Short communication

Comparison of two methods for calculating the frictional properties of articular cartilage using a simple pendulum and intact mouse knee joints

Elizabeth I. Drewniak \textsuperscript{a}, Gregory D. Jay \textsuperscript{b}, Braden C. Fleming \textsuperscript{a}, Joseph J. Crisco \textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a} Bioengineering Laboratory, Department of Orthopaedics, The Warren Alpert Medical School of Brown University/RH, Providence, RI, USA
\textsuperscript{b} Department of Emergency Medicine, The Warren Alpert Medical School of Brown University/RH, Providence, RI, USA

ARTICLE INFO

Article history:
Accepted 18 May 2009

Keywords:
Coefficient of friction
Pendulum
Viscous damping
Articular cartilage

ABSTRACT

In attempts to better understand the etiology of osteoarthritis, a debilitating joint disease that results in the degeneration of articular cartilage (AC) in synovial joints, researchers have focused on joint tribology, the study of joint friction, lubrication, and wear. Several different approaches have been used to investigate the frictional properties of articular cartilage. In this study, we examined two analysis methods for calculating the coefficient of friction ($\mu$) using a simple pendulum system and BL6 murine knee joints ($n = 10$) as the fulcrum. A Stanton linear decay model ($\text{Lin} \mu$) and an exponential model that accounts for viscous damping ($\text{Exp} \mu$) were fit to the decaying pendulum oscillations. Root mean square error (RMSE), asymptotic standard error (ASE), and coefficient of variation (CV) were calculated to evaluate the fit and measurement precision of each model. This investigation demonstrated that while Lin $\mu$ was more repeatable, based on CV (5.0% for Lin $\mu$; 18% for Exp $\mu$), Exp $\mu$ provided a better fitting model, based on RMSE (0.165 for Exp $\mu$; 0.391 for Lin $\mu$) and ASE (0.033 for Exp $\mu$; 0.185 for Lin $\mu$), and had a significantly lower coefficient of friction value (0.022 ± 0.007 for Exp $\mu$; 0.042 ± 0.016 for Lin $\mu$) ($p = 0.001$). This study details the use of a simple pendulum for examining cartilage properties in situ that will have applications investigating cartilage mechanics in a variety of species. The Exp $\mu$ model provided a more accurate fit to the experimental data for predicting the frictional properties of intact joints in pendulum systems.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Osteoarthritis is a common degenerative joint disease that can be characterized by the gradual loss of articular cartilage (AC) within synovial joints such as the knee. In a healthy state, AC is a relatively smooth tissue that covers articulating surfaces, distributes loads, decreases stresses on contact areas, and allows for motion of two surfaces while minimizing friction and wear. In attempts to better understand how and why cartilage becomes osteoarthritic, many researchers have investigated the coefficient of friction ($\mu$) of AC using a variety of methods, including whole joints in pendulums (Crisco et al., 2007; Jay et al., 2007; Jones, 1936; Stanton, 1923; Teeple et al., 2007; Wright and Dowson, 1976), cartilage plugs with custom-built apparatuses (Caligaris and Ateshian, 2008; Forster and Fisher, 1996; Gleghorn et al., 2007; Krishnan et al., 2005; Linn, 1967; Schmidt and Sah, 2007; Tanaka et al., 2004; Wright and Dowson, 1976), and atomic force microscopy (AFM) (Coles et al., 2008; Park et al., 2004).

Cartilage plugs are extremely useful in the study of the mechanical properties of AC; however, they pose challenges when using small animal models, including mice. Despite their small size, murine models have many benefits, including transgenic capabilities related to the development and homeostasis of AC. A study by Jay et al. (2007) investigated the frictional properties of Prg4 mutant mice using a simple pendulum system. Like Jay et al.’s study, the present study examines the frictional properties of mouse knee cartilage using a pendulum, but there were some differences between the two studies, including pendulum weight, resting angle, range of motion, and data analysis. Of note, the method described herein allows for collection of three-dimensional (3-D) joint motion and automated data processing.

A recent study examined two mathematical models for calculating $\mu$: a Stanton linear decay model ($\text{Lin} \mu$) and an exponential decay model ($\text{Exp} \mu$) that accounts for viscous damping caused by extra-articular structures (Crisco et al., 2007). The objective of the present study was to compare these two models for calculating $\mu$ using experimental data collected and processed with an automated approach. This objective was accomplished using a simple pendulum system and BL6 mouse knees.
2. Methods

Using procedures approved by the RIH Animal Welfare Committee, hind limbs from 10-week-old BL6 mice \( (n = 10) \) were excised and flash frozen with liquid nitrogen post-euthanasia. Specimens were stored at \(-80^\circ C\) for 1–7 weeks. Pilot data showed no differences between \( m \) of AC from fresh and frozen knee joints. On the day of testing, specimens were thawed and the skin, musculature, and supporting connective tissue were dissected away, leaving the joint capsule intact. The proximal femur and distal tibia were rigidly embedded in square, 6.25-mm-wide brass tubes with a urethane-potting compound (Smooth-ON, Easton, PA). The pendulum arm, weighing approximately 50 g (\(-2x's \) body weight) was fit to the tube encasing the femur. The tube encasing the tibia was rigidly fixed with four set screws to a platform designed to place the resting angle of the knee at \(-24^\circ\) when the pendulum was in equilibrium. This resting angle was chosen following analysis of small rodent kinematic studies (Fischer and Blickhan, 2006; Fischer et al., 2002). Four reflective markers were attached to both the pendulum arm and to the base of apparatus (Fig. 1). The pendulum was rotated to place the knee joint at an initial offset angle of \(-12^\circ\), released, and allowed to oscillate freely. Five trials were collected for each knee. Pendulum motion was tracked in 3-D at 100 Hz (VICON, Centennial, CO.) with rotational accuracy of better than 0.05 \(^\circ\) and translational accuracy of better than 0.06 mm. Oscillation data was then processed with Visual3D software (C-Motion, Inc., Germantown, MD) and custom MATLAB (MathWorks, Inc., Natick, MA) code to determine the peak amplitude of each cycle of oscillation.

Two models for computing \( m \) were fit to the experimental peak amplitude data using custom MATLAB code. The Stanton \( \mu \) model provided a linear fit (Lin \( \mu \)), while the second model fit the experimental data with an exponential curve (Exp \( \mu \)) that included a calculation for viscous damping (\( c \)) (Crisco et al., 2007). The goodness of fit of each model was described using the root mean square error (RMSE). The asymptotic standard error (ASE) was calculated to determine the uncertainty of the curve-fitted parameters relative to each model. The Lin \( \mu \), Exp \( \mu \), and \( c \) values were determined for each specimen by averaging over the five trials. Mean (\( \pm SD \)) \( \mu \) values for each model were then calculated across all specimens. The measurement precision of each model in estimating \( m \) was quantified using coefficient of variation analysis (CV). The reliability of each model was quantified with an intra-class correlation coefficient (ICC). The RMSE, ASE, CV, Lin \( \mu \) and Exp \( \mu \) values were evaluated for statistical differences with a Mann–Whitney Rank Sum Test (SigmaStat3.5, Systat Software, Inc., San Jose, CA). A significant value of \( p < 0.05 \) was set a priori.

3. Results

With an initial offset angle of \( 12\pm1^\circ \), the BL6 knees oscillated for \( 78\pm25 \) cycles before damping brought the pendulum to equilibrium (Fig. 2). In all trials, the decay in peak amplitude was

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)
The two methods for computing \( \mu \) of AC yielded significantly different results. Based on the calculated CV and ICC values, the Lin \( \mu \) model had increased measurement precision and reliability, likely providing a more useful tool for detecting subtle differences among experimental groups. Additionally, a majority of studies that have investigated the frictional properties of AC with pendulums and whole joints have used the Stanton model, making it useful for drawing comparisons with other values in literature (Charnley, 1960; McCutchen, 1962; Stanton, 1923; Tanaka et al., 2005, 2004; Teeple et al., 2007; Unsworth et al., 1975; Wright and Dowson, 1976). Conversely, Exp \( \mu \) provided a better fit to the experimental data, based on RMSE and ASE, especially noting that the amplitude decay was curvilinear. Exp \( \mu \) also accounts for viscous damping, and significantly lower \( \mu \) values.

Conflict of interest statement

The authors of this manuscript have nothing to disclose/no conflict of interest.

Acknowledgments

The authors would like to acknowledge their funding sources: NIH AR050180, NIH P20-RR024484, RH Orthopaedic Foundation, Inc., and University Orthopaedics, Inc. Thanks to VICOM for use of cameras and software for motion capture. Thanks to Jason Machan, PhD for help with statistical analysis. The authors also thank Michael Rainbow, Evan Leventhal, and Chung-Ja Cha, PhD for their assistance.

References
