Review Article

Biomechanical and tribological properties of the temporomandibular joint: a narrative review

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Background and Objective: Osteoarthritis in the temporomandibular joint (TMJ-OA) is known as the end stage of TMJ disorders (TMDs), and most of TMJ-OA patients exhibit joint pain as a main symptom. TMJ-OA is a multifactorial disease, associated with articular cartilage breakdown and eventual joint destruction. Functional overloading and increased joint friction in the TMJ are recognized to induce degradation and abrasion of the joint components, leading to the onset and progression of TMJ-OA. Therefore, insight into the biomechanical and tribological properties of the articular components in the TMJ might contribute to better understanding of the etiology of TMJ degradation, leading to the development and progress of effective treatment remedy for TMJ-OA. The challenging project in TMJ biomechanics aims to identify biomechanical microenvironment in the TMJ, to develop the diagnosis system for TMDs, and to develop a new treatment remedy for TMDs including TMJ tissue engineering.

Methods: The databases PubMed, MEDLINE, and Web of Science were searched to retrieve relevant articles published in English from January 2000 to December 2020 using the keywords "temporomandibular joint" "friction" "joint lubrication" and "tribology" to investigate the biomechanical and tribological properties of the TMJ.

Key Content and Findings: The present review consists of three parts. Part I is a brief review of the biomechanical properties of the TMJ articular components. In Part II, the TMJ lubrication is explained from the viewpoint of the joint tribology. In the final remarks, the possibility of TMJ computed simulation will be discussed.

Conclusions: Future studies with much efforts are required to measure and visualize the biomechanical microenvironment within the TMJ during mandibular movements in clinical aspect.

Keywords: Temporomandibular joint (TMJ); biomechanical behavior; temporomandibular disc; articular cartilage; joint lubrication

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Introduction

The temporomandibular joint (TMJ) contributes to controlling loads exerted by mandibular movements. Adequate loading in the TMJ promotes tissue remodeling (1). Tissue remodeling is a crucial event for normal functional demands, enhancing homeostasis of the joint. However, excessive and/or abnormal mechanical stress to the TMJ may lead to degradation and abrasion of the joint components (2). Functional overloading and increased joint friction may interact as etiological factors capable of initiating changes in structure of the TMJ

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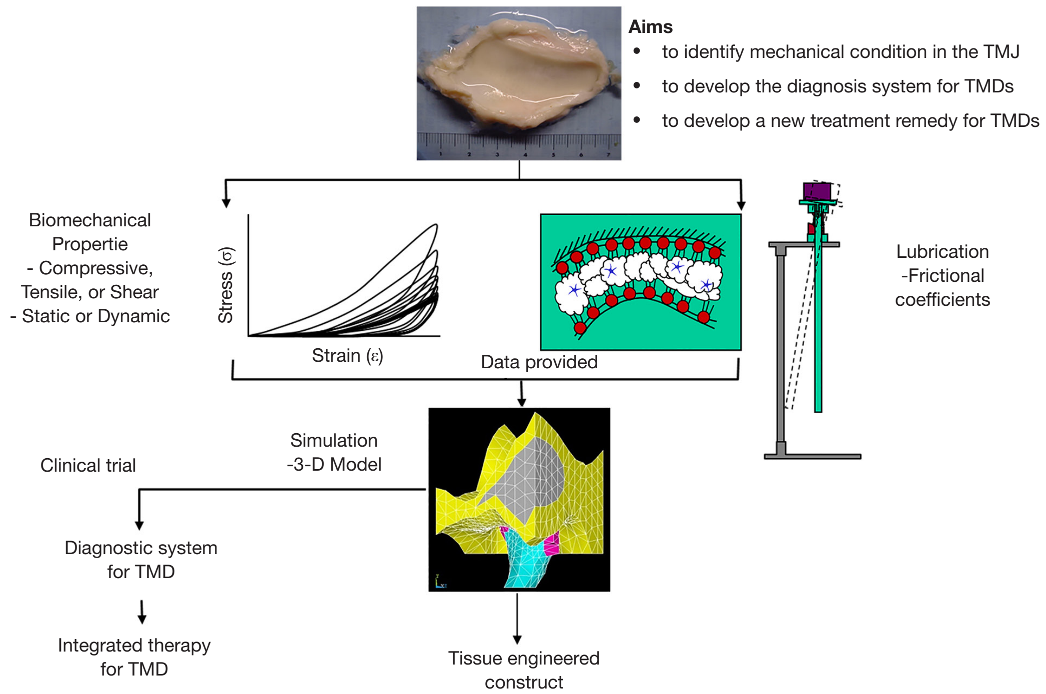

Figure 1 The challenging project in TMJ biomechanics aiming to identify biomechanical microenvironment in the TMJ, to develop the diagnosis system for TMDs, and to develop a new treatment remedy for TMDs including TMJ tissue engineering. TMJ, temporomandibular joint; TMD, TMJ disorder.

(3,4). In particular, fatigue failure and damage of the joint components are linked to loop and sustained compression and shear movements (5-7).

Epidemiologic literatures reported that approximate 25% of the population exhibit some symptoms of TMJ disorders (TMDs) such as joint sound, joint and/or masticatory muscle pain, and limited mouth opening, and one-fifth of those need treatment (8,9). Osteoarthritis in the TMJ (TMJ-OA) is known as the end stage of TMDs, and most of TMJ-OA patients exhibit joint pain as a main symptom. When the joint deterioration starts, TMJ-OA impairs patients' health, leading to various structural and functional degradation (10).

Taken these considerations, better understanding the mechanical microenvironment in the TMJ is a key step for the development and progress of effective treatment remedy for TMJ-OA. To develop an evidence-based approach to clinical management and treatment for TMJ-OA, we should do fully effort to TMJ biomechanics including biomechanical and tribological properties of the TMJ components, leading to the strategy for joint regeneration and tissue engineering in future (*Figure 1*). This paper reviews the biomechanical properties of the TMJ components, and the tribological properties of the TMJ lubrication. In addition, the possibility of TMJ computed simulation will be discussed.

Methods

Search strategy

PubMed, MEDLINE, and Web of Sciences were searched to retrieve relevant articles published from January 2000 to December 2020 using the following keywords: temporomandibular joint, friction, joint lubrication, and tribology.

Study selection

Inclusion criteria were original articles and review articles with a precise definition of the TMJ, published in English, time of publication: January 2000 to December 2020. Relevant publications from the list of references were retrieved and further analyzed to examine whether they matched the inclusion criteria. Data retrieval and extraction were performed by the author. The quality of the retrieved articles was not elucidated.

Part I. Biomechanical properties of the temporomandibular disc and cartilage

Mandibular movements induce various loading in the TMJ, which is divided into static and dynamic loading (see Appendix 1). For instance, clenching, grinding and bruxism result in static loading; talking and chewing include dynamic loading. It is generally accepted that dynamic loading is subject to anabolic effect in the joint components, while static loading is subject to catabolic effect. In addition, there are three loading types: compression, tension, and shear. During mandibular movements, these loading types act together on the articulating surfaces. By joint loading, the condylar and temporal cartilages and the TMJ disc suffer from deformations, which depend on their biomechanical properties. Furthermore, Kim *et al.* (11) indicated that the subchondral bone is also responsible for bearing static and dynamic loading in humans.

Previously, the elastic behaviors of the TMJ disc and cartilage have been investigated. The tensile moduli mainly depend on the amount and orientation of collagen fibers (6,12,13). Furthermore, elastin fibers in the TMJ disc might interact with collagen fibers, resulting in its sufficient resistance to tension (14,15). The compressive moduli mainly depend on the density of the proteoglycans, especially large chondroitin sulfate (6,13). Exploration of shear behaviors in synovial joints is of great importance, because shear loading is associated with fatigue, damage and degeneration of cartilage (6,16). The shear modulus of the TMJ disc in human is lower than their tensile and compressive moduli, but it increases with age (16), leading to secondary tissue damage.

The average of the elastic modulus in the TMJ disc was 25–30 MPa, while the elastic modulus of the mandibular condylar cartilage was 5–12 MPa (17-19). Recent study indicates both TMJ disc and mandibular condylar cartilage had similar magnitudes of values and behavior under unconfined compression (20). Comparing to the elastic moduli in the other tissues, the average value in the TMJ disc was almost similar to those in the intervertebral disc and knee meniscus, which was smaller than those in tendon and ligament, and larger than those in articular cartilage. Considering the magnitude of TMJ loading during function, the TMJ disc and mandibular condylar cartilage were stiff enough to work as a stress absorber and shock absorber in the TMJ and enable functional joint movements (6,13,21). In summary of static tests, the TMJ disc and mandibular condylar cartilage show a viscoelastic behavior during various movements, and through this behavior, they play essential roles as a stress-absorber and protector for the surrounding tissues.

The dynamic properties of the TMJ disc and articular cartilage are generally increased with increments of loading frequency and strain. For instance, during dynamic compression of the TMJ disc, the maximal stress and the resultant energy dissipation became greater with increases of the indentation amplitude and frequency (22-24). Similarly, the dynamic shear and compressive moduli of the mandibular condylar cartilage were increased nonlinearly with increasing frequency irrespective of the strain amplitude (25-29). Furthermore, it is accepted that the curves with the experimental top and bottom stresses in cyclic loading are close or similar to the theoretical stress-relaxation curves according to the quasi-linear viscoelastic theory (30-32).

Furthermore, dynamic shear behaviors of the TMJ disc and condylar cartilage are anisotropic (8,33-35) (see Appendix 1). Under dynamic shear in the antero-posterior direction, a storage modulus (G') of about 1.0–1.5 MPa and a loss modulus (G") of about 0.2–0.3 MPa were found in the TMJ disc (8,32,33), while a storage modulus of 1.5–2.0 MPa and a loss modulus of 0.4–0.5 MPa were in the mandibular condylar cartilage (34,35). The dynamic shear modulus was approximately 3–5 times smaller in the medio-lateral direction than in the antero-posterior direction, which means that the TMJ disc and mandibular condylar cartilage exhibit weak in the masio-lateral shear compared to in the antero-posterior shear.

By a series of studies, we properly understood the biomechanical behaviors of the mandibular condylar cartilage and TMJ disc in both static and dynamic aspects. The mandibular condylar cartilage and TMJ disc contribute to stress reduction and distribution in the TMJ components, mandibular movement promoter and energy dissipation within the joint tissues. Without the energy dissipation due to the disc, TMJ components including mandibular condyle and articular cartilage might fail leading to TMJ-OA (36).

Part II. Tribological properties of the TMJ lubrication

In healthy TMJ, the disc smoothly moves forward and downward during jaw opening without discomfort and

Table 1 Summary of frictional coefficient in the TMJ

Joint condition	Frictional coefficient	Significance
Intact joint	0.0164±0.0020	#
PBS	0.0223±0.0050	†
Gauze scouring	0.0398±0.0047	‡
Sandpaper scouring	0.0520±0.0088	&
HA 1000	0.0290±0.0047	
HA 1700	0.0204±0.0045	
HA 2350	0.0192±0.0028	

Data from Kawai *et al.* (44) and Tanaka *et al.* (46). #, P<0.01 *vs.* PBS, Gauze scouring, Sandpaper scouring, and HA 1000; †, P<0.01 *vs.* Gauze scouring; ‡, P<0.01 *vs.* Sandpaper scouring; &, P<0.01 *vs.* HA 1000, HA 1700 and HA 2350. PBS: the upper joint compartment was washed with phosphate-buffered saline; Gauze scouring: the articular surfaces were scrubbed with a PBS gauze to break fluid film; Sandpaper scouring: the articular surfaces were scrubbed with coarse sandpaper to break boundary lubrication; HA 1000: a 1% sodium HA with a high molecular weight of 1,000 kDa was added to the upper compartment; HA 1700: a 1% sodium HA solution with a high molecular weight of 1,700 kDa was added to the upper compartment after articular scouring; HA 2350: a 1.5% sodium HA solution with a high molecular weight of 2,350 kDa was added to the upper compartment after articular scouring. TMJ, temporomandibular joint.

pain, and the frictional force between the disc and articular cartilage surfaces has been considered to be negligible because of the presence of healthy synovial fluid. When the synovial fluid degenerates and its viscous property downregulates subsequently, it is likely to remove from the articular surfaces during jaw movements. This means a reduction of joint lubricants from the articular surfaces. Therefore, to study the frictional coefficient in the TMJ is of great importance for evaluating biomechanical microenvironment in the TMJ.

Generally, lubrication modes in synovial joints can be divided into fluid film and boundary lubrication (see Appendix 1). The fluid film lubrication mainly depends on synovial fluid, and the boundary lubrication on joint components such as the TMJ disc and articular cartilages. Immediate after shear and/or compression, the interstitial fluid in articular cartilage has pressure caused by the biphasic tissue structure. Synovial fluid is also thought to be pressurized status between articular surfaces (37). Pressurized interstitial fluid may contribute to bearing compressive force but not resistance to shear force (38).

In healthy joints, the frictional coefficient between articular surfaces has been reported a range of 0.001–0.1 (39-42). For the TMJ, we firstly reported the frictional coefficient of porcine TMJ by using the pendulum-type friction tester (43,44), although Nickel and McLachlan (45) investigated the coefficient of friction between the TMJ disc and acrylic resin plate. The mean frictional coefficient of intact porcine TMJ was 0.0164±0.0020 at the onset of loading with a 50-N (*Table 1*). The loading time longer, the greater the frictional coefficient. The frictional coefficient of the TMJ exceeded 0.0220±0.0014 after the prolonged loading. With an 80-N load, the frictional coefficient was on average 0.0191±0.0021 at the onset of loading, which was significantly greater than that with a 50-N load. This indicates that longer and/or larger loading to the TMJ induces an increment of the frictional coefficient in intact porcine TMJ, although the maximum values of frictional coefficients in the TMJ are within the normal range in synovial joints.

It is well recognized that an increase of frictional coefficient is one of the major trigger for disc displacement (47). We also evaluated the effects of lubrication breakdown on the frictional coefficient in the porcine TMJ (44,46,48). First, to experimentally reperceive breakdown of fluid lubrication, the articular surfaces of the TMJ disc and cartilage were cleansed with phosphate-buffered saline (PBS) (44). The synovial fluid was expelled from the joint cavity and replaced with PBS. By the breakdown of fluid lubrication, the frictional coefficient of the porcine TMJ was significantly increased to 0.0223±0.0050 (*Table 1*). Furthermore, to break down the boundary lubrication, the articular cartilage surface was wiped the fluid off with PBS gauze (44). As the result, the coefficient of friction in the porcine TMJ was further increased to 0.0398±0.0047 (*Table 1*). This indicates that the breakdown of both fluid film and boundary lubrication synergistically affects the coefficient of friction in the TMJ. In addition, to elucidate the effect of incongruent articular surface on the frictional constant in the TMJ, the amorphous layer of the articular cartilage was disrupted by scouring with sandpaper, resulting in producing the OA-lesion. After scouring with sandpaper, the frictional coefficient of the porcine TMJ tremendously increased to 0.0520±0.0088 (*Table 1*). These findings suggest that articular congruency also affects the frictional coefficient in the porcine TMJ.

Hyaluronic acid (HA), non-sulfate glycosaminoglycan, is one of the principal components of synovial fluid playing a crucial role in the rheological biomechanics of synovial joints (49). Although the concentration and molecular weight of HA are different with age, synovial fluid in healthy joints contains high molecular weight HA, while OA joints include much amount of low molecular weight HA, leading to the inflammatory condition. Synovial viscosity is dependent on both the concentration of HA and its molecular weight. In OA-joints with much amount of low molecular weight HA, the synovial fluid has a reduced viscosity. For this reason, it has been used for around 50 years to treat knee OA in humans. Many studies reported and confirmed the meaningful benefit of HA supplementation in OA treatment (50,51). For TMJ-OA, exogenous viscosupplementation has been recognized to relieve joint pain and increase maximal jaw opening without pain in patients with TMJ-OA (52). Especially, HA with high molecular weight may be the better candidate to improve masticatory system in TMJ-OA. Therefore, the role of HA in TMJ lubrication was recognized clearly by the measurements of the frictional coefficients in the TMJ after the application of high molecular weight HA (44,46).

After applying additive high molecular weight HA to incongruent joint like TMJ-OA joint, the coefficient of friction was decreased significantly by 43-56%, although the coefficient of friction did not recover to the level of the intact joints even if application of high molecular weight HA (44,46). Taken together, these studies confirmed the beneficial effect of high molecular weight HA in TMJ-OA.

Regarding the mechanism of TMJ lubrication, Nitzan (47) strongly suggested that surface active phospholipids (SAPLs) enhance boundary lubrication in the TMJ and play a role as protector of intracapsular articular surfaces. SAPLs are polar lipids which connect with the articular surface via their polar ends, thus orientating their non-polar moieties outward. The non-polar moieties provide a hydrophobic function, by which the articular surface has a relatively lower surface energy, resulting in less ability of friction. HA with high molecular weight locates between articular surfaces and protects the SAPLs from direct invasion by phospholipase A2 (PLA2). PLA2 is secreted from synoviocytes, chondrocytes, and osteoblasts into synovial fluid, and its activity induces the lysis of the SAPLs. To confirm this mechanism of TMJ lubrication, the effect of SAPLs on the frictional coefficient in the TMJ was examined (53). After treatment with bovine pancreas secreted PLA2, the SAPLs on the articular surfaces disappeared. Furthermore, the frictional coefficient of the sPLA2-treated mandibular condyle was significantly higher than that of intact joint (53). We also measured the frictional coefficient in porcine mandibular condyle after digestion with hyaluronidase to examine the role of HA in synovial fluid in joint lubrication (54). As the result, the coefficient of friction in the porcine TMJ significantly increased by 35% after treatment with hyaluronidase.

A mucinous glycoprotein called proteoglycan 4 (PRG4), also known as lubricin (55,56), covers the articular surfaces and functions synergistically with HA (57,58). This enables to form non-contiguous nanofilm, resulting in its lubricating and antiadhesive properties when connecting with the articular surface (59). Apart from the lubrication function, several studies demonstrated that PRG4 plays a crucial role in synovial cell proliferation and adhesion (57,60). PRG4 can mediate the proliferation of synovial cells for maintenance of cartilage surfaces (60). PRG4 knockout mice show synovial hyperplasia, deterioration of articular cartilages in the TMJ with an enhancement of chondrocyte proliferation and their redistribution in clusters with loss of superficial zone chondrocytes (60). Furthermore, PRG4 concentrations were significantly decreased in the synovial fluid of TMJ-OA (61). These findings indicate that PRG4 exerts essential direct and indirect roles to preserve TMJ structural and cellular integrity (62). Intraarticular supplementation with PRG4 might be an effective remedy for TMJ-OA with loss of joint lubrication (57).

In summary, the TMJ lubrication system is a key mediator for mandibular dynamics. To understand the development and breakdown mechanisms of the TMJ lubrication is indispensable to a novel new treatment remedy for TMJ-OA.

Final remarks

The biomechanical models of human masticatory system are powerful tools for evaluating the biomechanical microenvironment in the TMJ. Previously many researchers have attempted to develop two-dimensional or three-dimensional TMJ models for simulation and animation of the TMJ motion and stress analysis in the TMJ during masticatory function without invasive approach (22,55-57,63-66). With a revolution in computer science, the models have been in reality simulations including four-dimensional simulation. Furthermore, the biomechanical and tribological information about the TMJ components as described above enables to approach complete real model as much as possible (*Figure 2*). Obviously, the numerous assumptions underlying these FE models of the human

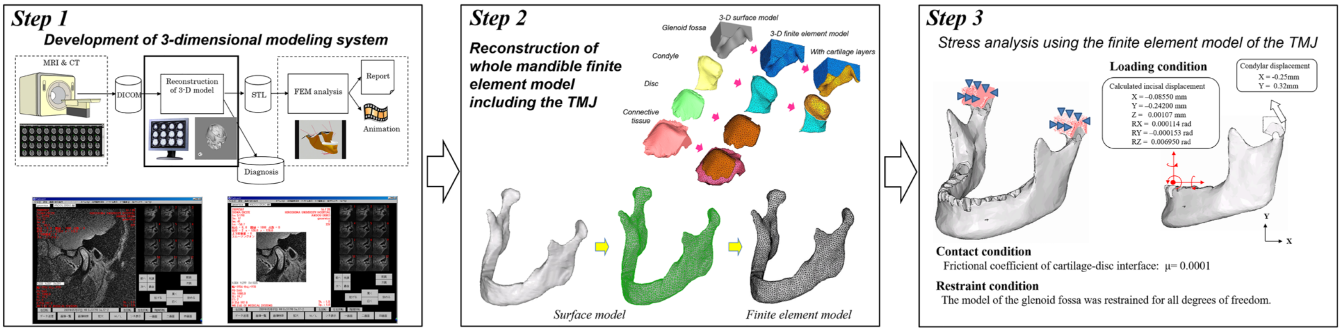

Figure 2 The individual TMJ three-dimensional modeling system. TMJ, temporomandibular joint.

TMJ should be addressed when interpreting its predictions even if obtaining numerous information (67). Moreover, the results obtained from FE analysis cannot be immediately adopted to clinical practice without further consideration. Nevertheless, it must be emphasized that the strength of this method is that it may enable us to perform intervention study.

As a conclusion, biomechanical model of the human TMJ and its application to stress analysis during mandibular movements are absolutely not perfect. Except for the model analysis, however, we have no way to examine the biomechanical microenvironment in the TMJ by no or less invasive procedure. In contrast, better understanding of biomechanical environment within the TMJ is absolutely necessary for the diagnosis and prognosis of treatment of masticatory dysfunction. Future studies with much efforts are required to measure and visualize the biomechanical microenvironment within the TMJ during mandibular movements in clinical aspect.

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Footnote

Conflicts of Interest: The author has completed the ICMJE uniform disclosure form (available at https://fomm.amegroups.com/article/view/10.21037/fomm-20-83/coif). The author serves as an unpaid editorial board member of *Frontiers of Oral and Maxillofacial Medicine* from May 2020 to Apr 2022. The author has no other conflicts of interest to declare.

Ethical Statement: The author is accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Summary of TMJ dynamics

Viscoelasticity

The TMJ disc and cartilage exhibit both elastic and viscous characteristics (6). This characteristic property is called viscoelasticity. The viscoelasticity depends mainly on fluid flow through and out of the articular tissues. Immediately after the onset of loading, the small pores in articular tissues impede rapid flow of fluid through the collagen network. The load gradually induces a fluid release from the loaded site by the permeability of collagen fibers (68). This fluid flow results in stress relaxation and creep phenomenon.

Dynamic shear behavior and property

In shear, one boundary surface moves parallel to an adjacent surface. The articular cartilages deform by external shear loading, while internal forces are induced within itself. Shear strain is calculated from the change in length per unit of original length (*Figure S1*). Internal stress is calculated from external force per unit area.

White arrows indicate external shear loading. Shear stain is calculated from the change in length (ΔL) per unit of original length (Lo).

There are two major types of loading on the articular tissue: static and dynamic. Static loading is generated during clenching and grinding, while dynamic loading is during talking and chewing. Under dynamic loading, the articular tissues quickly settle into a steady-state response. To determine the behavior during dynamic loading, a cyclic stress is commonly used for the dynamic tests (69).

According to the viscoelastic behavior of articular components, the stress response to a cyclic strain commonly delays to some extent, and the onset of stress is started with a delay of less than quarter-cycle of loading from strain application (5,6). If the material is purely elastic the onset of strain and stress is at the same time. If the material is purely viscous fluid, the stress response is started with a delay of quarter-cycle of loading.

For viscoelastic materials, the complex dynamic shear modulus G* composes of the storage modulus G' and the loss modulus G". The G' and G" are defined by

$$G^* = G' + iG'' \qquad [1]$$

where $i = \sqrt{-1}$. G' implies the elastic deformation in dynamic shear and is directly proportional to the energy storage in a cycle of deformation. G" shows the viscous deformation in dynamic shear and is also proportional to the average dissipation or loss of energy as heat in a cycle of deformation.

Frictional coefficient

The coefficient of friction, μ, is a constant for the onset of friction between two surfaces. The lower a frictional coefficient, the higher the force required for sliding. The value of the frictional coefficient is defined as

$$\mu = \text{frictional force (F)/normal force (N)} \qquad [2]$$

The direction of the forces given in this equation is as shown in *Figure S2*.

Fluid film and boundary lubrication

The lubrication system in synovial joints has been identified as boundary and fluid film. The former mainly depends on articular components such as the TMJ disc and articular cartilages, and the latter on a synovial fluid. Boundary lubrication appears when separating the bearing surfaces with nano-level space. It occurs when each load bearing surface is covered with a thin cartilage layer that forms SAPLs layer (47,70). SAPLs are polar lipids and their polar ends bind to articular surface. In healthy joint, the hydrogen connection between SAPL molecules provides highly efficient condensation. Fluid film lubrication involves a synovial fluid by which articular surfaces are separated. Pressurized fluid might contribute to the bearing of normal load with little or minimal resistance to shear force, facilitating a very low frictional coefficient. Furthermore, immediately after loading application, fluid film lubrication occurs with pressurization, motion, and deformation acting to drive viscous lubricant through the gap between the articular surfaces. Typically, surface lubricated by a fluid film have a lower frictional coefficient than do boundary lubricated surfaces.

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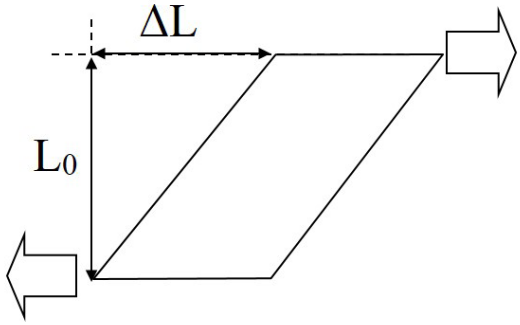

Figure S1 Diagram showing the shear strain.

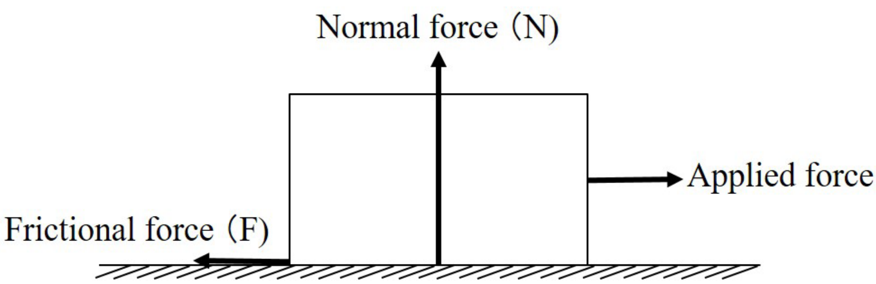

Figure S2 Diagram showing the frictional force.

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