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The role of oral soft tissues in swallowing function: what can tongue pressure tell us?

JA Kieser,* MG Farland,* H Jack,* M Farella,* Y Wang,† O Rohrle‡

*Sir John Walsh Research Institute, Faculty of Dentistry, University of Otago, Dunedin, New Zealand.
†Auckland Bioengineering Institute, University of Auckland, Auckland, New Zealand.
‡Cluster of Excellence for Simulation Technology, Universitat Stuttgart, Stuttgart, Germany.

ABSTRACT

Tongue pressure data taken from healthy subjects during normal oral activities such as mastication, speech and swallowing are providing us with new ways of understanding the role of the tongue in craniofacial growth and function. It has long been recognized that the sequential contact between the tongue and the palate plays a crucial role in the oropharyngeal phase of swallowing. However, because the focus of most research on intraoral pressure has been on the generation of *positive* pressure by the tongue on the hard palate and teeth, generation and coordination of *absolute* intraoral pressures and regional pressure gradients has remained unexplored. Ongoing research in our laboratory has uncovered highly variable individual pressure patterns during swallowing, which can nonetheless be divided into four stages: *preparatory, primary propulsive, intermediate* and *terminal*. These stages may further be sub-classified according to pressure patterns generated at the individual level as *tipper* or *dipper* patterns in the preparatory stage, *roller* or *slapper* in the primary propulsive and *monophasic* or *biphasic* during the intermediate stage. Interestingly, while an increase in bolus viscosity can result in significant changes to pressure patterns in some individuals, it has little effect in others. Highly individual responses to increased viscosity are also observed with swallowing duration. The above, together with other findings, have important implications for our understanding of the aetiology of widely differing conditions such as protrusive and retrusive malocclusions, dysphagia and sleep apnoea, as well as the development of novel food products.

Keywords: Swallowing, tongue, intraoral pressure, dysphagia, tongue thrust.

Abbreviations and acronyms: CPG = central pattern generator; EMG = electromyography; IOPI = Iowa Oral Performance Instrument; MRI = magnetic resonance imaging.

INTRODUCTION

Researchers from a large range of backgrounds have stressed the role of tongue movements in an equally wide range of functional and developmental fields, including craniofacial development, mastication, swallowing, texture appreciation, dysphagia and phonetics. Food acquisition and ingestion are basic physiological functions of all higher life forms and represent the sole means by which non-gaseous material can be extracted and ingested from the environment. Ingestion by swallowing is a highly complex process involving voluntary and reflexive motor control, intraoral sensory processing, salivation and visceral regulation.[1] Towards the end of mastication, the tongue plays a critical role in organizing the bolus and subsequently propelling it towards the oesophagus. The physical and gustative properties of the bolus initiate sensory messages to the masticatory and swallowing central pattern generators (CPGs) and once the bolus has acquired desirable rheological, surface and particle size characteristics, a swallow threshold is crossed and the bolus passes from the mouth.[2–4]

Disruption of normal swallowing, referred to as dysphagia, is frequently associated with neurological disorders such as cerebrovascular accidents, cerebral palsy and Parkinson's disease.[5,6] Dysphagia can prove fatal and often requires extensive rehabilitation. Additionally, the literature is replete with descriptions of the possible relationships between abnormal swallowing patterns and craniofacial development.[7–10] Yet despite its obvious clinical importance, it remains unclear what the exact role of the tongue is during swallowing.

This article will provide an overview of the development of the role of the tongue in swallowing, the anatomy of the tongue, tongue pressure measurement and modelling, and normal human swallowing patterns.

Early development of swallowing

The process of swallowing is initiated early during the foetal period (week 9 to birth).[11] It is during this time that three distinct anatomical regions, the oral cavity, pharynx and oesophagus begin to coordinate their functions. The ontogeny of the highly integrated and complex sensorimotor system required for swallowing is initiated during this period and continues to develop after birth.[12,13] Foetal ultrasound studies have shown that non-nutritive swallowing is present in most foetuses by week 15 of gestation, with forward tongue thrusting and cupping reported at 28 weeks gestation.[14] Foetal swallowing is thought to be critical in the regulation and maintenance of amniotic fluid volume and composition, recirculation of solutes from the foetal environment and the maturation of the foetal craniofacial region.[15]

While infants delivered near-term are typically total oral feeders, the course to coordinated sucking, swallowing, and breathing, is different in preterm infants delivered at shorter gestation.[16] Preterm infants tend to be neurologically immature and unable to perform coordinated rhythmic sequences that involve complex integration of anatomic structures such as the cheeks and lips, jaw, tongue, palate and pharynx. Miller and Kang[17] reported that lingual activity patterns on ultrasound showed significantly greater displacements and excursions when preterm infants were sucking for nutritive purposes as compared to non-nutritive sucking on a pacifier. The latter is characterized by organized bursts of lingual movement separated by brief pauses in motor activity[18] and these are thought to represent ontogenetic maturation of morphologic and neurological systems.[19] Recent evidence suggests that the subsequent maturation of swallowing from preterm to term and beyond is characterized by increased swallowing rates, longer sucking bursts and larger volumes per suck.[20–22]

Several attempts have been made to understand how the infantile anatomy of oral and facial structures defines and facilitates nipple feeding. The mandible is disproportionately small compared to the skull and the tongue fills the oral cavity, thus restricting the range of tongue movements. Moreover, the fat pads in the cheeks narrow the oral cavity in the lateral dimension.[23,24] It has been suggested that this anatomical configuration supports the act of suckling, defined as backward-forward tongue movement to extract liquid from the breast or bottle.[11]

Two major factors now influence the ontogeny of swallowing; firstly, the eruption of teeth and secondly, the introduction of spoon-feeding. Because the developing dentition increasingly assists in processing food, the teeth play a crucial role as sensory receptors during biting and chewing.[11] Additionally, the introduction of spoon-feeding initiates a number of transitions that eventually terminate in adult self-feeding ability.[24] These are accompanied by concomitant achievement of respiratory muscle integration.[25] Children from 1 year upwards continue to refine their oral skills and expand the kinds of foods they accept, thus becoming increasingly efficient at chewing and swallowing foods that require more extensive oral manipulation. Their oral processing development is essentially geared to the table food consumed by their family and peers.

Functional anatomy of the tongue

For an understanding of tongue function during swallowing we need firstly to consider the complex architecture of that organ. Essentially, there are two types of tongue muscles – extrinsic and intrinsic. The former have a highly complex, three-dimensional arrangement (Fig. 1). In addition to the longitudinal muscle, which reaches from the tip of the tongue posteriorly to insert into the hyoid bone, transverse and vertical muscle fibres form a muscular wall that envelops the longitudinal muscle on either side of the tongue (Fig. 2). Saito and Itoh[26] have demonstrated the highly interwoven microarchitecture of the intrinsic tongue muscles, prompting the suggestion that this forms the structural basis for the hydrostatic deformation, essential to the tongue's numerous functions.[27,28]

Numerous authors have detailed the extent and spatial relationships of the extrinsic and intrinsic muscles of the tongue.[29–31] The anterior two-thirds of the tongue is a bilateral structure, in keeping with its embryonic derivation from two lingual processes of the first branchial arch,[32] hence the extrinsic muscles do not cross the midline (Fig. 1).

A significant challenge to swallowing research has been to understand how these muscles act during tongue function. Because the tongue is surrounded by teeth and jaws, its movements cannot easily be

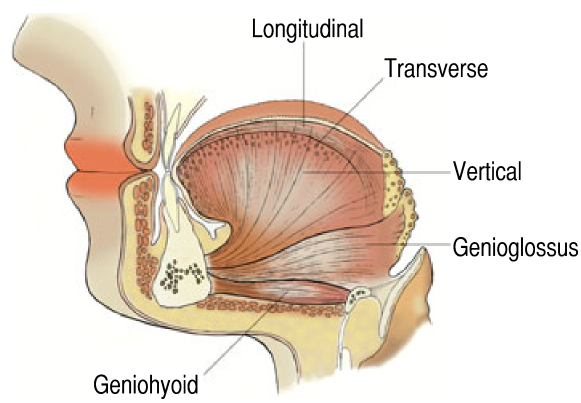

Fig. 1 Gross anatomy of the tongue as seen from the midline. In addition to extrinsic muscles, three sets of intrinsic muscles (longitudinal, transverse and vertical) intertwine beneath the dorsal surface of the tongue.

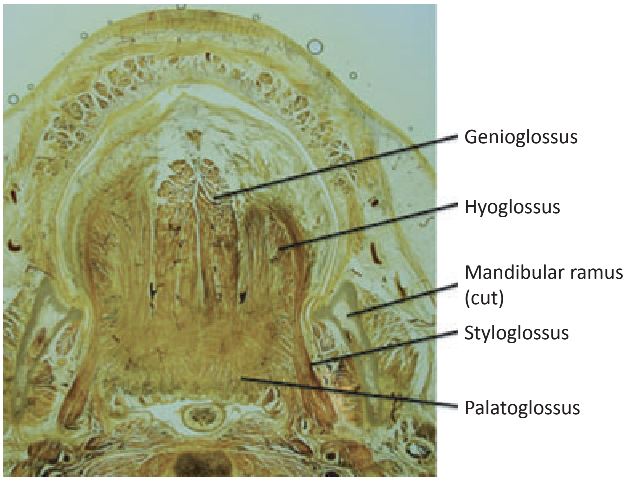

Fig. 2 Complex arrangement of the extrinsic tongue muscles as seen in an ultra-thin cadaveric section at the occlusal plane level. While genioglossus and hyoglossus sweep upwards into the body of the tongue, styloglossus and palatoglossus enter the tongue from above.

observed, and needs to be inferred. One of the most prevalent theories is that the tongue is a muscular-hydrostat, in other words, it functions in much the same way as a trunk or a tentacle. These are complex, solely muscular, biomechanical systems that generate movement and deformation through the incompressible nature of muscle tissue, as well as synergistic activation of orthogonally oriented muscle fibres,[28] rather than the support of bony structures.[33] Kier and Smith[33] have advanced a biomechanical interpretation of such movements where longitudinal muscle fibres, arranged at the outer margins of the organ to create bending movements through unilateral recruitment, while perpendicular muscle fibres create longitudinal elongation by reducing the transverse cross-sectional area of the organ (as in squeezing a balloon). Unfortunately, the way in which tongue muscle contractions are coordinated to achieve movement and shape deformation, remains unclear.

Recent advances in computational modelling allow for more detailed studies of particular patterns of muscle recruitment in the tongue. In particular the combination of experimental data and anatomical-realistic computational tongue models provide a powerful framework to analyse existing hypotheses on muscle fibres' contributions for specific movements. To do so, three-dimensional continuum-mechanical models of the tongue, including a detailed description of the muscle fibre distributions, are required.

As far as modelling (skeletal) muscles are concerned, most research focuses on representing muscles as mass-less springs and neglecting the effects of the surrounding soft and hard tissues.[34–36] Modelling the deformations of a three-dimensional muscular-hydrostat requires a complex mechanical modelling approach. Essentially, what this means is that because tissue mechanics are highly complex, and because it is impossible to derive a single equation to model all aspects of tissue behaviour under any type of loading regime, we need to balance the need to accurately model tissue behaviour with the need to have a simple equation for such modelling. Since three-dimensional continuum-mechanical models of (skeletal) muscles are computationally challenging and expensive, they are less common than discrete multi-body methods. Nevertheless, three-dimensional continuum-mechanical models for skeletal muscles and the tongue have been developed and used for more than two decades.[37–40] Major advantages of such models are they can interact with surrounding tissues and can be further extended to take into account the underlying electro-physiological properties like muscle fibre recruitment, cross-bridge dynamics, or calcium cycling.[41] The main difference between modelling tongue mechanics and skeletal muscle mechanics is the tongue's complex distribution of interlacing muscle fibre groups. However, the fibre distribution cannot be simplified or ignored. It is well known that the complex muscle fibre architecture plays a crucial role in tongue mechanics.[42] Hence, all existing tongue models appeal to a more or less detailed description of the muscle fibre distributions.[39,40,43–45] Figure 3 depicts the different muscle fibre groups of the Wang *et al*. model.[40]

The true advantages of computational models emerge in scenarios where no or only incomplete experimental data can be obtained. Analysis of the tongue's function can essentially only be determined by fine-wire or needle electromyography (EMG). However, computational models can qualitatively determine the activity of specific muscle fibre groups by solving an inverse problem, i.e. by using experimentally determined motion trajectories of (parts of) the tongue as input to compute the respective muscle fibre group activities. The challenge is to obtain motion trajectories of the tongue while performing

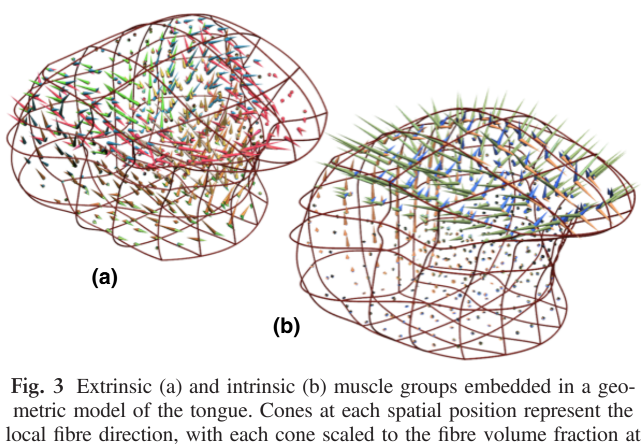

Fig. 3 Extrinsic (a) and intrinsic (b) muscle groups embedded in a geometric model of the tongue. Cones at each spatial position represent the local fibre direction, with each cone scaled to the fibre volume fraction at that locus.

specific tasks, e.g. swallowing or speech production. Ways of doing this include magnetic resonance imaging (MRI)[46] or electromagnetic articulographs to determine the motion of (parts of) the tongue within the oral cavity. More recently, articulographs previously employed to analyse speech[47–49] or mastication,[50] have been used. A major drawback, the lack of knowledge on how to distribute the sensors on the tongue surface to obtain robust sensor trajectories that can be used in inverse simulations, has recently been overcome by Wang *et al.*,[40] who used computational modelling. This has stimulated our most recent research in combining tagged MRI data[46] with an anatomical-detailed computational model of the tongue. Results suggest that tongue propulsion is driven by the co-contraction of the hyoglossus, the mylohyoid and the styloglossus muscles fibre groups. As these *in silico* experiments[51,52] included contact between the tongue and the bony structures of the oral cavity, i.e. the teeth and the hard palate, these simulations are now being utilized for further investigating intraoral pressures during swallowing.

Intraoral pressures

Despite significant advances in technology and imaging, there remains an incomplete understanding of how the tongue transports the bolus to the pharynx during the oral stage of swallowing. Fundamental to this process is the application of a force of the appropriate magnitude and timing. This not only initiates, but also maintains, bolus movement at an appropriate speed and direction. Currently, there are very limited data on the generation and coordination of absolute intraoral pressures and resultant pressure gradients.

In 1990, Dodds *et al.*,[53] published a paper in which they described the radiographic positioning of the liquid bolus using sagittal and coronal views of the oral cavity. They noted that during the oral phase of swallowing, the bolus is located within a spoon-like depression of the mid-tongue. Concurrently the posterior tongue is elevated and a seal is formed with the soft palate to prevent premature entry of the bolus into the unprepared pharynx. The anterior two-thirds of the tongue now elevates and rolls back posteriorly in a piston like manner, effectively forcing the bolus into the oropharynx. This study was purely descriptive of tongue shape and bolus position and clearly did not factor in the absolute pressures involved in this process.

Early attempts at pressure recording involved the use of manometers and strain gauge pressure transducers.[54] A more recent development saw the introduction of the Iowa Oral Performance Instrument (IOPI), a hand-held single intraoral air filled bulb, connected to a digital pressure recorder.[55,56] Two of the major drawbacks of this approach are the inability of assessing pressure changes during function, and the recording of positive pressure only.

In an effort to increase the accuracy of the regional distribution of linguo-palatal pressures, Ono *et al.*[57] and Hori *et al.*[58] introduced a custom-fitted palatal plate fitted with pressure sensors. This gave clear information about the order, magnitude, and direction of linguo-palatal forces over the hard palate during water swallowing. They found that coordination of the tongue contacting the hard palate typically showed a sequential pattern from the anterior-median, anterior-lateral, posterio-lateral and posterio-median respectively. However, their device was only able to measure positive pressures and as such, failed to give a complete description of intraoral pressures generated during swallowing.

Given observations on the relationship between tongue movements and the aetiology of malocclusion,[59–62] and the assumed importance of tongue function in the generation of a zone of equilibrium and its role in denture stabilization[63,64] we decided to investigate the patterns of intraoral pressure generated during swallowing. This has hinged on the development of a rigid appliance, to which pressure sensors, capable of measuring absolute pressure, were attached.[65–68] Briefly, our results show that participants produce personally distinct and consistent 'signature' pressure patterns, and that these patterns are retained during different types of swallow. Our observations are consistent with those by Shaker *et al.*[69] who documented wide inter-subject pressure variability, with between-individual differences appearing to be most notable at the front of the palate. These findings suggest there is a range of bolus-holding strategies and individuals may exercise a considerable degree of voluntary control over their pattern of tongue movement during swallowing.

Features of a typical swallow

Based on the results of our studies, we have been able to identify three different basic swallowing patterns, classified heuristically as: *Type I, squeezer* – characterized by a closely timed front-to-back progression of peak pressures (much like squeezing a toothpaste tube); *Type II, slider* – characterized by a relatively effortless and extended swallow; and *Type III, slapper* – characterized by large and defined positive and negative pressure fluctuations with a greater amplitude range than the first two types.

Because of the marked inter-subject variability in pressure patterns complicating swallow analysis, we developed an overlay of the pressure profiles of multiple individuals on a fixed readily identifiable point within each swallow. This reduced the basic swallow

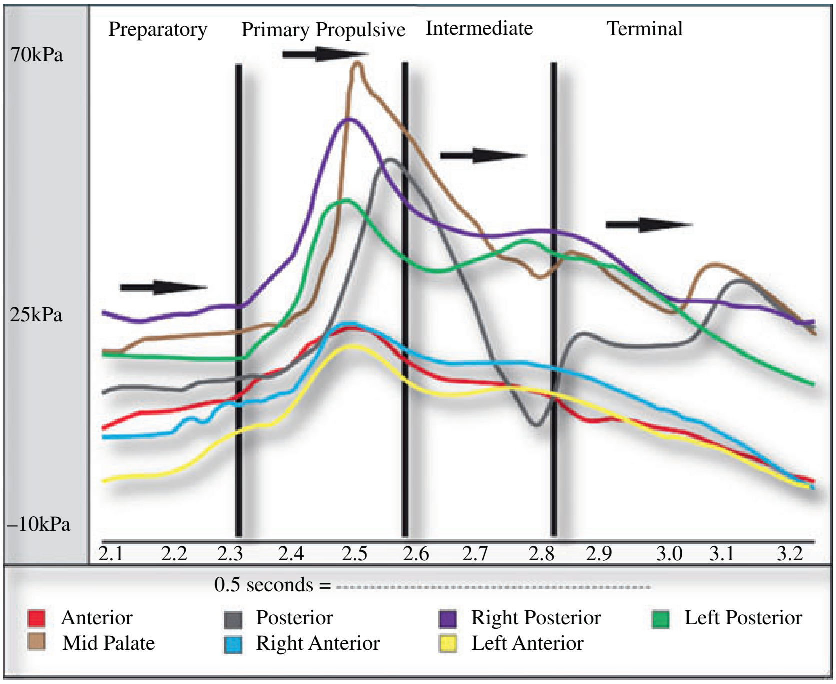

Fig. 4 The four basic patterns of the oral phase of swallowing: (1) *preparation* and containment of the bolus; (2) *primary pressure* wave; (3) *intermediate pressure* gradient from the anterior and lateral margins of the tongue towards the midline, followed by a sequential, secondary rostro-caudal midline pressure wave; and (4) *terminal return* to pre-swallowing pressure.

pattern of the oral phase into four stages (Fig. 4): *Stage 1 preparation* – characterized by containment of the bolus and is highly variable in terms of pressure amplitude and duration; *Stage 2 primary pressure wave* – a highly stereotyped primary pressure wave which has a defined sequential onset and offset of pressure. It begins with a sudden rise of pressure in the anterior of the mouth and terminates after a peak is reached at the posterior midline; *Stage 3 intermediate stage* – when present it is characterized by a fall in pressure as measured at the anterior and lateral parts of the mouth, while the midpalatal and posterior midline is still experiencing the primary pressure wave. These then begin to rise in pressure as the midpalate and posterior midline pressures decline, resulting in a relative pressure gradient from the anterior and lateral margins of the tongue towards the midline, followed by a sequential, secondary rostro-caudal midline pressure wave with the same pattern of onset as the primary wave; and *Stage 4 terminal phase* – where the pressures at all sites return to pre-swallowing levels.

Intraoral pressure and the lower incisor teeth

Recent research on swallowing has focused on the relationship between the tongue and the hard palate; however, little is known about the pressures generated on the lower teeth. To further investigate this concept, we used a custom-made clear acrylic stent to house four pressure sensors, to record pressures at the midline and canine on both the labial and lingual tooth surfaces.

During each saliva swallow light labial pressure (<20 g/cm^2) was recorded for the majority of subjects, which was in agreement with the findings of earlier research.[70] The pressures generated on the lingual surface were approximately twice as heavy as those on the labial surface. Interestingly, the mean pressures recorded on the lingual surfaces were considerably lower than pressures reported by previous authors.[71,72] This could of course be due to differences in measurement techniques, as these studies relied on strain gauges or hydraulic pressure systems.

The pattern of pressure generated on the lingual surfaces was more complex than on the labial surface. These findings are highly suggestive of the more complex nature of the muscular activity needed for the tongue to transport the bolus, whereas the lip only requires a brief contraction to ensure that anterior oral seal is maintained. This question remains the focus of our research.

CONCLUSIONS

The results outlined above have contributed to our understanding of the mechanics of swallowing, mastication and also the role of these activities in the development and eventual positioning of the dentition. In the main, they emphasize the huge level of inter-individual variation in the behaviour of the tongue during normal function. This research will serve as a base for future studies into the effects of clinical insertion of oral appliances or expansion of the maxillary arch. For instance, while severe malocclusions may be treated with a combination of orthodontics and surgery, there is currently no information available on changes in tongue function during swallowing following surgico-orthodontic therapy. Additionally, it is known that a number of neuromuscular conditions such as Parkinson's and Huntington's diseases, muscular dystrophy and cerebral palsy affect the tongue's motor functions. Yet little is known about the exact nature of these negative impacts on the tongue. Finally, despite numerous studies documenting orofacial dysfunction, little is known about the precise interaction of movement between tongue and lips during phonation and deglutition. Hence, evidence-based treatment of dyskinesia of the lips and tongue will have to await the results of further studies.

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DISCLOSURE

The authors have no conflicts of interest to declare.

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Address for correspondence:
Professor Jules Kieser
Director, Sir John Walsh Research Institute
Faculty of Dentistry
University of Otago
Dunedin
New Zealand
Email: jules.kieser@otago.ac.nz

