3D FINITE-ELEMENT MODELING OF THE SOFT PALATE REVEALS SYNERGIC ACTIONS OF SPEECH MUSCLES

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INTRODUCTION

The velopharyngeal (VP) mechanism is a complex deformable system consisting of several muscles and complicated soft tissue geometry within the soft palate. Understanding the mechanics of this system is essential for developing effective treatments for speech disorders and improving surgeries for cleft palate patients. However, the mechanics of the soft palate are complex. Several muscles interact with one another to move the soft palate during speech, and the physics of the interactions between these muscles are poorly understood. The goal of this work is to develop a multi-muscle model of the soft palate and use model to examine how the various muscles of the soft palate contribute to the movement of the soft palate during speech.

METHODS

We created a 3D finite element model of the VP mechanism based on MRI scans of a 20-year-old Japanese male subject with normal VP anatomy. The model components included the soft palate, the posterior pharyngeal wall (PPW), the levator veli palatini muscle (L), the musculus uvulae (U), and the palatopharyngeus muscle (P) (Figure 1).

Simulations were based on the muscle and soft tissue mechanical properties from the literature [1,2]. The soft tissue was modeled as an isotropic, hyperelastic Mooney-Rivlin material with elastic modulus of 25kPa and muscle was modeled as a transversely isotropic material. Muscle fiber trajectories for the muscle material were determined using computational fluid dynamics [3]. We used Sefea™ (Strain-Enriched FEA, AMPS Technologies) finite element solver with explicit strain energy function specification and automatic meshing of 4-node enhanced tetrahedral elements to run the simulations [4]. In these half-symmetry simulations, we activated all combinations of the three simulated palate muscles. We measured soft palate elevation, closure force, and contact length (Figure 2a) for each combination at muscle activation levels ranging from inactive to fully active, smoothing the variables to remove numerical noise.

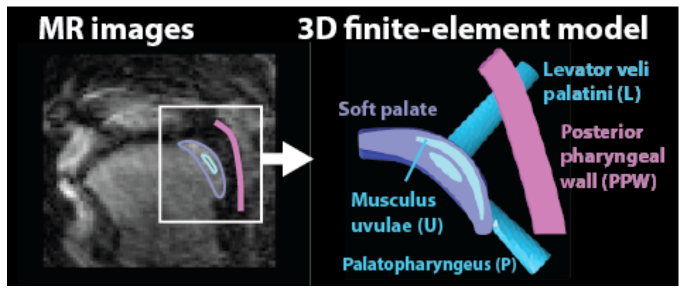

Figure 1: We used MR images to create a 3D finite-element model of the velopharyngeal mechanism with three muscles (cyan).

RESULTS

The different combinations of muscle activations show markedly different deformations (Figure 2b). Deformations in dynamic speech MRI data [5] compared favorably with model deformations for L activation (Figure 2c). L and LU activation reached similar soft palate elevations as the MRI data (Figure 2d). Experimental speech data for closure force [6] compared most favorably with L and LU activation (Figure 2d). L, LU, LP, and LUP activation combinations were able to produce contact length ranges measured in a previous MRI study [7] (Figure 2d).

DISCUSSION

The different deformations created by muscle activations show both synergistic and antagonistic actions. For example, L and P synergize to retract the velum towards the PPW. However, their effects on soft palate elevation are antagonistic. Proper action of L (the largest palate muscle) is necessary but not sufficient to reproduce data comparing favorably with experimental data in normal speech (Figure 2d). These deformation patterns and future modeling studies will help in surgical planning for cleft palate patients (where the musculature must be surgically reconstructed) and aid in clinical assessment of dysfunctional motor control during speech. More broadly, these simulations demonstrate the applicability of muscle biomechanical analysis to studies of speech function.

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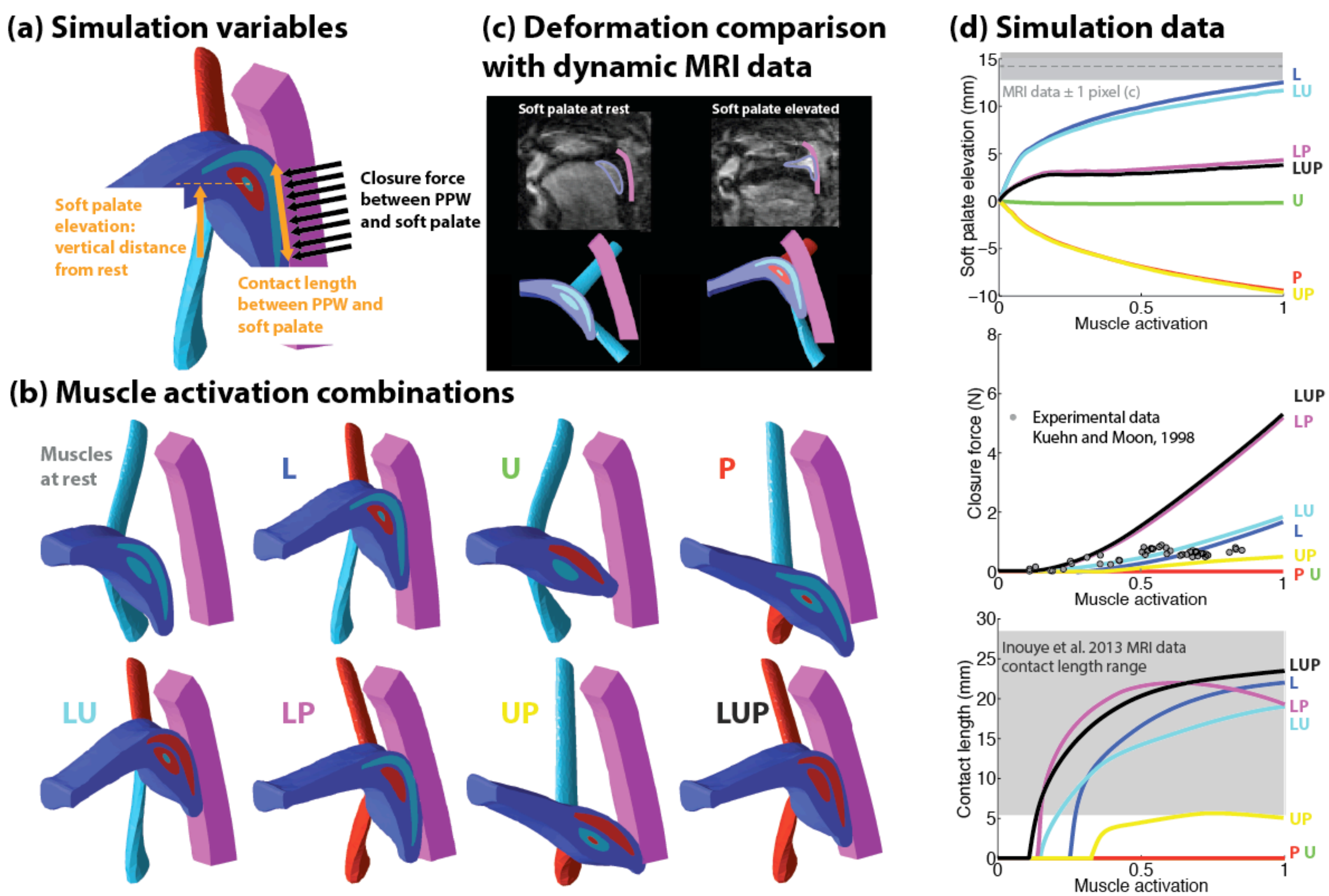

Figure 2: (a) Measured simulation variables. (b) Different muscle activations produced markedly different deformations. Red muscles are active; cyan muscle are inactive. (c) Deformations in dynamic MRI data [1] compared favorably with model deformations for L activation (d) Activation of L is necessary for the model data to compare favorably with experimental values, highlighting the importance of its proper reconstruction in cleft palate repair.