay model predicted that the µ significantly increased with ACL T, whereas the exponential decay model predicted that it did not change. The exponential decay model predicted that the VC significantly increased with ACL T. The reasons for this are unknown but could be due to altered kinematics with loss of roller-sliding bearing constraints resulting in unstable transcondylar joint movements of the joint, or loss of cartilage stiffness associated with a decrease in lubricin within articular cartilage [4]. It must be noted that both models were lumped-parameter models that treated the knee as a single system, therefore it is not known which tissues or combina-

tion of tissues of the knee joint were responsible for the observed damping behavior. The models also did not account for air resistance acting on the pendulum nor non-linear damping coefficients, but these effects are likely to be consistent across groups. Considering that the exponential decay model provided a dramatically better fit to the experimental data than the linear model (Fig. 1), we conclude that the increased damping associated with ACL T was due to an increase in damping behavior that is proportional to rotational velocity (VC) rather than damping associated with friction (µ).


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