The Effect of Experimental Cartilage Damage and Impairment and Restoration of Synovial Lubrication on Friction in the Temporomandibular Joint

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Aims: *To evaluate how the frictional coefficient of the porcine temporomandibular joint (TMJ) is affected by an impairment of the synovial lubrication produced by an experimental abrasion of the articular cartilage and the application of hyaluronic acid (HA) with different molecular weights to the abraded cartilage surfaces.* ***Methods:*** *Erosion of the articular cartilage was produced by scouring it with sandpaper. Impairment and restoration of synovial lubrication were modeled by washing the joint space with phosphate-buffered saline (PBS) and by the application of HA with different molecular weights. After measuring the frictional coefficients in the intact TMJs (n = 10), the effects of washing with PBS, sandpaper scouring, and the application of HA were subsequently examined.* ***Results:*** *The mean frictional coefficient in the intact joint was 0.0154 (SD 0.0043). After PBS washing and sandpaper scouring, it increased significantly to 0.0235 (SD 0.0052) and 0.0520 (SD 0.0088), respectively. Subsequent application of HA resulted in a significant decrease (43% to 56%) of the frictional coefficient. Observations by scanning electron microscopy showed that after sandpaper scouring, the superficial cartilage layer was disrupted and inner layer was exposed, creating an irregular surface.* ***Conclusion:*** *Joint friction may increase by approximately 350% following an experimental scouring of the cartilage surface and impairment of synovial lubrication. Lubrication by means of HA decreased joint friction by approximately 50%.*

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In the temporomandibular joint (TMJ), the condyle-disc complex articulates against the glenoid fossa. During translatory movements, the disc slides against the fossa with very low friction.[1,2] Indeed, the coefficient of friction in the joint is almost zero,[3,4] due to the smooth articular surfaces and the presence of synovial fluid. Therefore, shear loading of the disc has been considered to be negligible.

One of the principal components determining the rheologic properties of synovial fluid is hyaluronic acid (HA).[5] It is generally recognized that viscosity increase of synovial fluid is proportional to the molecular weight and concentration of HA.[6,7] Although the exact role of HA in synovial lubrication is still unclear,[8,9] injection of HA into affected joints improves their mobility and suppresses pain and inflammation.[8]

Osteoarthritis (OA) affects the mobility of joints. The osteoarthrotic process starts with degeneration of the articular cartilage, which becomes eroded and irregular; the underlying bone is

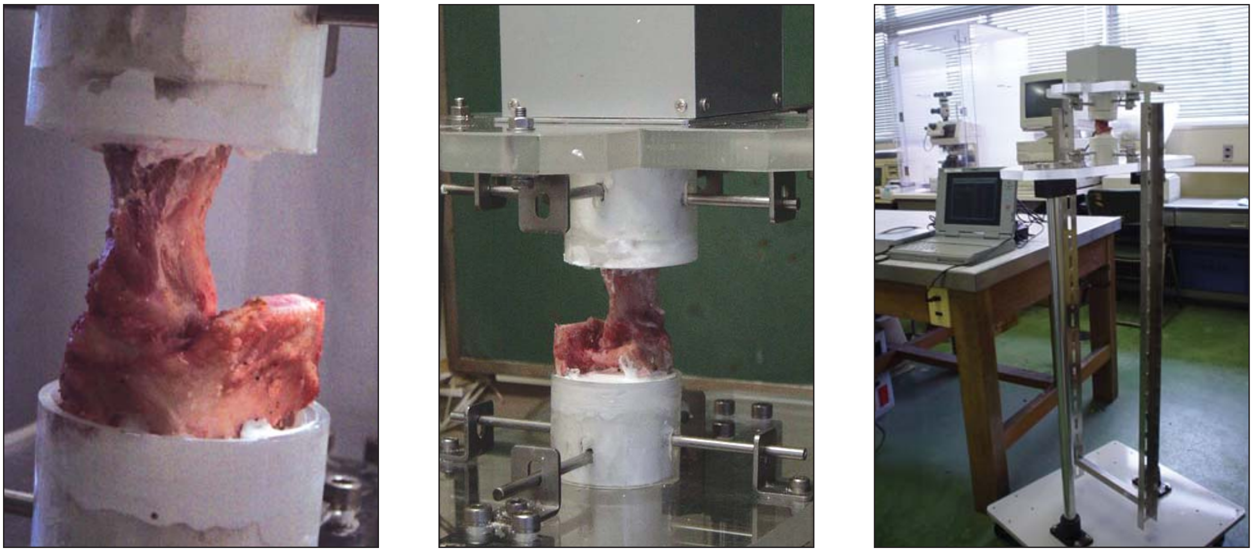


Fig 1 Photographs of the pendulum-type friction tester.

also affected.[10,11] The TMJ disc can also be damaged, which may lead to subsequent perforation. The disease may progressively lead to complete destruction of the articular cartilage with contact between the articulating bony surfaces.[12] The synovial fluid may play a role in the osteoarthrotic process, as its viscosity is reduced by a decrease in both concentration and molecular weight of HA[13] that may lead to an increase in joint friction.[11,13,14]

The aim of the present study was to evaluate how the frictional coefficient of the porcine TMJ is affected by an impairment of the synovial lubrication produced by experimental abrasion of the articular cartilage and the application of HA with different molecular weights to the abraded cartilage surfaces. The authors hypothesized that the higher the molecular weight of HA in the range tested was, the greater the lubrication improvement between the eroded joint surfaces would be.

Materials and Methods

Ten TMJs of 10 pigs (ages 6 to 9 months; body weight 115 kg; genders not known) were obtained from a slaughterhouse (Japan Agriculture, Hiroshima, Japan). The protocol of the experiment was approved by the Animal Care and Use Committee at Hiroshima University.

The joint was separated from the skull by means of an osteotomy through the temporal bone and from the mandible by an osteotomy through the condylar neck at the level of the coronoid process. The dimensions of the condyles were 14.3 ± 2.0 mm and 24.0 ± 2.9 mm (mean ± SD) in the anteroposterior and mediolateral directions, respectively. Except for the joint capsule, almost all soft tissues, including ligaments and muscles, were carefully removed. Before osteotomy, the relationship of condyle and fossa in maximum intercuspation was recorded by marking 4 points on the condyle and fossa and measuring the distances between these points. This was necessary in order to mount all the joints in the pendulum tester in the same condyle-fossa relationship. During the experiments, the joints were covered with a gauze soaked in phosphate-buffered saline (PBS) to keep them moist.

A pendulum-type friction tester with an oscillation cycle of approximately 1 to 2 seconds was used as the experimental apparatus (Fig 1). The temporal bone of the TMJ was fixed to the lower plate, which was connected with the base column by means of plaster stone, and the condyle was attached to the upper plate, which was connected with the frame of the pendulum. The total weight of the upper plate and the frame of the pendulum was 40 N, and the compressive load that was applied in the present study was 80 N.

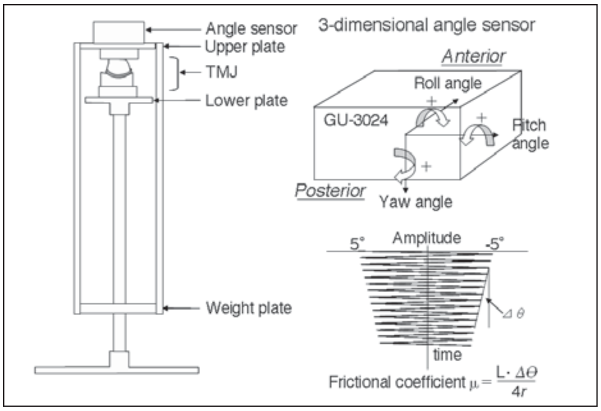


Fig 2 Schematic illustration and picture of the pendulum-type friction and a sample of the damping curve recorded by the 3-dimensional dynamic angle-sensor.

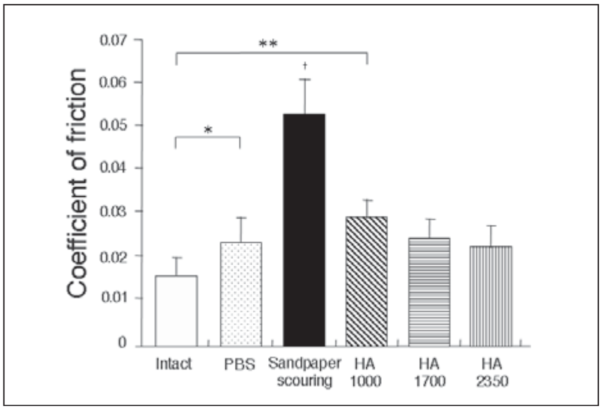


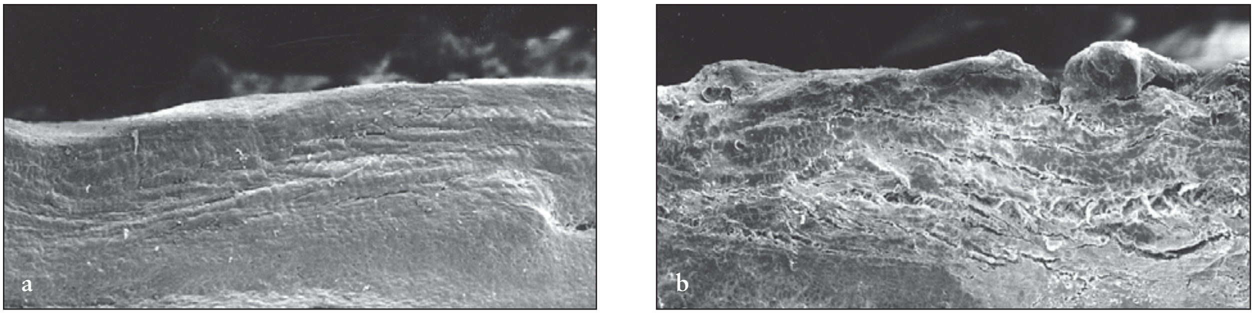
Fig 3 Means and standard deviations of frictional coefficient, as measured in the intact TMJ, after washing with PBS, after scouring with sandpaper, and after application of HA with molecular weights of 1,000 kd, 1,700 kd, and 2,350 kd (n = 10). The error bars indicate standard deviations. $*P < .05$ (Scheffé test); $**P < .01$ (Scheffé test). †The frictional coefficient in the TMJ after sandpaper scouring was significantly ($P < .01$) larger than those in the other conditions.

The loading procedure was similar to that used in a previous study.[2] Briefly, the distance L between the center of gravity and the fulcrum was between 40 and 100 mm, and was calculated as $gT^2 / (2\pi)^2$ where T was the cycle time of oscillation and g the acceleration by gravity. The initial swing was approximately 5 degrees, which was started immediately after the load was set. The displacement was measured by means of a 3-dimensional dynamical angle-sensor (GU-3024, Data Tek, Tokyo, Japan) placed on the upper plate (Fig 2). The sensor consisted of 3 accelerometers and 3 gyrocompasses, which measured the rolling, pitching, and yawing angles and their angular velocities. From these data the 3-dimensional condylar displacements were calculated. The input-output digital signals of the sensor (sampling rate: 60 times per second; resolution: 0.5 degrees) were transmitted to the data processor.

The frictional coefficient μ was calculated by the equation[15] $\mu = L \bullet \theta / 4r$, where θ is the average amplitude difference between the third single swing and the 12th swing on a decreasing curve. The first 2 cycles were excluded from the analysis, as they were affected by the start-up friction. The radius of the condylar head r was estimated from a drawing of the condylar outline that was traced from a lateral view photograph of the condylar head.

The frictional coefficient was calculated for each joint under different conditions. The first recording was performed immediately after mounting the joint on the experimental tester. At that time, the cartilage of the articular fossa and of the disc as well as the synovial fluid were assumed to be intact. After the first test, the upper joint space was exposed and the TMJ was separated into the glenoid fossa and the condyle-disc complex. Before the second series of measurements, the fossa surface and the cranial surface of the disc were washed with PBS (pH 7.2, 35°C) for 20 minutes in order to eliminate the synovial fluid. Consequently, the coefficient of friction that was measured in this experiment was related to the use of PBS as a lubricant. Thereafter, the cartilage of the fossa and the disc were scoured with sandpaper, and a third recording was performed. Scouring was performed in the anteroposterior direction until the superficial layer was removed. The cartilage surfaces of 5 joints were analyzed by means of scanning electron microscopy (SEM) after PBS washing and scouring with sandpaper.

The frictional coefficients of the abraded TMJ surfaces were measured using PBS, and 3 different solutions containing HA of various molecular weights (Seikagaku Kogyo, Tokyo, Japan). The solutions were prepared by basic or enzymatic hydrolysis of rooster comb hyaluronan. The solutions applied were 1% sodium HA solutions with mean molecular weights of 1,000 kd (HA1000), 1,700 kd (HA1700), and 2,350 kd (HA2350); they



Figs 4a and 4b Fossa surfaces observed by SEM after *(a)* PBS washing and *(b)* sandpaper scouring. After PBS washing, the superficial amorphous layer of the articular surface was still intact and congruent. After sandpaper scouring, the amorphous layer was disrupted and the inner layer was exposed, creating an irregular surface.

were applied to the glenoid fossa by the use of a syringe. The fossa surface and the cranial surface of the disc were washed thoroughly with PBS after each test. A series of tests using different HA solutions was performed; the tests were performed in random order.

Statistical analysis was performed using StatView (Abacus Concepts, Piscataway, NJ). Differences between the frictional coefficients obtained under the different conditions were analyzed for statistical significance first by means of ANOVA, and successively by the post-hoc Scheffé test. The level of significance was set at $P < .05$.

Results

The mean frictional coefficient of the intact joint was 0.0154 (SD 0.0043) (Fig 3). After washing with PBS, the frictional coefficient increased to 0.0235 (SD 0.0052), and after scouring with sandpaper, it further increased to 0.0520 (SD 0.0088). Both of these increases were statistically significant ($P < .05$ and $P < .01$, respectively; Fig 3). After application of HA with different molecular weights (HA1000, HA1700, and HA2350) as a lubricant, the frictional coefficient decreased significantly ($P < .01$) to 0.0291 (SD 0.0039), 0.0244 (SD 0.0042), and 0.0223 (SD 0.0047), respectively (Fig 3). The frictional coefficient with HA1000 was significantly ($P < .01$) larger than that in the intact joint. The coefficient of friction did not recover to the level found for the intact joints after application of HA.

Figure 4a shows an example of the articular surfaces of the glenoid fossa after PBS washing and sandpaper scouring. After PBS washing, the superficial amorphous layer of the articular surface was still intact (Fig 4a). After scouring with sandpaper, the articular surface was disrupted and the inner layer was exposed, creating an irregular surface (Fig 4b). These surface alterations resembled those normally found in the cartilage of joints at an advanced stage of OA.

Discussion

The present study aimed to clarify the effect of surface damage and synovial lubrication impairment on friction in the TMJ. The frictional coefficient of the TMJ depends on the condition of the articular cartilage, disc, and synovial fluid.[2,16] In this study, the frictional coefficient increased by approximately 150% that of the intact joint after washing with PBS. This was due to the replacement of synovial fluid by the nonviscous fluid PBS and not to the opening of the joint capsule and the resulting separation of the fossa from the condyle-disc complex. Indeed, in another study the present authors found that the opening of the joint capsule alone did not change the frictional coefficient (unpublished data). This is probably because the angle of the initial swing was small and the condylar movement was not restricted by the surrounding tissues, including the joint capsule, throughout the measurements. Furthermore, the frictional coefficient in the TMJ depends on loading time.[2] In the present study the time effect was negligible because an intermittent loading was applied.

After sandpaper scouring the frictional coefficient became approximately 350% larger than that in the intact joint. This finding indicates that the articular surface abrasion had a larger effect on the frictional coefficient than the lack of synovial fluid alone. The increase in friction may induce an increase in the tractional force within the TMJ disc,[17] resulting in a degeneration of this structure.

The porcine TMJ was used to measure the frictional coefficient in the joint. The porcine model was chosen because of its structural and functional similarities to the human TMJ. Structurally, the porcine TMJ has a similar shape, and its mandibular halves are rigidly fixed, as in the human.[18] Functionally, the pattern of pig chewing is similar to that of human chewing,[19,20] although pigs chew faster than humans.[18] Therefore, the results obtained from this study are likely to be representative of the human TMJ. Although degradation is generally more extensive in the lower than in the upper joint space in patients with internal derangements, the lower joint space was not exposed in the present study; this joint space is less easily accessible, since the disc is tightly fixed to the condyle at the condylar poles.

Although some investigators have questioned the effect of HA on the joint lubrication,[21,22] the results of the present study suggest that lubrication can be restored to a certain extent by the addition of HA. Indeed, HA application to the eroded cartilage surfaces reduced the frictional coefficient by approximately 50%. However, the effect of the HA molecular weight was almost negligible, since the frictional coefficients with HA1000, HA1700, and HA2350 did not differ significantly. Even with the most adequate lubrication, the friction in the damaged joints remained higher than that measured in the intact joints.

Obara et al[23] evaluated the lubricating ability in OA in stifle joints of horses and its recovery by additive HA. They demonstrated that the addition of HA was effective in the early stage of OA but was ineffective in cases of advanced OA where the articular surfaces were severely affected. This difference in effect may be caused by the presence or absence of congruent articular surfaces. Judging from the SEM finding in the present study, the rough cartilage surface after sandpaper scouring resembled the cartilage of joints with an advanced OA. It was after sandpaper scouring that the joints had the largest mean coefficient of friction. The establishment of a fluid film on such a rough surface is probably difficult, and the solid contact boundary between cartilage and disc may occur over a wider area. In synovial joints, both boundary lubrication and fluid film lubrication take place.[24] The present authors hypothesized that the application of HA with high molecular weight on the sandpaper-scoured surfaces would establish a new boundary lubrication. The fact that the friction remained higher than in the joints with an intact cartilage surface, however, seems to indicate that fluid film lubrication cannot be completely reestablished when the articular surfaces show severe irregularities.

Clinically, the application of HA may coat a damaged surface and protect the cartilage against further degradation.[25,26] Rydell and Balaz[25] reported that a 1- to 2-µm-thick layer of HA adherent to the articular cartilage surface produced by HA injection contributes to the repair of the cartilage surface layer. Indeed, HA seems to play an important part in wound healing, modulation of inflammatory response, and stimulation angiogenesis.[26] In addition, HA provides lubrication and thereby decreases wear and tear to a minimum.[27]

In this study, measurements of the frictional coefficients in the sandpaper-scoured joint, which was tested using PBS as a lubricant, were made. When this scoured joint served as a lubricant control for the tested HA groups, HA application induced approximately 50% reduction of the frictional coefficients in the TMJ. The results, therefore, show that the presence of HA did reduce the friction of artificially damaged joint surfaces. This emphasizes that intra-articular injection of HA has the potential to become an effective nonsurgical treatment for OA in the TMJ through the reduction of TMJ friction.

Acknowledgments

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