Modelling mastication: the important role of tendon in force transmission

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The human masseter has a complex structure: it is composed of several compartments of pennated muscle fibres, separated by interleaving tendon sheets (Figure 1). The interaction between pennated fibres and internal tendon allows us to bite with forces that can exceed 200 N. For applications such as estimating the efficacy of dental implants, or for predicting the functional outcome of surgical procedures like mandibular reconstruction, it is important that a biomechanical model capture this complex architecture.

Most existing models for studying mastication rely on line-based, lumped-parameter muscle models. These line-based models are limited: they assume uniformity throughout the muscle, and cannot represent broad attachment areas like in the case of the masseter. In [1], Rohrle et al. compare line-based representations of the masseter to a 3D finite element (FE) model. They show that using line-based muscles introduce significant errors in predicted force distributions, to the point where it can lead to different predicted clinical outcomes. One of the limitations of the study was that the largest isometric bite force their FE model could reproduce was 77N. It did not include tendon properties.

We show that modelling internal tendon is essential to recovering force gains due to pennated fibres. We explore two methods for incorporating tendon into FE models. The first is the traditional approach, where elements conform to muscle-tendon boundaries. The major challenge here is creating a well-structured mesh that adheres to internal constraint surfaces. The second method is to create separate models for the thin tendon structures, then couple them to the muscle volume via a system of constraints. This lets us use a well-structured low resolution model to represent the bulk of the muscle, reducing system complexity.

Using the ArtiSynth simulation platform [2], we test a simplified bipennate muscle under isometric contraction conditions. Using both techniques to include tendon, we were able to reproduce force gains predicted by the theory of physiological cross-sectional area if the tendon is sufficiently stiff. Moreover, the two techniques produce nearly identical force-activation curves. This suggests we are justified in using the model-coupling approach. Interestingly, by increasing fibre pennation without including tendon properties, we actually saw a reduction in net force production. We then applied the method to a complete model of the masseter coupled to the maxilla and mandible. We found that by modelling tendon properties, we were able to increase simulated maximal bite forces to more realistic levels compared to without tendon (167 N vs. 78 N). This emphasizes the important role of internal tendon in force transmission in multi-pennate muscles.

References: