Bone 106 (2018) 35–41

Contents lists available at ScienceDirect

Bone

journal homepage: www.elsevier.com/locate/bone

Full Length Article

Determination of sex differences of human cadaveric mandibular condyles using statistical shape and trait modeling

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ARTICLE INFO

Article history:
Received 8 June 2017
Revised 29 September 2017
Accepted 2 October 2017
Available online 04 October 2017

Keywords:
Temporomandibular disorders
Anatomy
Gender differences
Dental morphology
Statistical shape modeling

ABSTRACT

The objective of this study was to elucidate sex differences in the anatomy of human temporomandibular joint mandibular condyles using a statistical shape and trait model (SSTM). Mandibles were obtained from 16 human cadavers (79 ± 13 years). The condyles were scanned using micro-computed tomography with 27 μm resolution. An image processing algorithm was used to segment the bone, determine the border of the entire mandibular condyle and trabecular bone compartments, and create triangulated meshes of the compartments. One subject was chosen as the template and was registered to the other individuals using a coherence point drift algorithm. This process positioned all vertices at corresponding anatomic locations. For the trabecular bone region, around each vertex position, the average bone image intensity, which is proportional to bone density, and microstructural traits, including trabecular bone volume fraction, thickness, separation, connectivity, and connectivity density were calculated. For the entire mandibular condyle mesh, the surface vertices were extracted to represent the overall anatomy of the condyle. Using a SSTM, the shape and trait information was reduced to a small set of independent and uncorrelated variables for each individual. Wilcoxon rank sum tests were used to test for differences in the variables between sexes. A lasso approach was used to determine a set of variables that differentiate between sexes. Male condyles were on average larger than female condyles, with complex differences in the microstructural traits. Two out of 15 principal components were statistically different between males and females ($p < 0.1$). The lasso approach determined a set of 7 principal components that fully described the complex shape and trait differences between males and females. A SSTM was able to determine sex-dependent differences in the shape of the mandibular condyle. These differences may alter the biomechanics of the joint and contribute to the development of temporomandibular joint disease.

1. Introduction

The temporomandibular joint (TMJ) is a synovial joint that has a fibrocartilaginous articular disc located between the eminence of the temporal bone and the mandibular condyle. The TMJ allows for normal opening and closing of the mandible and is essential for everyday functions such as mastication and speaking. The mandibular condyle plays an important role in bearing the loads of the TMJ, and degeneration of the TMJ can develop when applied articular joint loads surpass the adaptive capacity of the TMJ.

TMJ disorders (TMD) are widespread, afflicting between 5% and 40% of the adult population [35–40]. TMD encompass several conditions including orofacial pain, restricted mandibular movement, clicking and popping sounds from the jaw joint, and locked jaws. About 10% to 15% of TMD patients have osteoarthritis, characterized by a degenerative joint which results from erosion of articular cartilage and degeneration of subchondral cortical and trabecular bone [41,42]. Researchers estimate that within a 6 to 12 month period >5.3 million people in the United States seek treatment for TMD [43]. Symptoms can become chronic and difficult to manage, severely reducing quality of life. Unfortunately, the exact etiology for TMD is not fully understood. While TMD is reported in virtually all populations and age groups [37,39,42,44], many studies have consistently indicated that TMD is more prevalent for women than men [38,45–47].

While the etiology of TMD is likely multifactorial, it is widely believed that local, joint tissue level biomechanics resulting from daily functional mastication or other jaw motion plays a major role in the development and progression of TMD [41]. The large degree of incongruity between the upper and lower articular surfaces of the joint allows large, six degree of freedom movement of the mandible with respect to the maxilla [20]. This motion is guided by the shape of the articular surfaces of the joint, muscles, ligaments, and occlusion of the teeth [41,42]. Several studies have investigated the correlation of TMJ anatomy with TMD,

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https://doi.org/10.1016/j.bone.2017.10.003
8756-3282/

revealing associations between TMD and occlusal curvature, dental occlusion, and articular eminence inclination [17,18]. An additional study investigated several discrete measures of skeletal, denture base, and dental characteristic measurements between patients and asymptomatic controls, finding significant differences in several measures [15]. However, the significance of relationships between individual traits and disease status remains unclear, since other studies did not find correlations between anatomy and TMD [16,27,28,30].

Conversely, statistical shape modeling (SSM) is capable of describing the complex geometry of three-dimensional structures. SSM has previously been applied to image processing tasks such as image segmentation, registration, object recognition, and diagnosis [1,2,11,13,19,26,29], and more recently extended and applied to investigating the risk of knee osteoarthritis [6] and the risk of skeletal fracture [3–5,7,8]. SSM reduces the shape dimensionality of the object of interest from a large set of highly correlated variables (typically a set of surface vertices) to a compact set of independent and uncorrelated variables. SSM provides a parametric framework for representing variability in a large number of individual complex anatomical shapes instances within a specific population or subpopulation [21]. Furthermore, other traits in addition to geometry, such as density, can be incorporated into the model to create a statistical shape and trait model (SSTM) [24].

We hypothesize that differences in TMJ anatomy between males and females could result in different biomechanics that leads to a higher prevalence of the disease in females. Furthermore, while individual anatomical measures may not show correlations with TMD or sex, combinations of anatomical traits represented using a SSTM may show correlations. Thus, the objective of this study was to evaluate whether a SSTM can be used to investigate the sex differences in the shape and traits of human mandibular condyles.

2. Methods

2.1. Study population

Fresh human mandibles were obtained from 16 individual cadavers (9 males, 7 females, 79.00 ± 13.10 years) that were provided by the Body Donation Program at The Ohio State University (Fig. 1a). Temporomandibular joint disorder (TMD) was not reported in the medical history of the donors and there was no gross evidence of TMD observed on the specimens. The mandibles were stored at −21 °C until utilization. After thawing at room temperature, all soft tissues were removed from the mandibular bone surface. Then, mandibular condyles were dissected at the point of sigmoid notch concavity parallel to the occlusal plane in the transverse direction using a low speed saw under water irrigation. A total of 11 right and 5 left side condyles were randomly chosen for the current study.

The mandibular condyle specimens were scanned by a three-dimensional (3D) micro-computerized tomography (micro-CT) scanner (SkyScan 1172-D, Kontich, Belgium) with the scanning and reconstruction voxel sizes set at 27 × 27 × 27 μm^3. The same scanning conditions (70 kV, 141 μA, 0.4° rotation per projection, 8 frames averaged per projection and 120 ms exposure time) were used for all specimens.

Image Processing:

All left condyles were reflected across the sagittal plane so that the geometry reflected that of the right condyles. A local thresholding technique was used to segment the bone from the background [33]. Within a moving window, Sobel edge detection was used to detect the edges that indicate the transition from bone to non-bone. The local threshold for the window was determined as the average of the gray value of the edges (MATLAB v2015B, The MathWorks, Inc. Natick, MA) (Fig. 1b). Segmentations of the cortical and trabecular compartments of the mandibular condyles were created using a series of erosion and dilation steps [9]. First, the marrow cavities were filled using dilation, hole-filling, and erosion steps, which created a segmentation of the entire mandibular condyle. Next, the inverse of the bone segmentation, which represents the marrow region, was used to segment the trabecular structure. Erosion followed by dilation was used to remove the trabeculae, creating a mask for the trabecular compartment. Subtracting the trabecular compartment from the entire mandibular condyle segmentation yielded the cortical compartment (Fig. 1c).

A volumetric tetrahedral mesh of the trabecular compartment (66,629 elements, 12,549 nodes) and the entire mandibular condyle (243,862 elements, 52,028 nodes), including both the cortical and trabecular compartments, was created [34]. The outer cortical boundary and outer trabecular boundary of each condyle were described by the outer triangulated surfaces of the volumetric mesh (2501 nodes) (MATLAB v2015B, The MathWorks, Inc. Natick, MA). Mesh correspondence between individuals was established using the set of surfaces. One subject was arbitrarily chosen as the template, and the template surface mesh was registered to the surfaces of the other individuals

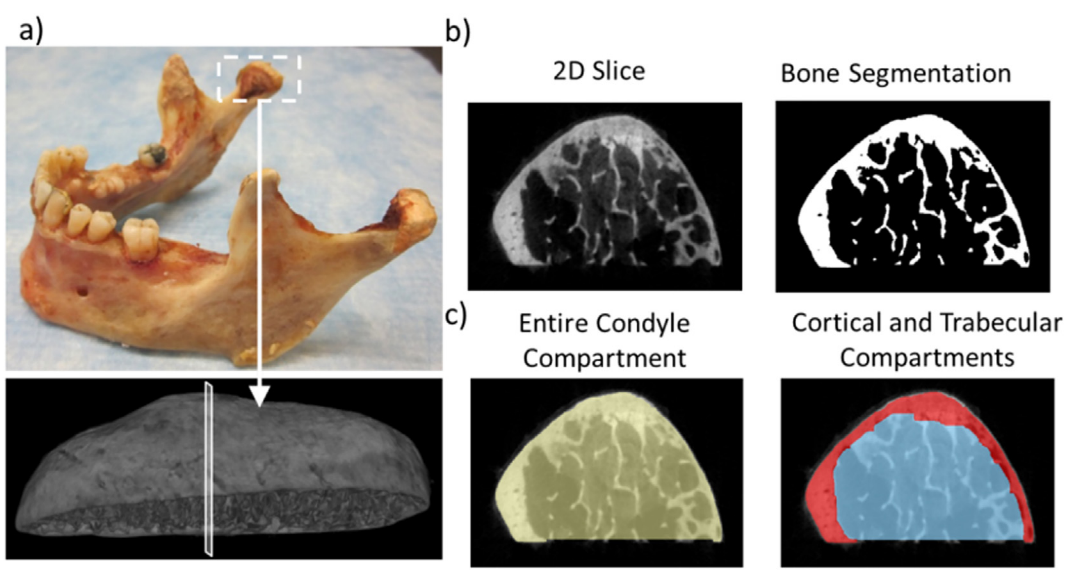

Fig. 1. a) Top: Human cadaveric mandible with the condyle area encircled. Bottom: 3D rendering of micro-CT data of the condyle. b) 2D slice at the location shown in the 3D rendering, along with the resulting bone segmentation after local thresholding. c) Entire condyle compartment shown with a yellow overlay and cortical and trabecular compartments shown with red and blue overlay, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)