Friction Properties of Synovial Joint Lubrication by Precise Tracking Pendulum Tester

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INTRODUCTION:
Osteoarthritis (OA) is the most common degenerative joint disease in the field of orthopaedics. In advanced stages of OA, the patients suffer from severe pain, functional limitations in the affected joints, and restriction of mobility. For detecting early OA and the prevention of progression in OA by novel therapeutic strategies, they are important to understand the functional properties of synovial joint and to establish the precise measurement technique.

Pendulum friction test is one of the mechanical evaluations for lubrication properties of joints [1-3]. The advantages of this method are the natural motion without the constraints of joint and also preservation of the joint capsule, the synovial fluid in it and the tendons and ligaments around the knee. However, previous method has to be under assumption of uniform rotation during joint motion, but actually this is not true. In this study, the frictional properties of the synovial joint were measured by using a novel system based on the pendulum tester. As the results, the measured frictional coefficients were dependent on the phase of joint motion, which indicate that the lubrication properties of synovial joint are well-related to the velocity of joint motion.

METHODS:
Novel measurement system based on the pendulum friction tester is shown in Fig. 1. The distal end of tibia of the sample joint was attached to the base plate and the femoral shaft was attached to the pendulum. The pendulum motion were calculated from two translational displacements by laser displacement sensors (LK-G30, Keyence, Tokyo, Japan), and angular displacement by an accelerometer detecting the gravity direction (100 Hz). Healthy Japanese white rabbits were used in this work. Four knees were resected at the proximal of the femoral shaft and at the distal end of the tibia, and then secured to polyethylene tubes with bone cement. Except for the joint capsule, the tendons, and ligaments around the knee, all soft tissues were removed from the joint. The tubes were attached to a pendulum friction tester. During the experiments, the joints were kept moist with saline injection to the joints.

Based on the damping oscillation of the pendulum, the energy loss $\Delta E(t)$ caused by the joint friction is represented by Eq. (1).

$$\Delta E(t) = \mu(t) \cdot r(t) \cdot \Delta \theta(t) \cdot m g$$  \hspace{1cm} (1)

where $\mu(t)$ is the frictional coefficient, $r(t)$ is the radius of joint rotation, which is the distance between instantaneous center and contact position of joint, $\Delta \theta(t)$ is the change of an angular displacement of pendulum, $m$ is the mass of pendulum (2.3kg) and $g$ is gravitational acceleration. While the changes of mechanical energy $\Delta E(t)$, which is the sum of kinetic and potential energy is represented by Eq. (2).

$$\Delta E(t) = I(\Delta \theta(t)/\Delta t)^2 + m g l (1-\cos \theta)$$  \hspace{1cm} (2)

where $I$ is the moment of inertia of pendulum, $l$ is a distance between the center of gravity and the center of rotation of pendulum. Assuming $\Delta E(t) = \Delta E_0(t)$, the frictional coefficient $\mu(t)$ was calculated by Eq. (3).

$$\mu(t) = \frac{I(\Delta \theta(t)/\Delta t)^2 + m g l (1-\cos \theta)}{r(t) \cdot \Delta \theta(t) \cdot m g}$$  \hspace{1cm} (3)

RESULTS:
Typical results of changes in the knee joint angles (red), measured frictional coefficients (blue) and average frictional coefficients (green) at each period are shown in Fig. 2. It could be observed that synovial frictional coefficients were not uniform but dependent on the phase of joint movement, ranging from 0.003 to 0.03 by our experiments. Particularly, frictional coefficients elevated significantly around most flexed and extended position, when the pendulum was mostly stationary. Average frictional coefficient at each period is about 0.005.

DISCUSSION:
The normal frictional coefficient between the cartilage surfaces of synovial joints is reported to be range from 0.001 to 0.1 [e.g. 1-3]. The average frictional coefficient of the rabbit knee measured by this system was 0.005, which is consistent with previous reported value, ranging from 0.002 to 0.013 (average 0.007) [1]. As the results in this work, however, the measured frictional coefficients were dependent on the phase of joint motion significantly. These results indicate that the lubrication properties of synovial joint are well-related to the velocity of joint motion as the fluid lubrication, since it is regarded that synovial joint lubrication depends on both of the boundary lubrication and fluid lubrication by synovial fluid. Therefore, this method may evaluate not only cartilages in the joint but synovial fluid in joint capsule, for example, OA knees.

SIGNIFICANCE:
The frictional properties of the synovial joint were measured by using a novel system based on the pendulum tester. Measured frictional coefficients were dependent on the phase of joint motion, which indicate that the lubrication properties of synovial joint are well-related to the velocity of joint motion.

REFERENCES:

![Figure 1 Pendulum-type friction tester for joint with two laser displacement sensors and an accelerometer for measuring pendulum motion.](image1)

![Figure 2 Relationship between knee joint angle (red), friction coefficient (blue) and average friction coefficient (green) at each period.](image2)