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Fretting wear behaviors of mandibular condylar cartilage of nature temporomandibular joint in vitro

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ABSTRACT

Torsional fretting tests of condylar cartilage against a ZrO_2 ball were carried out. The damage characteristics were discussed based on an analysis of frictional kinetics behavior, SEM observations, and histological stainings. The results indicated that fretting behaviors were strongly dependent on the angular displacement amplitudes and the number of cycles. The worn surface was characterized by netlike shape ridges along the radial direction, and three parts were detected. The wear mechanism of condylar cartilage performed mainly as delamination and micro-fracture of collagenous fibers. As the damage characters are very special, a model of the condylar cartilage surface damage was established.

1. Introduction

Many clinical conditions, including but not limited to arthritis, trauma and congenital or acquired joint diseases, lead to a loss of cartilage tissue in human joints and bone-to-bone contact, which causes long-term debilitating pain, ultimately limiting patient function and mobility. The intrinsic vascular and neural nature of cartilage provides little scope for its natural self-repair [1–3]. Knowledge about cartilage tribological function is of utmost importance in understanding cartilage disease processes and developing new therapeutic interventions and techniques for treating those pathologies. McCutchen described articular cartilage as a bearing material that is deformable, porous and soaked with liquid [4]. The tribological behaviors of articular cartilage are greatly affected by biphasic lubrication, contact stress, and various structural components [2]. Research on the biotribology of articular cartilage on various in vitro experimental models holds a distinct advantage to understand cartilage natural behavior, degradation processes, and evaluate cartilage treatment therapies.

Temporomandibular disorders (TMDs) have considerable prevalence with 16%–59% of the population having symptoms and 33%–86% having clinical signs [5]. Quality large-scale epidemiological research on TMDs was widely published and many relevant papers found the frequent occurrence of deterioration and abrasion of cartilage [6].

The temporomandibular joint (TMJ) is one of the diarthrodial synovial joints in the human body. It is one of the most important parts of the human masticatory system. TMJ distinguishes itself from other synovial joints in several aspects. The bilateral TMJs must function together, and the range of motion has a fixed endpoint in the dentition [7]. Unlike most other diarthrodial synovial joints in the human body, in the TMJ the articular surfaces are separated by a cartilaginous articular disc with non-uniform thickness [8,9] (Fig. 1). This disc is able to move together with the mandibular condylar along the articular eminence, whilst the condylar is simultaneously rotating underneath [7]. Furthermore, the articular surfaces of the TMJ are highly incongruent. Due to this incongruency, the contact areas of the opposing articular surfaces in the absence of the TMJ disc would be very small, and upon joint loading this would lead to large peak loads and friction. However, the presence of the TMJ disc [10,11] and articular cartilage [11] are believed to prevent load concentrations. Although the construction of the TMJ is beneficial for rapid and smooth mandibular movement, it is also vulnerable to failure.

The mandibular condylar cartilage, lining the end of mandibular condylar, plays a crucial role as a stress-distributing and load-absorbing structure in the function of the TMJ [12]. It facilitates articulation with the TMJ disc and reduces point loads on the underlying bone [13]. It is of the fibrous type and is therefore structurally different from the generally applied hyaline articular cartilage [14]. The three-dimensional collagen network, proteoglycan network consisting of glycosaminoglycan chains and the surface amorphous layer of cartilage have contributed

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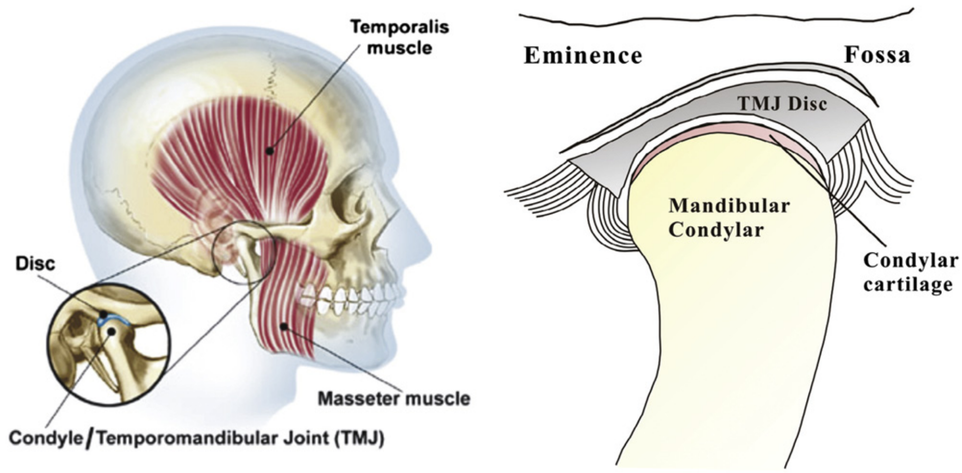

Fig. 1. Temporomandibular joint and mandibular condylar.

a lot to its frictional properties [15]. Mandibular motions can be continuous or intermittent. These motions, sometimes combined together, result in static and dynamic loading to the mandibular condylar cartilage [6]. Dynamic loading occurs during, for example, talking and chewing; static loading occurs, for example, during clenching and bruxism [16]. Bruxism is the parafunctional habit of tooth clenching and grinding [17]. Many relevant papers noted the relationship between bruxism and mandibular condylar cartilage injury [5]. Among the potential reasons, it is widely accepted that cartilage injury is strongly related to the wear mechanisms resulting from relative joint movement [18,19]. Such dysfunction could lead to degenerative changes in mandibular condylar cartilage as it has been associated with prolonged overloading [20], which may cause lubrication breakdown of the joints [5]. As a result, only solid to solid contact may exist between the articular surface and the TMJ disc [21]. Furthermore, during bruxism or clenching, the amplitude of the relative oscillatory movement is small enough, which may possibly be associated with fretting damages of the cartilage.

Literature reviews showed that rolling, pin-on-disc, and reciprocated sliding were the common test methods to evaluate the performance of natural or artificial joint materials. But their motions were very different from the actual motion situation of TMJ, in which the condyle undertakes translatory as well as rotary movement during jaw movements. Study on torsional wear is rare till date. In this paper, the fretting wear behaviors of mandibular condylar cartilage under the torsional wear model were investigated.

2. Materials and methods

2.1. Preparation of specimens and counterbody

Fresh, skeletally mature bovine TMJ (18–22-month-old) were obtained from a local abattoir and stored at $-20\,^{\circ}$C. The joints were thawed at 4 °C for about 12 h before the specimens were prepared. Cartilage specimens were removed using a cutting machine or surgical saw from the anterior facet of the mandibular condylar and produced with dimensions of 10 mm × 10 mm × 10 mm, which included the original cartilage layer and the subchondral bone (approximately 8 mm). Throughout the procedure, the cartilage surface was hydrated regularly with PBS solution (a kind of simulative body fluid). A hard material ZrO_2 ball with a diameter of 28 mm was selected as the counterbody for the tests (Fig. 2).

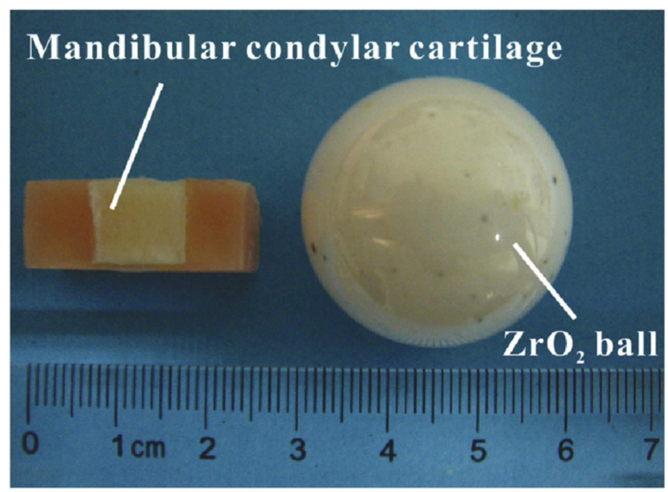

Fig. 2. Morphology of the cartilage specimen and the counterbody.

2.2. Torsional fretting wear test

A new torsional fretting rig with a ball-on-flat configuration was developed from a low-speed reciprocating rotary system with high precision (rotational speed: 0.001–30 r/min, resolution of rotational angle: 0.01°) [22]. It consists of four main modules that are shown schematically in Fig. 3. The zirconia ceramic ball (I) was immersed in PBS solution and fixed on a low-speed reciprocating rotary motor system (II). The cartilage specimen was mounted on the upper holder (III), which is linked to a six-axis torque/force (three kinds of load and three kinds of torques in the *x*, *y*, and *z* directions) sensor (IV) through a spring suspension. The fretting process was computerized and variations of the torques (T) versus torsional angular displacement amplitude (θ) can be recorded as a function of the cycles. In order to ensure pure torsional fretting, the centerline of the ball specimen was superposed strictly to the rotary axis of the motor system at all times. Angular displacement of the contact pair was measured by a sensor in the motor system [23]. In this study, according to the varied forces occurring during the mandibular movements supported by previous studies [24], the torsional wear tests were carried out at a constant rotary speed of $0.2^{\circ}\,s^{-1}$ under normal loads of 5 N, 10 N, 20 N, and 50 N. The angular displacement amplitudes were set at 0.5°, 1°, 2.5°, 5°, and 10°. The number of cycles was varied from 1 to 5000. A total number of five tests were performed for each experimental parameter.