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Short communication

Pendulum mass affects the measurement of articular friction coefficient

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ABSTRACT

Friction measurements of articular cartilage are important to determine the relative tribologic contributions made by synovial fluid or cartilage, and to assess the efficacy of therapies for preventing the development of post-traumatic osteoarthritis. Stanton's equation is the most frequently used formula for estimating the whole joint friction coefficient (μ) of an articular pendulum, and assumes pendulum energy loss through a mass-independent mechanism. This study examines if articular pendulum energy loss is indeed mass independent, and compares Stanton's model to an alternative model, which incorporates viscous damping, for calculating μ. Ten loads (25–100% body weight) were applied in a random order to an articular pendulum using the knees of adult male Hartley guinea pigs ($n=4$) as the fulcrum. Motion of the decaying pendulum was recorded and μ was estimated using two models: Stanton's equation, and an exponential decay function incorporating a viscous damping coefficient. μ estimates decreased as mass increased for both models. Exponential decay model fit error values were 82% less than the Stanton model. These results indicate that μ decreases with increasing mass, and that an exponential decay model provides a better fit for articular pendulum data at all mass values. In conclusion, inter-study comparisons of articular pendulum μ values should not be made without recognizing the loads used, as μ values are mass dependent.

1. Introduction

Studies of articular cartilage have used whole joint pendulums or cartilage plugs to measure the friction coefficient (μ) of the articular surface (Jones, 1934; Tanaka et al., 2004; Wright and Dowson, 1976). Friction measurements are important to determine the relative tribologic contributions made by synovial fluid or cartilage, (Kawai et al., 2004; Mori et al., 2002; Tanaka et al., 2005) and/or to assess the efficacy of therapies for preventing the development of post-traumatic osteoarthritis (Jay et al., 2007; Kawano et al., 2003; Teeple et al., 2007). Whole joint pendulums have the benefit of allowing the joint to be examined as an intact system in that the opposing articular surfaces are matched as they would be in vivo, the endogenous synovial fluid is enclosed in the capsule, and trauma to the cartilage is eliminated.

Stanton's Eq. (Stanton, 1923) is the most frequently used formula for calculating the whole joint μ:

$$\mu_L = \frac{\Delta\theta \times L}{4r} \tag{1}$$

where $\Delta\theta$=change in the peak rotation of the pendulum per cycle about the flexion–extension (F–E) axis of the joint, L=distance between the pendulum center of gravity and the center of the F–E axis, and r=radius of the femoral condyles. This equation assumes that the peak F–E amplitude decays linearly with time, and thereby implies that energy loss is through a mass-independent mechanism (Crisco et al., 2007).

While the lubricating mechanisms of articular cartilage are not fully understood, it is likely that boundary lubrication (Charnley, 1960; Jay et al., 2001; Kumar et al., 2001), hydrodynamic lubrication (Jones, 1934; Kawano et al., 2003; Mori et al., 2002), fluid pressurization (Krishnan et al., 2003; Krishnan et al., 2004), and elastic deformation (Dowson and Jin, 1986) all contribute to the low μ in the knee joint. Whole knee experimental decay curves have been observed as being curvilinear (Jones, 1936; Teeple et al., 2007) which suggests energy loss via viscous damping, as well as energy loss due to capsular and ligamentous

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attachments (Charnley, 1960). We have previously published an alternative method for calculating μ of the articular pendulum (Eqs. 2–7) (Crisco et al., 2007) that incorporates a viscous damping coefficient to separate non-linear contributions to energy loss from frictional damping in the articular pendulum. Crisco et al. (2007) applied this calculation method to theoretical pendulum decay curves with a single decay time and mass, but only briefly postulated on how changes in mass might affect the model. Using our alternate calculation may provide an improved method for measuring joint friction in whole joint pendulum systems across a range of masses, allowing the advantages of a whole joint measurement while accounting for both linear and nonlinear modes of damping.

The objectives of this study were to determine if articular pendulum energy loss is mass independent, and to compare the two μ calculation models over a range of masses. To address these aims, articular pendulum data were collected from guinea pig knee joints loaded with ten separate masses. μ values were calculated using both Stanton's equation and the exponential decay model.

2. Methods

Experimental data for an articular pendulum were obtained using four hind limbs from two adult male Hartley guinea pigs (ages 9 and 12 months). The animals were euthanized under a protocol approved by the Institutional Animal Care and Use Committee. After euthanasia, the hindlimbs were disarticulated at the hip, dissected to the knee joint capsule, wrapped in saline-soaked gauze, and frozen at $-20\,^{\circ}$C degrees until the day of testing. On the day of testing, each specimen was thawed for 2 h at room temperature and then mounted in the pendulum for friction testing.

The pendulum used for this study has been previously described (Fig. 1) (Teeple et al., 2007). A series of ten tibiofemoral compressive loads, ranging from 260–900 g (25–100% average body weight), were applied in random order to each specimen. Motion of the tibia relative to the fixed femur was recorded using a motion analysis system (Optotrak, Northern Digital Inc., Waterloo, Ontario), which measures 3-D rigid body motion with an accuracy of 0.1 mm and 0.1 degrees. Three infrared light-emitting diodes were mounted to the tibia/pendulum and femur/base to define the rigid bodies and to measure rotational motion about the knee: flexion–extension, internal–external, and varus–valgus (Grood and Suntay, 1983). Rotations were referenced to an anatomic coordinate system established using the Optotrak digitizer prior to testing on each knee for each weight (Churchill et al., 1998; Teeple et al., 2007).

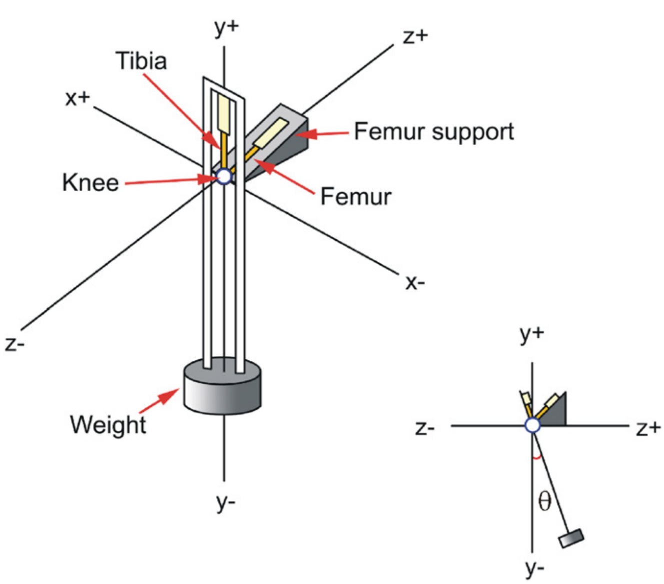

Fig. 1. Pendulum Apparatus. The pendulum utilizes the knee joint as the fulcrum, swinging the tibia relative to a fixed femur at a frequency of approximately 1 Hz while a compressive load is maintained across the tibiofemoral joint. The addition of load to the pendulum was done by screwing cylindrical masses into the base of the pendulum. The load's effect on period, center of gravity, and effective length were calculated and accounted for in both calculation models (Used with permission, Teeple et al., 2007).

Peak amplitudes were plotted versus cycle number for each mass, and the resulting decay curve was used to calculate μ. Two models were used to fit the decay curve: Stanton's equation, producing a linear fit (μ_L), and a previously published decay function incorporating a viscous damping coefficient (c), providing an exponential fit (μ_E) (Crisco et al., 2007). Root mean square error (RMSE) was used to determine the goodness of fit of each model to the experimental data curve.

Our previously published viscous damping model is briefly covered below. The equation for pendulum amplitude is

$$\theta_n = \theta_o\left[e^{-2n\zeta} - \delta\frac{1+e^{-\zeta}}{1-e^{-\zeta}}\left(1-e^{-2n\zeta}\right)\right] \tag{2}$$

Where

$$\zeta = \frac{j\pi}{\sqrt{1-j^2}} \tag{3}$$

$$j = \frac{cT}{4\pi I} \tag{4}$$

$$\delta = \frac{\mu_E mgrT^2}{4\pi^2 I\theta_o} \tag{5}$$

therefore,

$$\mu_E = \frac{4\delta\pi^2 I\theta_o}{mgrT^2} \tag{6}$$

$$c = \frac{4j\pi I}{T} \tag{7}$$

$\theta_n =$ peak displacement as a function of cycle number n, T=time between cycles, I=the moment of inertia about the joint centre, r=joint radius.

Statistical analyses were carried out using SAS version 9.3 (The SAS Institute, Cary, NC). Generalized linear mixed models for log-normal distributed data were used to model and compare μ and RMSE as a function of mass, model used, and their interaction. Models had random intercepts and slopes for mass nested within limb and grouped by equation. These parameters were permitted to have independent variances for slopes, intercepts, and covariances for each equation (unstructured variance–covariance structure block-diagonal by equation). A linear mixed model (Gaussian distribution) was used to model c from the exponential equation as a function of mass, with a random slope and intercept (unstructured variance–covariance structure). All models also used degree-of-freedom adjusted classical sandwich estimation to adjust for any model misspecification.

3. Results

Both μ_L and μ_E declined proportionally as mass increased. μ_L declined significantly (p=0.0008) faster with approximately 68% (95%CI 57%–86%; $p<0.0001$) decrease in value per kg, while μ_E decreased by 58% (95%CI 46%–67%; $p<0.0001$) per kg (Fig. 2).