A Prosthetic Total Joint Replacement System for the Human Temporomandibular Joint

David C. Ackland, PhD, John Russell Dow, BSc, Jason D'Souza, BSc, Adrian Moskaljuk, BSc, Nick D'Arcy-Evans, BSc, Christopher Hart, MDSc, BDSc, Peter V. Lee, PhD, George Dimitroulis, MDSc(Melb), PhD(Melb), FDSRCS(Eng), FFDRCS(Irel). 1, 2

1University of Melbourne, Parkville, Australia, 2St Vincent's Hospital, Melbourne, Australia.

Disclosures:

Introduction: The Temporomandibular joint (TMJ) is an important component of the lower jaw (mandible) that is essential for speech, chewing, swallowing, and for expressing emotion. Painful disorders involving the TMJ, including osteoarthritis, are relatively common, with prevalence ranging from 16-59% [1]. TMJ replacement surgery is the established treatment for end-stage TMJ osteoarthritis; however, current TMJ prosthetic implant designs face a range of problems including fracture from metal fatigue; screw loosening; and difficulty in placement of the prosthesis to avoid the facial and trigeminal nerves. In order to address these limitations, a novel TMJ prosthetic replacement design was produced. The aim of this study was threefold. Firstly, to develop a musculoskeletal finite element of the TMJ based on the Visible Human Male (VHM) dataset; secondly, to use this model to evaluate the functional performance of the TMJ prosthetic total replacement system; and third, to compare the TMJ contact-mechanics of the TMJ prosthesis results to those of the natural TMJ.

Methods: Axial images from the Visible Human Male dataset were digitally segmented (Amira, VSG) and combined to reconstruct 3-D surfaces of the mandible, glenoid fossa and articular cartilage and discs. The major muscles of mastication - the masseter, temporalis (anterior and posterior), lateral and medial pterygoids - were also digitally reconstructed. Lines of action of each muscle, defined as the straight line between centroids of origin and insertion, were measured relative to an orthogonal coordinate system associated with the mandible. Muscle volumes and muscle fiber lengths were measured and used to calculate maximum isometric muscle force for each muscle, as described previously [2]. Using the measured muscle lines of action, and assuming ideal actuators, muscle forces during a normal chewing bite were computed by summing moments in three-dimensions about the TMJ joint centre. A static optimisation routine was used with a cost function chosen to minimise the sum of the squares of muscle activation subject to a bi-lateral bite force of 200N positioned at the second molar. Muscle forces were constrained within zero and their maximum isometric forces. TMJ contact forces were computed. The calculated muscle forces were used as boundary conditions in a finite element model of the human jaw (Abaqus, Simulia). The anatomy of the jaw included the three-dimensional surfaces of the mandible, glenoid fossa, articular cartilage and discs generated from the Visible Human Male dataset. Material properties of the bone, cartilage and discs were taken from the literature. A simulation of a normal chewing bite was performed and articular cartilage and disc contact stresses were calculated.

A novel TMJ total joint replacement system was designed by an experienced oral and maxillofacial surgeon (G.D). A virtual surgery of the musculoskeletal model was simulated with guidance from the surgeon. The left natural condyle and fossa were removed and the TMJ components placed according to the subject anatomy. The condylar component was fixed with three screws (superior, mid and inferior), while the fossa component was rigidly fixed to the temporal bone. The model was modified to represent the detachment of the lateral pterygoid during surgery. Muscle and joint forces were re-calculated, and a finite element model simulation performed to calculate implant stresses and strains during a chewing bite.

Results: The ipsilateral masseter was the largest force generator, with a peak resultant force of 108.4N (Table 1). The pre-operative joint reaction forces were 98.9N and 86.3N at the left and right TMJ, respectively. The total reaction force calculated at the teeth was 173.0N. Pre-operatively, the maximum contact stress in the left and right condylar cartilage was 1.1MPa and 1.5MPa, respectively (Fig. 1).

Post-operatively, the TMJ joint reaction force magnitudes on the left and the right TMJ were 79.1N and 78.3N, respectively, with a joint-reaction force at the teeth of 182.8N. Post-operatively, the maximum contact stress in the right condylar cartilage decreased from 1.5MPa to 1.2MPa. At the TMJ joint prosthesis, the maximum contact stress at the condylar component and the fossa component was 85.0MPa and 166.1MPa, respectively (Fig. 2). The maximum stress and strain magnitudes in the condylar component were 279.9MPa and 2253.7x10-06, respectively, occurring in the region of the screw hole closest to the implant condyle head. The maximum stress of the screw at this location was 338.2MPa.

Table 1: Maximum isometric muscle forces, and muscle forces estimated for a chewing bite (Newtons)
Discussion: Muscle recruitment patterns predicted by the musculoskeletal model are in qualitative agreement with EMG data reported previously [3]. Our results showed that the location of highest stresses in the prosthesis was at the superior screw-hole interface (closest to the condyle head). This is due to this location being the closest implant-bone fixation point relative to the TMJ joint-contact centre. This finding is important in component design since the screw closest to the condyle head is most difficult to place intera-operatively; therefore, the combined issues of high stress and the potential for the screw being inserted incorrectly during surgery represents a primary complication risk. While the contact forces at the TMJ were of lower magnitude post-operatively, most likely due to the detachment of the lateral pterygoid, the contact stresses in the TMJ component were orders of magnitude higher in the condylar head of the TMJ than in the condylar cartilage pre-operatively. This finding indicates the potential for excessive wear in this contact region, and suggests greater contact area in the implant design could mitigate these large contact stresses.
Significance: This study provides first estimates of muscle and joint-contact loads in the TMJ both before and after total joint replacement surgery. The findings have implications for TMJ prosthetic implant design.

Acknowledgments: N/A

References: REFERENCES:
2. Hart HF et al. (2012) Quadriceps volumes are reduced in people with patellofemoral joint osteoarthritis. OA&C, 20(8), 863-868