Applying a 3D biomechanical model to 2D ultrasound data

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Abstract

A 3D biomechanical model of a tongue has been created using bespoke hexahedral manual mesh creating software. The software allows meshes to be created and vertices to be added, removed and moved in 3D, either individually or in selected groups. After a mesh has been digitally sculpted by hand, edges of the hexahedra can be assigned to "muscles". These "muscles" are controlled by manipulating the nominal length. A change in the nominal "muscle" length invokes Hooke's Law (modified so stiffness increases as the muscle contracts) to calculate the forces applied to every vertex in the mesh. Each vertex is moved iteratively until the forces on all vertices reach an equilibrium. The iterative calculation also includes a hydrostatic (volume preservation) component in the form of pressure force inside each hexahedron.

This equilibrium based approach has no temporal component so it cannot be used to predict movement. It does not explicitly model momentary imbalances in internal muscle forces which may occur during highly dynamic movement, although some implicit modelling may occur if it is not given time to iterate to equilibrium at a given time point. The big advantage of this technique over the more popular Finite Element Modelling approach is that it is flexible and stable. It does not lock up like Finite Element Models often do and is reasonably robust to arbitrary mesh design changes. Different shapes and muscle configurations can therefore be tested without worrying about the effect it may have on the stability of the modelling process.

A tongue mesh, once created, can be posed by contracting the assigned muscle groups. A midsagittal section of the 3D model can be superimposed on 2D midsagittal ultrasound data imported into the meshing software and the model then manually posed to fit each successive frame using landmarks on the ultrasound image as a guide. As the model is fitted to successive ultrasound frames (at 120fps), the patterns of "muscle" contraction over time are revealed. During the fitting process, choices in which muscles to contract can be influenced by attempting to avoid discontinuities in muscle contraction from frame to frame. This, in part, mitigates for any "many-to-one" muscle–to-shape mapping problem that may or may not exist. The result is a dynamic 3D model of tongue movement to match the 2D ultrasound data with associated muscle contraction time series generated as an important byproduct of the fitting process.

In this paper, validity of a given 3D tongue model is evaluated by comparing the predicted 3D tongue palate contact patterns with the actual patterns recorded by EPG. Results seem to indicate that, if the assumption of sagittal symmetry inherent in the present model is not too bold then the parasagittal shape of the tongue can be predicted from 2D midsagittal ultrasound data. Figure 2. Shows palate proximity patterns predicted by a model fitted to the midsagittal ultrasound of the sentence "The price range is smaller than any of us expected." The actual contact patterns measured by EPG at the same time points in the sentence, are similar if the asymmetries are ignored. This predictive ability is reasonable, within the terms dictated by symmetry, since the muscles which lie off the midline such as styloglossus, hyoglossus, transversus, inferior longitudinalis and verticalis all have an effect on the midsagittal tongue position and shape as well as forming an intrinsic part of the parasagittal lingual tissue.

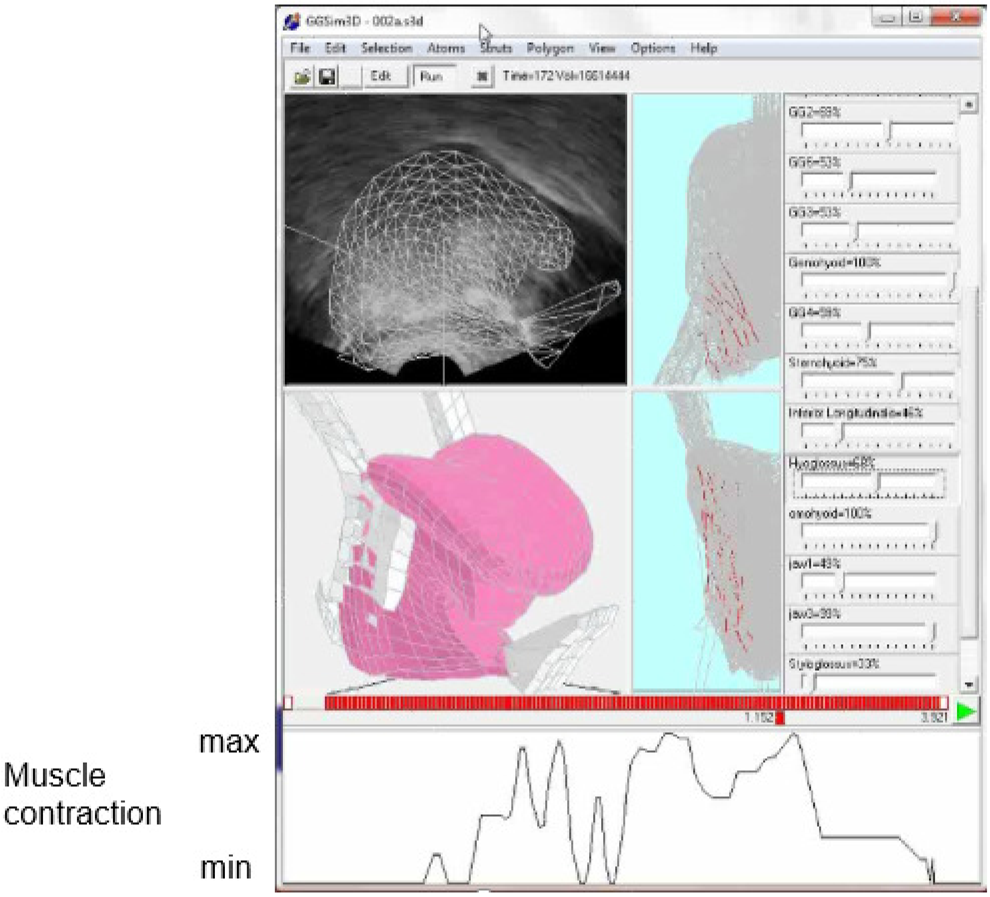

Figure 1. Top left: Single ultrasound frame with midsagittal section of 3D model superimposed. In this case the tip would be extended to fit the ultrasound image by relaxing the inferior longitudinalis and relaxing the anterior portion of the genioglossus. Middle left: The full 3D tongue shape. Right side: A set of sliders controlling each muscle. Bottom: The muscle contraction time series for the highlighted muscle (hyoglossus) Red bar: this is a series of approximately 400 ultrasound frames. Any or all frames can be selected and manually matched to the model. Unselected frames have nominal muscle lengths set to values linearly interpolated from neighbouring selected frame values.

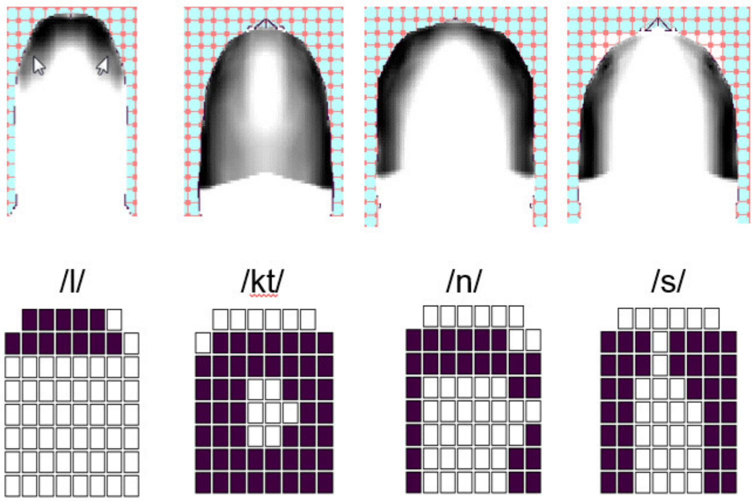

Figure 2. Top row: Shows distance from the model tongue to the model hard palate represented by greyscale where black is contact and white is ~1cm or greater. Bottom row: EPG patterns of the same segments from the same spoken sentence by the same speaker.