Load response of the human masticatory system during chewing: A multi-body musculoskeletal modelling study

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Abstract. At present, little is known about the dynamic force and pressure distributions at the occlusal surface during mastication, as these quantities currently cannot be measured directly. The objective of this study was to develop a three-dimensional model of the mandible and dental structures, and perform simulations of dynamic chewing to evaluate the load on the dental structures. One male subject was recruited and computed tomography (CT) scans were reconstructed to develop a finite element (FE) model of the masticatory system and dental structures. Motion data was obtained from experiments in which an individual performed maximal effort dynamic chewing cycles on a rubber sample with known mechanical properties. A finite element model simulation of one recorded chewing cycle was then performed to evaluate the deformation of the rubber and the resulting load on the bone, enamel and dentin of the 1st and 2nd molars. The results suggest that transverse shearing forces during chewing may be responsible for peak stresses in the dental structures and alveolar bone while normal forces appear to be responsible for peak stresses in the condyle, condylar neck and articular disc regions. The evaluation of occlusal loading during mastication may assist in development of new dental materials, in designing effective and long-lasting restorations such as crowns and bridges, and for evaluating functional performance of prosthodontic components such as dental and/or maxillofacial implants.

Introduction

The human masticatory system is essential for speech, expression of emotion and nourishment. Accurate modelling of the load response of the masticatory system is important in evaluating the performance of dental and maxillofacial prosthetics. Previous studies have modelled bite force as a point load or sphere-contact with a dental crown to simulate the action of a bolus; however, it is unclear how bite force magnitude and direction affect stresses and strains in the dental, mandibular and temporomandibular (TMJ) joint structures. The aims of this study were twofold. Firstly, to develop a rigid-body musculoskeletal model of a subject's masticatory system, and use this model to evaluate muscle recruitment during a maximum-force bite; and second, construct a finite element (FE) model of the subject's jaw and masticatory system to explore the influence of bite force on the stresses and strains incurred by the dental, mandibular and TMJ structures.

Methods

One male subject (32 years of age) was recruited and was scanned with Computed Tomography (CT) to visualize the major masticatory structure. The resultant image stacks were digitally segmented to reconstruct 3D surfaces of the mandibular cortical and cancellous bone, the enamel, dentin and pulp of the 2nd mandibular molar as well as the articular fossae. The subject was then fitted with a customised dental brace with 3 retro-reflective markers rigidly connected and 4 additional markers placed on the subject's forehead. Jaw kinematics and bite force during a clench manoeuver were measured during a series of motion analysis tasks in which the subject was instructed to bite into a piece of rubber placed between his right mandibular and maxillary 1st and 2nd molars. The resultant jaw kinematics was recorded with a Vicon motion analysis system, and maximum bite force estimated mathematically [1].

A three-dimensional rigid-body musculoskeletal model of the subject's masticatory system was created using OpenSim (Figure 1). The model was actuated by 12 pairs of Hill-type musculotendon actuators with their lines of actions derived from the subject's CT scans, and muscle-tendon parameters scaled from a previous model [2]. Static optimization was used to decompose the calculated bite forces into individual muscle and joint forces during the maximal clench. These forces were used as boundary conditions in a subject-specific FE model of the subject's masticatory system comprising the mandible (cortical and cancellous bone), 2nd mandibular molar (enamel, dentin, pulp), articular discs and articular fossae. Two bite simulations were performed: a concentrated force – the normalcomponent of the maximum bite force – applied to the center of the occlusal surface (CF), and the calculated three-dimensional maximum bite force distribution obtained during the gold standard clench maneuver (GS) (Figure 2).

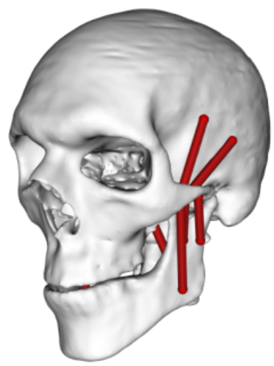

Figure 1: Three-dimensional musculoskeletal model of the masticatory system

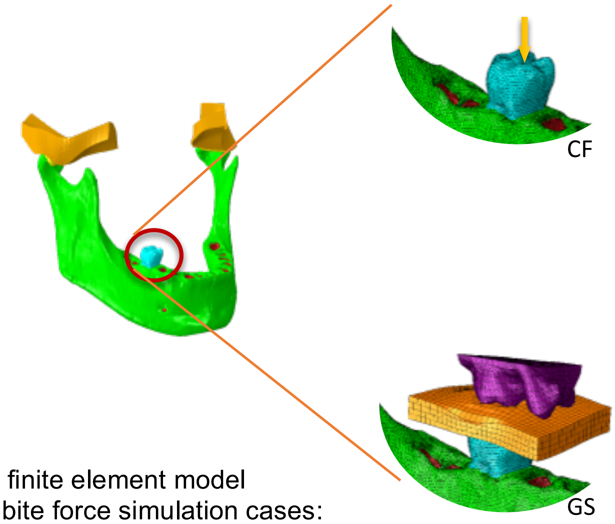

Figure 2: Jaw finite element model including two bite force simulation cases: concentrated point force (CF), and gold standard bite force distribution at the occlusal surface (GS)

Results and Discussion

The maximum bite force magnitude measured was 617.8N. The superficial masseter contributed the most force out of all muscles. The muscle forces in the masseter group were approximately symmetrical while muscles in the temporalis group were highly unsymmetrical from the ipsilateral to contralateral side. The lateral pterygoid muscles had more tendency than any other muscles to generate medial-lateral force. The reaction force at the contralateral condyle of the temporomandibular joint was greater than the reaction force at the ipsilateral condyle during clenching, with a peak contralateral reaction force of 492.1 N. Maximum stresses in the GS simulation were 112.1 MPa, 68.2 MPa and 48.0 MPa for the mandibular cortical bone, enamel and dentin, respectively. The largest stresses in the dentin and PDL occurred in the GS simulation where transverse shearing forces were present. This also caused a high stress region in the alveolar bone (Figure 3), which was not observed in the CF case.

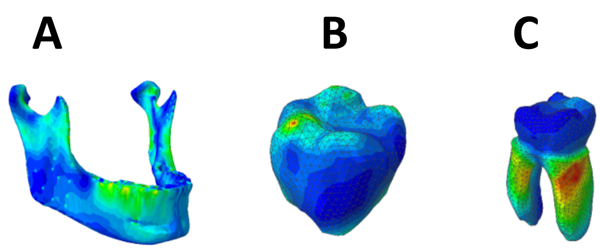

Figure 3: GS simulation results showing Von Mises stress distributions for the (A) mandibular cortical bone (B) enamel (C) dentin.

Conclusions

The present study showed that modelling the magnitude and direction of bite force is important in encapsulating the resultant magnitude of stresses and their distributions in the mandible, enamel, dentin, PDL and articular discs. Transverse shearing forces during chewing may be responsible for peak stresses in the dental structures and alveolar bone while normal forces appear to be responsible for peak stresses in the condyle, condylar neck and articular disc regions. This study also showed that during a unilateral bite, asymmetric muscle recruitment results in peak TMJ forces at the contralateral joint. The multibody musculoskeletal and finite element methods presented may be useful in surgical planning, evaluating dental implant performance, and assessment of maxillofacial prosthetics such as temporomandibular joint replacements.

References

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