

ANATOMICAL BIASING AND CLICKS: PRELIMINARY BIOMECHANICAL MODELLING

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ABSTRACT

It has been observed by several researchers that the Khoisan palate tends to lack a prominent alveolar ridge. A preliminary biomechanical model of click production was created to examine if these sounds might be subject to an anatomical bias associated with alveolar ridge size. Results suggest the bias is plausible, taking the form of decreased articulatory effort and improved volume change characteristics, however, further modelling and experimental research is required to solidify the claim.

Keywords: clicks, hard palate, alveolar ridge, anatomical biasing.

1. INTRODUCTION

This paper examines the production of clicks in the context of a three-dimensional biomechanical simulation. Specifically, we ask whether differences in the shape of the palate might influence certain aspects of click production, such as the muscular effort/articulatory ease, e.g. [9] and [13], or the dynamics of lingual cavity rarefaction. This work is situated within the larger context of research that seeks to address the question of whether variation in human vocal tract anatomy and physiology constitutes a systematic bias or pressure on speech sound systems. Such biases, while interesting at the level of individual variation, might also show localized patterns corresponding to wider populations of speakers sharing certain vocal tract traits.

It is an undeniable fact that human populations vary in certain systematic ways in their anatomy and physiology. This is true at both micro- and macroscopic levels, and advances in genetics will continue to elucidate the extent of these patterns of variation across populations. Early in the development of modern phonetic and phonological science, several proposals (e.g. [24] and [2]) were made which held that some of the diversity observed in speech sound systems around the globe might be owing to systematic variation observed in the anatomy and physiology of the speakers of language, in addition to the other factors driving language change and diversification. These ideas

were hastily dismissed as implausible, on the grounds that any human being can learn any human language.

It is an incontrovertible fact that normal variation of the human vocal tract does not preclude an individual from acquiring any spoken language. However, the hypothesis that human vocal tract morphology exerts a bias on the way we speak seems plausible, and the possibility that such biases might have expressions at the level of populations of speakers has never been satisfactorily ruled out. It also seems to have resulted in the unfortunate side-effect that details of vocal tract shape are rarely if ever correlated to production variables in phonetic research. A relatively recent return to the question of whether normal vocal tract variation can indeed exert such biases reflects the unresolved nature of the problem. Many examples exist for such research examining the individual level (e.g. [25], [3], and [18]), and these are laden with implications for impacts at broader levels, with some researchers even suggesting it may be a driver of change of certain aspects of entire phonological systems (e.g. [1], [5], and [17]).

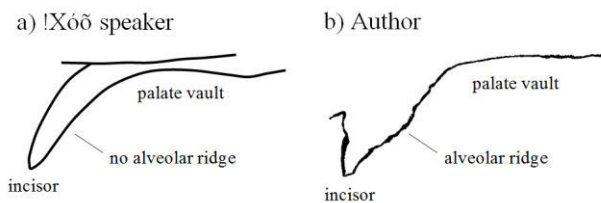
1.1. Why examine click production?

In the present study, we focus on the case of clicks. Clicks merit investigation because of their incredible rarity as phonemes, a fact which suggests there are biases against the phonological incorporation of these sounds. They are primarily associated with the so-called Khoisan languages (actually a group of language families, including Kx'a, San, and Tuu, which bear some family resemblance, and the isolates Hadza and Sandawe). They are also found in several Nguni Bantu languages (including Zulu, Xhosa, Ndebele, Swazi, and Sotho) and Dahalo, a Southern Cushitic language, all of which have evidently borrowed clicks through generations of extensive contact with various Khoisan languages [20].

Our inspiration for the present study comes from observations by Engstrand [6] (also [20], p. 4) and Demolin (p.c.) that clicks may be subject to a production bias grounded in the morphology of the palate. The ultimate source for this idea comes from Traill [21] (p. 101-102), who remarks in his

dissertation (on the subject of !Xóǀ, a language of the Khoisan group) that one cannot use the term *alveolar* to describe post-dental clicks in !Xóǀ since four of his five subjects “do not have an alveolar ridge” (p. 101). One of these palates is reproduced in Fig. 1 along with a comparison to the palate of author SRM, which exhibits a sizeable alveolar ridge.

Figure 1: Mid-sagittal palate profiles: (a) an example of a !Xóǀ speaker’s palate (retracing of Fig. 24 from Traill [21], p. 107) and (b) the palate of author SRM.



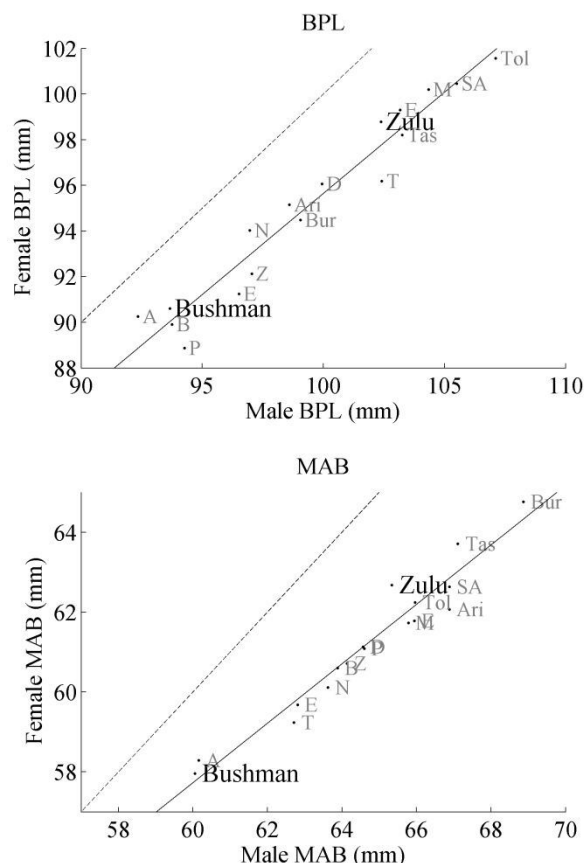
While such variation could easily be owing to Traill’s limited sample of !Xóǀ palates (although Traill notes that the pattern holds for the San in general, citing [22]), it is well established that other members of the Khoisan group show uniformity of head and palate morphology that distinguishes these groups from other nearby non-Khoisan populations. For example, [23] compares palatal measures made on plaster dental casts of Central Kalahari Bushmen (a sample comprised of individuals from the !Kung, Auen, Naron, Dukwe, and Heikum tribes), Vassekela Bushmen (originating from Angola); and Herero-speaking individuals, mainly Himbas, for comparison. Note that the former two groups (the Bushmen) consist of speakers of Khoisan click languages, but Herero (a Bantu language) lacks clicks. Sample sizes in this study are large (minimum of 76 and maximum of 158). The Bushmen groups generally have narrower and shallower palates, and the anterior flatness (i.e. lack of a prominent alveolar ridge reflected by highest scores for palate height in the canine region) is confirmed. The Vassekela Bushmen are intermediate, but classified with the Himbas as having a “shelved” palate: low at the front but suddenly increasing in height towards the back. The Bushmen palates were not necessarily shorter than those of the Himba.

Similar work [26] compares 110 male !Kung San (who speak a Khoisan language of Namibia) with a group of 138 males from Kenya and Uganda (containing both Bantu- and Nilotic-speaking individuals). This study demonstrates that the !Kung San palate is shorter, narrower, and shallower and characterized by a smooth, concave profile. Note

that the authors of [26] do not provide a detailed listing of the specific languages spoken by the non-Khoisan group, i.e. the Bantu and Nilotic speakers. However, it is stated that most of the Bantu-speaking individuals are from the Taita Hills, and the language of this area, Taita/Dabida, lacks clicks; and clicks are not found in Nilotic languages.

Craniometric data [8] show that Bushmen (Khoisan) palates (for males or females) tend to be smaller in comparison to many other populations (Fig. 2). Note that Zulus, whose language has clicks, fall towards the upper end of these variables.

Figure 2: Basion-prosthion length (BPL; proxy for palate length) and maxillo-alveolar breadth (MAB; proxy for palate width). Data from [8]. A = Andaman, Ari = Arikara, B = Berg, Bur = Buriat, D = Dogon (Mali), E = Egyptian, E = Eskimo, M = Mokapu, N = Norse, P = Peru, SA = South Australian, T = Teita (Kenya), Tas = Tasmanian, Tol = Tolai, Z = Zalavar. Dashed line = hypothetical 1:1 sexual dimorphism; Solid line = regression line.



In short, it seems that the Khoisan palate is distinguishable from palates of other groups, and that the trend of a lack of a prominent alveolar ridge detected in Traill’s x-rays may indeed be representative of the Khoisan group, although gene

flow with neighbouring groups and the resultant differentiation of palate shape (e.g. as reflected in the Vassekela) is a possibility.

1.2. Palate morphology and clicks: Hypotheses

Briefly, to produce a (lingual) click, the tongue must first form an enclosed space between the anterior occlusion (which defines the click’s place of articulation) and the velar-uvular region of the palate. Clicks do not typically require the tongue be flush against the palate, and, in fact, there is very often a central gap, as observed in x-ray ([21] and [10]), static palatography ([21] and [19]), and ultrasound (e.g. [12]) studies. The next step is to generate the velaric ingressive airstream, which depends on rarefaction of the air driven by localized lowering of the tongue body (the exact location of which is dependent upon click place of articulation). Finally, the oral seal is suddenly broken by the rapid release of the anterior occlusion, and the pressure differential created through rarefaction yields a transient acoustic signal audible as a click.

Our goal was to probe into the possibility that palatal morphology has consequences for click production and that this, in turn, might speak to a production bias which has led to the establishment and maintenance of clicks as speech sounds. The general question we ask is: what effect, if any, does palate shape have on the production of clicks?

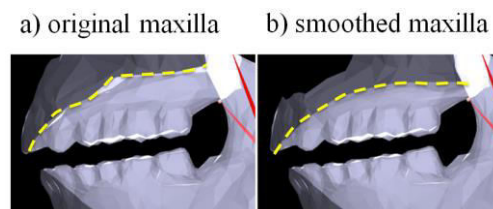
To address this question, we narrow our focus on the biomechanics of click production, and, on the alveolar ridge, which was identified as an important factor by other researchers. (Palatal dimensions may also be important, but in this preliminary modelling, these factors were not explored.) Given this focus, we suggest the following hypotheses regarding alveolar ridge shape and click production: (1) a smooth palatal profile requires less articulatory effort to form click stricture since the anterior tongue does not need to deform as much to form the lingual seal; (2) a smooth palate provides better volume change characteristics (presumably for achieving efficient aero-acoustic effects in click production, although this was not modelled).

To test these hypotheses, we assume that total muscle force is a good proxy for articulatory effort (following [9] and [13]). We also constrain our attention to the production of clicks which involve contact between the tongue tip/blade and the anterior palate, as these clicks are most relevant to hypothesis (1). Our simulations are place-abstract, but they most closely resemble dental clicks.

2. METHODOLOGY: CLICK SIMULATION IN ARTISYNTH

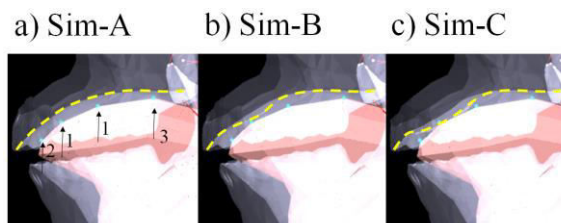
The biomechanical simulation of click production was created using the ArtiSynth biomechanical modelling toolkit (www.artisynth.org; [11]). This model is based on the 3-D finite-element (FE) tongue integrated with rigid-body skeletal structure for the maxilla and mandible as originally presented in [4] (and used in several subsequent studies; see [14], [16], and [17]).

Figure 3: Geometry (a) before and (b) after maxillary smoothing in the region of the alveolar ridge (midsagittal profile). The yellow dashed line highlights the contour of the mesh for comparison.



Alveolar ridge shape was systematically manipulated to simulate its effects on click production. To do this, it was first necessary to smooth the original maxillary geometry, which features a prominent alveolar ridge. Smoothing was accomplished manually using tools in Blender (www.blender.org) to deform the anterior palatal geometry such that the alveolar ridge convexity was entirely removed. Results of this process are illustrated in Fig. 3.

Figure 4: Mesh warping to control alveolar ridge size. Three simulation conditions (a) Sim-A, no warping, “no ridge”; (b) Sim-B, mild warping, “small ridge”; (c) heavy warping, “big ridge”. The yellow dashed line highlights the change in profile. Arrows show longitudinal locations of inverse-simulation nodes (see text below).



Next, to experimentally manipulate the shape of the alveolar ridge, a spherical warping field was used. This field radially displaces subjected mesh vertices within a limited radius of the origin of the warping field (which was placed approximately

above the anterior nasal spine). The magnitude of the displacement is given by $d = (r - p)/r$, where p is the Euclidean distance between a given vertex and the warping origin, and r is the radius of the warping field. The different grades of warping used are shown in Fig. 4 (note that the warping in Sim-B is intermediate between Sim-A and Sim-C).

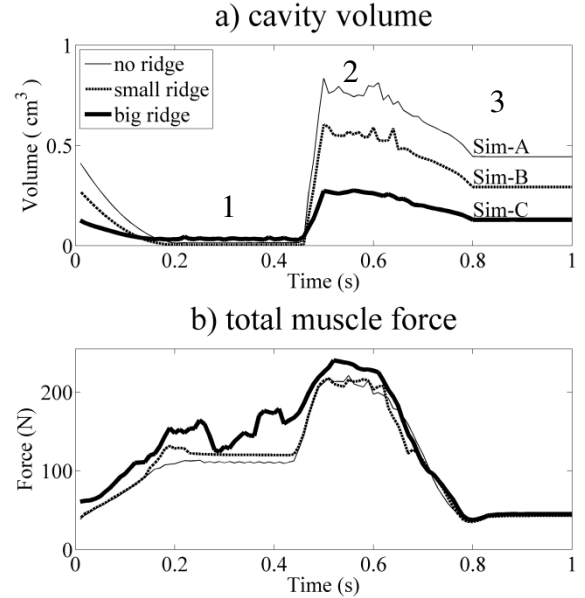
Finally, to simulate the dynamics of click production, ArtiSynth’s inverse controller was used. This takes temporal targets of nodal locations of the geometry as input and outputs a parsimonious set of muscle activations which achieve these temporal targets within the limitations set by tissue contacts, inertia, and material properties. Inverse targets were associated with FE nodes at longitudinal locations shown in Fig. 4a (blue circles or arrows), each of which had one midline and two lateral nodes. A rudimentary, somewhat idealized and place-neutral lingual click was defined as follows: first, all inverse targets were positioned at a short distance beyond the projection of each target’s corresponding FE node onto the nearest face of the maxilla mesh along the line of projection (thus, in each simulation, constriction is relative to maxilla shape); then, the midline nodes at the positions indicated by the two arrow-1s (Fig. 4a) were displaced to a position below their resting state positions (this simulated rarefaction); next, all targets at arrow-2 (Fig. 4a) were displaced to their resting state (simulating release of the front closure); finally targets at arrow-3 were returned to resting state (simulating release of the back closure). Note that no attempt was made to simulate the initial presence of an enclosed airspace during the establishment of palatal contact.

Three 1 second simulations were run which correspond with the geometries in Fig. 4. Total muscle force was observed along with the volume in the region of lingual rarefaction (arrows 1 and 2).

3. RESULTS AND DISCUSSION

Fig. 5 shows results for volume change and total muscle force. Overall, the effect of having a larger alveolar ridge, given the same relative palatal contact requirements and the same absolute lingual resting/return state, is to reduce the rate and amount of volume gain during release of the front closure (Fig. 5a, at 0.5 s) and to increase the articulatory effort in producing and maintaining closure whilst enlarging the air space. Also note that volume did not go to zero for the “big ridge” condition (phase 1, Sim-C), which indicates that this condition makes it harder for the model to establish full contact between the tongue and the palate.

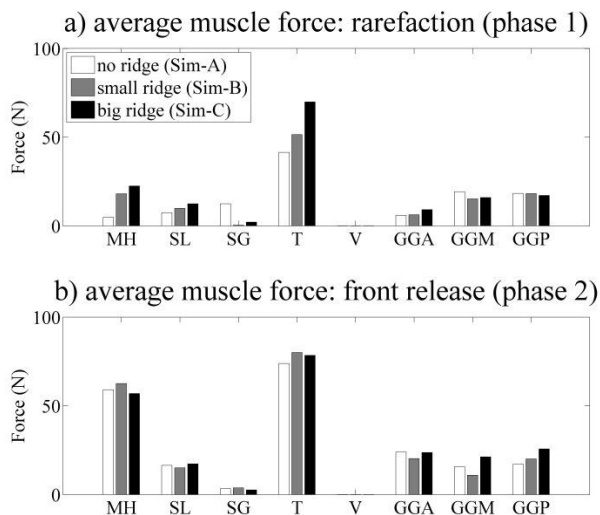
Figure 5: Lingual cavity volume (a) and total muscle force, smoothed with a moving average filter (b) for the three simulation conditions (see Fig. 4). Phases: 1 = rarefaction; 2 = release of front closure; 3 = return to resting state.



When examining specific muscle contributions (see Fig. 6), it is apparent that, during the rarefaction phase (Fig. 5a, 1; Fig. 6a), mylohyoid (MH) and transversus muscle force output increase with alveolar ridge size, followed by the superior longitudinalis and then, somewhat less so, by genioglossus anterior (GGA). The styloglossus and genioglossus medial (GGM) muscle outputs are actually higher for the “no ridge” condition (Sim-A).

The rather large values for the transversus muscles during phase-1 (Fig. 1a) can be associated with intrinsic lingual shaping to form and maintain contact against the palate. In the simulation, the rarefaction is probably driven by the GGM fibres; the verticalis might also play a role in real productions but it is inactive here. Relative to those muscles responsible for elevating the tongue against the palate, the activity of GGM seems low. Furthermore, during front release, MH and transversus are still very high which, in an effort to maintain the posterior closure, is possibly occurring to balance the forces working to release the front closure (mainly the GGA). Validation of these muscle activation patterns would be difficult to achieve with electromyography (and the authors are unaware of any such study for click articulation). Refinements to the geometry of the tongue might change the patterns substantially.

Figure 6: Average muscle force for the rarefaction (a, phase 1) and release of front closure (b, phase 2) phases corresponding to 1 and 2 in Fig. 5a. Muscles: MH = mylohyoid; SL = superior longitudinal; SG = styloglossus; T = transversus; V = verticalis; GGA = genioglossus anterior; GGM = genioglossus medial; GGP = genioglossus posterior.



The simulation exhibited some peculiarities. First, as is evident in Fig. 5, there is some noisiness, which is directly attributable to the interaction of collision mechanics and the inverse solver in ArtiSynth: if the inverse targets go beyond a site of collision, the inverse solver will continuously oscillate through various solutions. To minimize this, targets were placed as close as possible to the palate but still slightly above so as to ensure strong contact. Also, it was apparent that the tongue FEM discretization was not fine enough to achieve an anterior lingual deformation during rarefaction (Fig 5a, phase 1) sufficient to produce a gradual expansion of the volume (from phase 1 to 2). This may have also been the cause of the somewhat unexpectedly large muscle forces occurring at stage 2. Also note that, while in reality it may be that the negative pressure generated from rarefaction requires heightened muscle forces during this phase, no fluid-structure interaction was simulated, so this cannot be the cause of the increased force at this point. Finally, no attempt has been made to model the active contribution of the soft palate in the formation of the velar closure in click production. These aspects need to be resolved in future refinements to the model.

With these considerations of the limitations of this preliminary ArtiSynth model of click production in mind, the results are consistent with the hypotheses introduced in §1.2: (1) more muscle force is required to form click structure with a larger alveolar ridge, and (2) all things being equal, the

smoother the palate, the more rapid and larger the volume change. We suspect that greater articulatory effort (estimated through total muscle force) will have a negative bias on click appearance and maintenance at the diachronic scale. Larger and faster volume change ought to produce acoustically stronger click bursts with better transient properties. It also provides a wider range of volumes achievable depending on other factors, and this should increase the reliability of click production (cf. [3]). Finally, incomplete lingual-palatal contact in Sim-C could indicate that the alveolar ridge inhibits efficient lingual sealing, although finer FE discretization needs to be tested. The viscosity of saliva on the tongue and palate may also influence click biomechanics and consideration of these forces could be incorporated into future models.

This modelling supports the notion that alveolar ridge shape may be a source of biasing on clicks, but one that is weak at best. The borrowing of clicks by non-Khoisan groups with possibly quite different palate size (e.g. see Zulu, Fig. 2) and shape support this interpretation of a weak bias. Furthermore, clicks are a common paralinguistic sound, and they are often spontaneously produced by children. On this last point, however, it is possible that children, regardless of alveolar ridge size, benefit in click production from having overall smaller palate dimensions, not unlike the Khoisan (Fig. 2). As noted, palate dimensions were not considered here, but one can imagine how a narrow palate might facilitate click seal formation (although tongue size is relevant, too). Palate size might also influence the amount of pressure exerted by the tongue on the teeth [15].

In this preliminary work, the model abstracts away from place of articulation. However, place is likely important, and the details of muscle forces and volume change characteristics are very likely to be a function of a click place of articulation. In particular, given the relative rarity of palatal clicks and their resistance to borrowing (found only in Yeyi [7] outside of the Khoisan group), these may be most strongly subject to a bias. The direction of lingual motion in such clicks is different and could be a source of differential articulatory efficiency determined by palate shape. We intend to explore different places of click articulation in subsequent modelling work.

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