

ABSTRACT

Title of Dissertation: TONGUE-PALATE INTERACTION IN DISCRETE
AND SEQUENTIAL SWALLOWING

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Historically, swallowing motor control was thought to involve a central mechanism that generated patterned responses with little use of sensory input. Although increasing evidence of peripheral modulation has altered this concept, our knowledge about the flexibility in deglutitive motor control and performance is incomplete. This study sought to gain a better understanding by examining lingual motor strategies in light of changing bolus properties (volume, consistency) and task demands (discrete vs. sequential swallowing). Specifically, the timing and patterns of tongue-palate contact and the associated changes in tongue shape and action were examined in five normal adults using simultaneous electropalatography (EPG) and ultrasound. Tasks for discrete swallowing included 5 and 30 cc of water, 5 and 30 cc of gelatin, and saliva. Tasks for sequential swallowing involved drinking 200 cc of water at normal and fast rates. Two analysis schemes were used to make timing and percent-contact measurements: segmentation of

the EPG time series into four stages (prepropulsion, propulsion, full contact, withdrawal), and compartmentalization of the pseudopalate into six bins (front, central, back, lateral, medial, midline). Results showed little variation in contact pattern as a function of bolus property or subject, suggesting considerable stereotypy in lingual motor strategies for movement sequencing. However, unlike the conventional description, tongue-palate contact during propulsion was multidimensional with two distinct degrees of freedom in the front-to-back and the lateral-to-midline continua. Significant ($p < .01$) timing differences were found in that larger and thinner boluses were propelled faster than smaller and thicker ones, and dry swallows had longer full contact than water. For sequential swallowing during continuous drinking, the tongue used faster movement speed and overlapping gestures to meet the task demands, while propulsive contact pattern remained invariant. Thus, the change was not in motor strategies per se but in the timing coordination of the “drink” and “swallow” sequences. A 3-D model of oral lingual action for swallowing was proposed. Clinical implications were discussed. In sum, results of this study support the theory that swallowing motor control includes a peripheral mechanism capable of modulating centrally generated responses, and that the deglutitive motor program has both invariant and variant parameters.

TONGUE-PALATE INTERACTION
IN DISCRETE AND SEQUENTIAL SWALLOWING

by

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DEDICATION

To my husband, Dr. Peter H. Fishman,
to my mother, Mrs. Pa-Chun Chi,
and to my late father, Mr. Wan-Te Chi.

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CHAPTER I. INTRODUCTION

Research Rationale: An Overview

The tongue has long been recognized as the "principal mobile agent" (Bosma, 1957, p. 281) or the "primary manipulator" (Kennedy & Kent, 1988, p. 26) for oral and oropharyngeal transport of the bolus during swallowing. In recent years, there has been empirical evidence that oropharyngeal bolus propulsion is the direct result of tongue pumping action supplemented by pharyngoesophageal pressure change (Cerenko, McConnel, & Jackson, 1989; McConnel, 1988). The tongue's vital role in enacting swallow-related physiological events is further revealed in clinical reports that poor lingual control in neurologic and/or postsurgical oral cancer patients is a major cause of swallowing dysfunction (Hirano et al., 1992; Logemann, 1983).

Structurally as well as functionally, the tongue possesses diverse and unique properties. It is capable of performing a wide range of movements with multiple degrees of freedom. Such capability is based on the remarkable muscular-hydrostatic characteristic of its anatomic composition (Kier & Smith, 1985) and gained from interacting with other structures of the oral cavity, especially the hard palate (Stone, 1991, 1995). Tongue-palate interaction during swallowing conceivably serves critical roles in bolus formation, containment, and transport, and in the generation of pressure gradients

and force necessary for proper propulsion. However, our understanding of such interaction is by far incomplete.

The potential degrees of freedom in tongue movement suggests enormous potential flexibility in lingual motor control. It is commonly known that flexibility in control and performance is characteristic of motor systems for skilled actions. Indeed, the tongue's flexibility, as reflected in complex movement variations, is well documented for speech production (Stone, 1991, 1995). In contrast, little information is available about the extent of flexibility in deglutitive lingual motor control. Although there are many descriptive accounts of how the tongue moves during swallowing (Hamlet, Stone, & Shawker, 1988; Shawker, Sonies, Hall, & Baum, 1984; Shawker, Sonies, Stone, & Baum, 1983; Stone & Shawker, 1986), minimal data exist on deglutitive lingual motor strategies, or on how tongue movements adapt to changes in bolus properties and swallowing task demands. Only a few investigations, to date, have specifically examined the relation between bolus volume and lingual action during oral and pharyngeal transport of food (Hamlet, 1989; Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993; Martin, 1991).

One can only speculate that the paucity of data on deglutitive lingual motor flexibility is perhaps because swallowing is not a highly skilled motor behavior. Another reason could be that historically the theory of swallowing motor program was based on a central mechanism thought to make little use of peripheral information (see Miller, 1982). The modern concept of swallowing motor programming, however, does acknowledge the role of sensory modulation. Above all, a voluntary initial oral phase is as much a part of the complex swallowing process as the reflexive pharyngeal and esophageal phases. The

new evidence that, for example, larger boluses do induce more vigorous propulsive action from the tongue (Kahrilas et al., 1993) supports the notion that deglutitive lingual motor control has more flexibility/adaptability than previously believed. On the other hand, because of the biomechanical constraints of the oral cavity, the unidirectionality of the bolus translocation in oral transport, and the stringent requirement for airway protection during swallowing, it is theoretically implausible that for deglutition purposes, the tongue needs the same high degree of flexibility as the motor systems for expert skills such as playing a musical instrument with the hands. An investigation aiming at better understanding the extent of deglutitive lingual motor flexibility and at identifying variable versus invariant motor program parameters has, therefore, theoretical justification.

From the clinical perspective, improved knowledge on deglutitive lingual motor flexibility would have a positive impact on patient management. For decades, swallowing clinicians and researchers have continued the quest for a sound theoretical foundation on which to build effective clinical evaluation and treatment protocols. Information on the flexibility and/or invariance of lingual motor performance would contribute to this theoretical base, provide a physiological or kinematic framework for deriving explanations for dysphagia symptoms related to lingual motility deficits, and offer insights into appropriate management strategies.

The present study examined an important area--linguopalatal interaction during swallowing--where little research existed. Specifically, efforts were made to delineate the temporal and spatial details of deglutitive tongue-palate contact and to address lingual kinematic issues concerning response modulations due to changing bolus properties

(volume and consistency) and task demands (discrete swallowing vs. sequential swallowing at normal and fast rates). The underlying motive was that by exploring the effects of boluses and tasks on specific parameters of tongue action during swallowing, a better understanding would be gained of the flexibility in deglutitive lingual motor performance and of the swallowing motor program in general.

Review of Literature

The Tongue: Composition, Motor Diversity, and Innervation

The tongue is one of the most complex structures in the oral sensorimotor system. It is remarkably diverse in function and unique in biomechanical properties. In humans, the tongue participates in a great variety of oromotor behaviors, ranging from primitive (e.g., suckling), to stereotyped (e.g., swallowing), to highly skilled (e.g., speech). Its intrinsic anatomy is characterized by a mesh of vertical, transverse, and longitudinal muscle fibers, fat, and connective tissue with no bones or joints. Its extrinsic muscles--genioglossus, hyoglossus, styloglossus, and palatoglossus--all have bony origins but soft-tissue insertions (see Abd-el-Malek, 1939, Hiatt & Gartner, 1987, and Miyawaki, 1974). An organ composed primarily of muscles is constant in its volume due to the fact that a muscle is an incompressible liquid. Thus, a physical change of the tongue in one dimension is naturally compensated for by a change in at least one other dimension (Kier & Smith, 1985; Smith & Kier, 1989). These physical and biomechanical characteristics suggest enormous potential flexibility in movement.

The intrinsic muscles produce diverse shape changes in the tongue. Through contractions of its vertical and transverse muscles, the tongue lengthens, flattens, and widens. Through contractions of its superior and inferior longitudinal muscles either singularly or together, the tongue shortens and compresses, and its tip elevates or depresses. Differentially combined activations of these muscles accomplish still other kinematic goals or shape alterations such as bending, curling, stiffening, and leverage (Stone, 1990, 1991).

Actions of the extrinsic muscles add further complexity to the tongue's movement repertoire. The genioglossus protrudes the tongue, the hyoglossus retracts and depresses it, the styloglossus retracts and elevates it, and the palatoglossus elevates the base of the tongue (Hiatt & Gartner, 1987). Moreover, because of their insertions into the lateral aspects of the tongue and the intermingling of fibers, the styloglossus and hyoglossus can cause medial concavity or convexity in tongue shape, respectively. Because of its midsagittal insertion into the tongue, when coactivated with the styloglossus, the genioglossus can further deepen the central groove (Stone, 1991).

It must be emphasized that the lingual muscle groups do not function independently. The decussations of the intrinsic and extrinsic fibers mandate concerted movement efforts. It is only by intricately coordinated activities of several muscles as well as interactions with the other structures of the vocal tract that the tongue accomplished complex movements with multiple degrees of freedom (Hiatt & Gartner, 1987; Lowe, 1981; Stone, 1991).

Like any organ associated with diverse activity patterns, the tongue has an intricate neural control system with elements extending from the periphery through the brainstem to the cortex. At the periphery, motor innervation to the lingual musculature is supplied by fibers of the hypoglossal nerve (cranial nerve XII: for all except palatoglossus) and the pharyngeal plexus (derived from cranial nerves IX, X, and XI: for palatoglossus). In addition, the tongue is richly endowed with somatosensory and proprioceptive innervations (Bowman, 1968; Cooper, 1953; Fitzgerald & Sachithanandan, 1979; Landgren & Olsson, 1982; Lowe, 1981, 1984; Porter, 1966). At the brainstem level, the hypoglossal nucleus contains topographical representations for different lingual muscles, and receives afferent projections directly from the nucleus tractus solitarius, the trigeminal spinal and mesencephalic nuclei, and indirectly from the glossopharyngeal and vagus nerves (see Lowe 1981, 1984 for reviews). A recent electrophysiological study has confirmed that tactile and gustatory input to the posterior tongue is received in specific regions in the nucleus tractus solitarius (Halsell, Travers, & Travers, 1993). In humans and nonhuman primates, muscle-spindle afferents from the tongue are also sent to the hypoglossal nucleus through the hypoglossal nerve (Bowman & Combs, 1968, 1969; Fitzgerald & Sachithanandan, 1979). At the cortical level, as recent neurophysiological evidence shows, the tongue region of the primary motor cortex (tongue-MI) contains discrete efferent zones, and different changes in tongue shape and position are due to recruitment of different tongue-MI sites (Murray & Sessle, 1992a, 1992b, 1992c). The data cited here suggest several potential neural mechanisms through which peripheral

sensory input of various types may exert influences on the tongue and elicit adaptive lingual motor responses at the brainstem and the cortical levels during a variety of oromotor behaviors including swallowing.

Swallowing: Conceptual Framework for Tongue Kinematics

Neural Organization of Swallowing

Swallowing, "the transport of a bolus, liquid or solid, from the mouth to the stomach" (Hendrix, 1980, p. 1322), is one of the most basic and stereotyped behaviors of the animal world. All living organisms must ingest food and absorb nutrients for life sustenance purposes. Even in humans, swallowing is performed without effort or attention and with a considerable degree of semiautomaticity. On the other hand, it is unquestionably a motor sequence of extraordinary complexity, requiring the coordination of a great number of muscles, several cranial nerves, and the interaction of the respiratory and alimentary tracts. This complexity can be overlooked because of its seeming effortless and semiautomated processes. To represent swallowing accurately, the simplicity and complexity of the behavior must be reconciled.

Neural control theories. Two theories have been proposed to account for the regulation of the neuromuscular sequence of swallowing, namely, the reflex chain theory (Dodds, 1988; Dodds, Stewart, & Logemann, 1990; Miller, 1982) and the central pattern generator theory (Dodds, 1988; Dodds et al., 1990; Doty, 1968; Dubner et al., 1978; Miller, 1982). The reflex chain hypothesis proposes that swallowing is the motor

manifestation of a chain of linked reflexes. As the bolus is passed through the oral cavity, it stimulates intraoral sensory receptors, evoking the initial oromotor responses.

Subsequently, as the bolus continues its path through the pharynx and esophagus, receptors are stimulated along the way, thereby eliciting series of muscle contractions from one phase to the next. Inherent to this theory is the notion that peripheral sensory input is crucial in the initiation and modification of the swallowing motor output.

The central pattern generator (CPG) theory for swallowing is a “branch” of that hypothesized in general motor physiology. A CPG is a network of neurons responsible for generating the particular pattern of a motor sequence under experimentally induced conditions of complete deafferentation (Grillner & Wallen, 1985). Thus, conceptually, a hallmark feature of central pattern generators is their independence from peripheral sensory influences. In other words, once initiated, the entire sequence of muscle contractions associated with swallowing will course through a series of patterned neuromuscular responses with little peripheral modulation (Doty, 1968; Dubner et al., 1978; Sessle & Henry, 1989). Supporting evidence for this theory was derived from animal studies in which experimentally induced sensory deprivation did not alter the swallowing motor output or the activity patterns of swallow-related neurons (Car & Amri, 1987; Doty & Bosma, 1956; Doty, Richmond, & Storey, 1967; Kessler & Jean, 1985; Miller, 1972b; Sumi, 1964, 1970b).

The CPG hypothesis has gained emphasis over the years. However, as that occurred in general motor physiology¹, the theory also has undergone scrutiny. Increasing empirical evidence indicates that many of the swallowing motor components can indeed be modified by sensory input (Dubner et al., 1978; Jean, 1984b, 1990; Miller, 1982, 1986; Sessle & Henry, 1989). As a result, a revised theory proposes that swallowing is likely the efferent output of centrally orchestrated motor programs, but the generation of such programs is greatly influenced, if not routinely regulated, by peripheral feedback.

The precise mechanisms of interactions between peripheral sensory input and the swallowing motor programs remain unknown. It appears that one means of elucidating this issue in normal humans where central electrophysiological experimentation is impossible is to critically examine specific deglutitive motor elements while varying the properties of the material swallowed or the demands of the swallowing tasks performed.

Neural control elements. Despite the different theories, a number of basic elements are known to participate in the swallowing neural circuitry in mammals. These include the peripheral receptors, primary afferents with their sensory ganglia, medullary control neurons, motoneurons and their efferent fibers, and specific muscles

¹A large body of empirical evidence exists today, indicating a high degree of sensory regulation in the motor systems of locomotion, flight, respiration, and mastication in animals (for review, see Pearson, 1987 and Rossignol, Lund, & Drew, 1988). In speech research, there is also evidence for sensory influences on the timing and coordination of labial, mandibular, lingual, and laryngeal movements (see Abbs & Connor, 1991). As a result, the concept of central pattern generator has undergone revision. Today, the prevalent view in general motor physiology is that peripheral afferent signals are basic elements in the pattern-generating networks under normal operating conditions in intact nervous systems.

(Doty, 1968; Jean, 1984a; Miller, 1982). In addition, there are subcortical and cortical regions capable of modulating swallowing (Hockman, Bieger, & Weerasuriya, 1979; Martin & Sessle, 1993; Miller, 1982).

Physiological studies (Miller & Sherrington, 1916; Pommerenke, 1928; Sinclair, 1970; see Miller, 1982 for review) have identified a variety of oral, oropharyngeal, and hypopharyngeal sites sensitive to peripheral swallowing elicitation. Dorsal surface of the tongue is among these sites, the others being the soft palate, uvula, faucial pillars, valleculae, epiglottis, posterior pharyngeal wall, and the cricopharyngeal vicinity. The responsible receptors in these areas include mechanoreceptors (especially the slowly adapting type, cf. Dubner, Dubner, Sessle, & Storey, 1978), those sensitive to liquid stimulation (Shingai & Shimada, 1976; Storey, 1968), taste buds and chemosensory endings (see Dubner et al., 1978 and Miller, 1982), and thermosensitive terminals (see Chi-Fishman, Capra, & McCall, 1994). Many of the above-cited studies emphasize that successful swallow initiation depended on the properties of the stimuli applied and the size of the area stimulated. That is, peripheral sensory input must be of a specific pattern or strength, and a broad span of mucosal surfaces encompassing a sufficiently large population of sensory receptors must be activated. (For a review of oral receptor morphology and physiology, see Capra, 1995.)

Miller and Sherrington (1916), in particular, reported that in order for a bolus of meat or moist cotton (1 cc in volume), being dragged through the oral cavity with a string attached, to even inconsistently trigger a swallow in decerebrated cats, it had to make contact with "most of the whole circumference of the faucial opening" (p. 157). If a food

bolus alone does not necessarily provide all the impetus needed to trigger a response from the brainstem neurons controlling deglutition, what other factors must be in operation during normal swallowing? The answer may lie in the action of the tongue. Particles of the bolus, with their potentially diverse physical and sensory properties (e.g., volume, texture, taste, temperature), come in random contact with mucosal surfaces during oral preparation as a result of direct tongue action, gravity, or the biomechanical force generated by linguodental, linguopalatal, and linguobuccal interactions (cf. Kennedy & Kent, 1988). The tongue itself, in the process of manipulating, forming, and transporting the bolus, also makes repeated contact with a wide section of intraoral and oropharyngeal mucosa. Therefore, active movements of the tongue and the coupled motion of the bolus certainly have the potential of stimulating multiple intraoral and oropharyngeal receptors including those located on and in the tongue, thereby contributing to the generation of a swallowing response.

The role of the peripheral lingual elements extends beyond swallow elicitation. Through the detection of bolus properties as well as changes in tongue position and contact pressure, lingual mechanoreceptors and proprioceptors conceivably also participate in fostering modification of the preprogrammed swallowing motor responses (Dodds, 1988; Kahrilas, Logemann, Lin, & Ergun, 1992; Porter, 1966).

Most of the mucosal receptors participating in swallowing are supplied by the glossopharyngeal nerve, the trigeminal nerve (e.g., lingual branch for tactile information from the anterior tongue), the superior laryngeal nerve, and branches of the pharyngeal plexus. Several studies (Chi-Fishman et al., 1994; Doty, 1951; Sinclair, 1971;

Weerasuriya, Bieger, & Hockman, 1979) have shown that electrical stimulation of these primary afferents, especially the internal laryngeal branch of the superior laryngeal nerve, can elicit swallowing when the requirements for stimulus-pulse parameters are met.

It is commonly postulated that a “swallowing center” exists bilaterally in the medulla, which consists of two parts: dorsal and ventral. The dorsal part is comprised of neurons of the nucleus tractus solitarius and the adjacent reticular formation (see Miller, 1986 for review). Neuroanatomical tracings have confirmed that these medullary regions, through the glossopharyngeal and superior laryngeal nerves, have close connections with the oral, pharyngeal and laryngeal receptive fields capable of activating swallowing (Altschuler, Bao, Bieger, Hopkins, & Miselis, 1989; Åström, 1953; Beckstead & Norgren, 1979; Contreras, Beckstead, & Norgren, 1982; Cottle, 1964; Hanamori & Smith, 1986; Kerr, 1962; Sweazey & Bradley, 1986). This dorsal network is believed to serve the function of sensory integration and transmission of the integrated signals to the ventral part (Miller, 1972a).

The ventral part of the swallowing center is comprised of neurons located in the ventrolateral reticular formation adjacent to the nucleus ambiguus (Doty, Richmond, & Storey, 1967; Jean, 1984a; Kessler & Jean, 1985; Miller, 1972a, 1982, 1993; Nakayama, Neya, Watanabe, & Tsuchiya, 1974; Neya, Watanabe, & Yamasato, 1974; Roman, 1986). Nerve cells of the ventral network are thought to act as command or switching interneurons and send patterns of outgoing signals to the motoneurons involved.

Motoneurons participating in swallowing are located in the nucleus ambiguus, the trigeminal, facial, vagal and hypoglossal motor nuclei, and the spinal cord segments C1,

C2, and C3 (Amri & Car, 1988; Amri, Car, & Roman, 1990; Dodds et al., 1990; Doty, 1968; Jean, Amri, & Calas, 1983; Kennedy & Kent, 1988; Miller, 1993). Efferent fibers from these nuclei activate the peripheral motor elements to produce swallowing.

The relationship between deglutition and the hypoglossal nucleus is well documented. Past studies have shown that during swallowing the entire pool of hypoglossal motoneurons is activated (Miller, 1982) with generally strong and prolonged discharge spikes (Car & Amri, 1987; Sumi, 1964, 1969b). Electrical stimulation of the glossopharyngeal and the superior laryngeal nerves, while eliciting swallowing, can at the same time trigger excitatory responses from the hypoglossal motoneurons (Lowe, 1978). Although the hypoglossal nucleus is better known for its motor function, its connections with brainstem sensory nuclei (described earlier) cannot be overlooked. Direct afferent projections from the nucleus tractus solitarius--the dorsal swallowing center--to the hypoglossal nucleus represent one of the avenues through which different types of peripheral input (proprioceptive, tactile, pressure, and other types) may affect lingual motoneuron activities during swallowing and induce adaptive motor responses from the tongue.

Numerous oral, pharyngeal, and laryngeal muscles participate in the swallow synergy (see Donner, Bosma, & Robertson, 1985 for review). Electromyography (EMG) data from non-human mammals show intrinsic muscles in the posterior tongue and extrinsic muscles such as the styloglossus and palatoglossus to be among those that start the synergistic swallowing process (Amri, Lamkadem, & Car, 1989; Doty & Bosma, 1956; Kawasaki, Ogura, & Takenouchi, 1964; Lowe & Sessle, 1973, 1974; McNamara &

Moyers, 1973; Miller, 1972b; Miller & Bowman, 1974). Genioglossus, the tongue “protruder”, also exhibits distinct discharge patterns during swallowing (Lowe & Sessle, 1973, 1974; Miller & Bowman, 1974). There is further evidence that styloglossus and hyoglossus, the tongue “retractors”, coactivate with geniohyoid during swallowing to elevate the hyoid bone while the jaw muscles are simultaneously stabilizing the mandible (Amri et al., 1989). EMG data from humans are essentially similar, but with perhaps a stronger indication for intersubject variations (Bole, 1965; Cunningham & Basmajian, 1969; Hrychshyn & Basmajian, 1972; Lowe, Sessle, & Gurza, 1977; Milidonis, Kraus, Segal, & Widmer, 1993; Vitti, Basmajian, Ouellette, Mitchell, Eastman, & Seaborn, 1975).

Increasing empirical and clinical evidence suggests that suprabulbar mechanisms participate in the modulation of swallowing. (For detailed reviews, see Hockman et al., 1979, Martin and Sessle, 1993, and Miller, 1982). A number of cortical and subcortical sites have direct connections with zones of the brainstem swallowing center, as well as swallow-related motor nuclei including the hypoglossal (Bowman & Combs, 1969; Jenny and Saper, 1987; Jürgens, 1976; Kuypers, 1958a, 1958b; Niimi, Kishi, Miki, & Fujita, 1963; Porter, 1967; Rossi & Brodal, 1956; Sirisko, & Sessle, 1983; Walberg, 1957), and thus have the potential to exert descending excitatory or inhibitory influences. Among the documented regions are those in the anterolateral or dorsolateral frontal cortex (Sumi, 1969a, 1972a, Miller & Bowman, 1977; Penfield & Rasmussen, 1950; see Martin & Sessle, 1993 for review of supporting experimental lesion studies and clinical investigations). It has been shown that electrical stimulation to these and other

suprabulbar regions can directly elicit swallowing (Miller, 1920; Miller & Bowman, 1977; Sumi, 1969a, 1972b; Walker & Green, 1938), modify elicited deglutitive responses (Bieger & Hockman, 1976; Kessler & Jean, 1986; Sumi, 1971; Weerasuriya, Bieger, & Hockman, 1979), or evoke corresponding activity in brainstem swallow-related neurons (Amri, Lamkadem, & Car, 1991; Jean & Car, 1979; Sumi, 1970a).

Recent recordings of single neuron activity in the tongue region of the primary motor cortex (MI) showed swallow-related discharges, suggesting that tongue-MI neurons may participate in the initiation and regulation of swallowing (Martin, Murray, & Sessle, 1991; Murray & Sessle, 1990). Interestingly, a considerable number of tongue-MI neurons have been found to have mechanoreceptive fields on the superior surface of the tongue (Martin et al., 1991; Murray & Sessle, 1992a). Since the cortex has a well-established, crucial role in the integration of sensorimotor processes involved in complex voluntary behaviors, cortical regions including the tongue-MI zone conceivably are also important in the mediation of oropharyngeal sensory input for regulating the volitional aspects of deglutition, or in the final adjustment of certain kinematic parameters of swallowing.

Physiological Mechanism of Swallowing

Swallowing is commonly divided into sequential stages or phases based on anatomic landmarks and radiographic characteristics of structural or bolus movement (Dodds et al., 1990; Hendrix, 1980; Logemann, 1983, 1988; Miller, 1982, 1986). The purpose is often for simplicity of description. (See Kennedy and Kent, 1985, 1988 for

reviews of different proposals of swallowing stages.) It is generally agreed that at least three physiological processes exist in a deglutitive sequence, namely, oral, pharyngeal, and esophageal (Miller, 1986).

The oral stage is marked by voluntary division of the ingested material into smaller portions, followed by propulsion of the bolus from the oral cavity into the pharynx. During the pharyngeal stage, the bolus is propelled from the oropharynx through the hypopharynx and upper esophageal sphincter (UES) into the cervical esophagus. The ensuing esophageal stage, completely involuntary, involves the transport of bolus through the body of the esophagus and the lower esophageal sphincter into the stomach. For conciseness, the literature review that follows will focus on the kinematic events occurring after mastication and before esophageal transport. (For reviews of mastication and masticatory lingual kinematics, see Anderson and Matthews, 1976, Hiimeae and Crompton, 1985, Thexton, 1992, and Tomura, Ide, and Kamijo, 1981. For reviews of esophageal physiology, see Kennedy & Kent, 1988 and Nelson and Castell, 1988.)

Oral and oropharyngeal transport of bolus. Most accounts of deglutition describe a momentary, preswallow entrapment of the bolus in a central lingual groove (Bosma, 1957; Dodds et al., 1990; Kennedy & Kent, 1988; Roberts, 1957). This “spoon-like” depression is formed by approximation of the tip, blade, and lateral aspects of the tongue with the perimeter of the hard palate, and by elevation of the posterior tongue against a lowered soft palate. The approximation of the posterior tongue with the velum is said to create a high-pressure zone at the glossopalatal sphincter, serving to prevent premature bolus spillage (Dantas, Dodds, Massey, Shaker, & Cook, 1990). It should be pointed out

that the formation of a spoon-like depression on the tongue surface depends on how the bolus is held in the mouth. There is radiographic evidence that in some individuals the bolus is positioned under rather than on top of the tongue just before a swallow (Dodds, Taylor, Stewart, Kern, Logemann, & Cook, 1989). Obviously, the hold position will affect how the tongue initiates its transport movement.

Typically, oral transport of the bolus begins with elevation of the tongue tip (Abd-el-Malek, 1955; Cleall, 1965; Dodds et al., 1989, 1990; Roberts, 1957) and associated forward movement of the tongue blade (Stone & Shawker, 1986). The anterior, middle, and dorsal portions of the tongue then initiate firm, progressively expanding linguopalatal contact from front to back, and in doing so propel the bolus in the direction of the oropharynx (Dodds et al., 1990; Kennedy & Kent, 1988). As these activities occur, the posterior tongue and tongue base move downward and forward, opening the valleculae and enlarging the oropharynx (Dodds et al., 1990; McConnel, 1988). These movements cause the back of the tongue to assume the configuration of "a vertically steepening ramp" (Shedd, Scatliff, & Kirchner, 1960, p. 847). The original mid-tongue grooving has also progressed posteriorly to continue the channeling of bolus passage (Hamlet, Stone, et al., 1988). From a biomechanical perspective, these lingual motions create changes in oral and oropharyngeal volume, and the resulting pressure gradients likely also contribute to intraoral and oropharyngeal bolus displacement (Kennedy & Kent, 1988; McConnel, 1988).

Several other kinematic events occur sooner or later during oral transport. These include the onset of glottic closure (Shaker, Dodds, Dantas, Hogan, & Arndorfer, 1990),

velar elongation and elevation, and anterior and superior movement of the hyoid bone and larynx (Dodds et al., 1990; Logemann, 1983).

Pharyngeal transport of bolus. As the bolus reaches the oropharynx, the posterior tongue (including the tongue base) rapidly moves backward toward the soft palate and the posterior pharyngeal wall in a piston-like motion, exerting force on the bolus, driving it through the pharynx with the aid of gravity (Dodds et al. 1990; Ku, Ma, McConnel, & Cerenko, 1990; McConnel, 1988; Shedd et al., 1960). This rapid and forceful tongue motion has also been referred to as a “pumping action”² that works in concert with pharyngoesophageal pressure change to accomplish the bolus transport task (Cerenko et al., 1989; McConnel, 1988), or as a "stripping action" that has a close temporal linkage with maximal anterior displacement of the hyoid bone (Hamlet, Jones, Mathog, Bolton, & Patterson, 1988).

Successful pharyngeal bolus transport involves a number of other crucial kinematic events, some of which serve protective in addition to alimentary functions. Forceful contact between the elevated velum and the pharyngeal walls (posterior and lateral) in a sphincteric manner is achieved to prevent nasal regurgitation (Dodds et al., 1990; Shprintzen, Lencione, McCall, & Skolnick, 1974). Complete vocal-cord adduction, hyoid and laryngeal elevation, inversion of the epiglottis, and closure of the vestibule serve the purpose of maximal airway protection (Cook, 1991; Ekberg, 1986; Logemann et al., 1992; Shaker et al., 1990). Relaxation of the upper esophageal sphincter, coupled with

²This “pumping action” is not to be confused with the abnormal, repeated pumping tongue action seen in some patients with dysphagia as an ineffective attempt to transport the bolus through the oral cavity (Logemann, 1983).

shortening of the pharynx as a result of maximal anterosuperior movement of the hyoid bone and the larynx, enables entry of the bolus into the esophagus (Cerenko et al., 1989; Cook, Dodds, Dantas, Massey, et al., 1989; Jacob, Kahrilas, Logemann, Shah, & Ha, 1989; McConnel, 1988; McConnel, Guffin, Cerenko, & Ko, 1992).

There is some controversy over the nature and extent of pharyngeal constrictor contributions to bolus transport. Traditionally, it was held that the constrictors represented an “engulfment” mechanism for the bolus, and that their sequential activation in a caudally-directed progression generated the peristaltic wave responsible for bolus transport through the pharynx (Bosma, 1957; Cook, 1991; Dodds et al., 1990; Ekberg & Borgstrom, 1989; Kennedy & Kent, 1988; Negus, 1948; Palmer, Tanaka, & Siebens, 1988). However, recent manofluorographic evidence has shown that (a) bolus entry into the oropharynx corresponded to anterior movement of the tongue base, (b) subsequent bolus transit through the oropharynx corresponded to posterior movement of the tongue base, (c) continuing transit of the bolus through the hypopharynx and the cervical esophagus corresponded to progressive oropharyngeal pressure increases occurring while the tongue base makes firm contact with the pharyngeal walls, (d) this tongue-base-generated pressure is preceded as well as accompanied by continuous negative pressure in the pharyngoesophageal (PE) segment, and (e) pharyngeal wall contraction and the resultant constriction pressure wave begin as the bolus tail is passing through the cervical esophagus (Cerenko et al., 1989; McConnel, 1988). Given such evidence, the current view is that the tongue-generated pressure and the negative pressure in the PE segment are the principal contributors to pharyngeal bolus transit, and the constrictors contribute

more to post-transport clearance of residue than to the actual food transport (Kahrilas & Logemann, 1993).

Issues in Swallowing Kinematics

While decades of research have improved our understanding of deglutitive neurophysiology and kinesiology, the information is far from complete. One important question that has been only partially addressed is: What peripheral variables affect swallowing kinematics (movement duration, amplitude, velocity, etc.) in normal humans? Two categories of peripheral variables are of interest to the present investigation, namely, bolus properties and task demands. Literature pertaining to these aspects is reviewed below.

Effects of Bolus Properties

Primary properties of the bolus include volume, consistency, taste, and temperature. This study focused on volume and consistency due to the results of pilot work and the pseudopalate constraints discussed in Chapter II. The review below, therefore, includes only studies that addressed the effects of volume and consistency on swallow-related oral, pharyngeal, and laryngeal kinematics.

Volume. A number of studies, using different experimental methods, have shown that bolus volume can influence swallowing kinematics in the pharynx and larynx. For example, graded volume increases (2, 5, 10, and 20 cc in most studies) were found to induce progressively earlier onset of velar elevation (Dantas, Kern, et al., 1990), later onset of pharyngeal contraction (Jacob et al., 1989; Kahrilas et al., 1992), earlier and

longer anterosuperior hyoid movement (Cook, Dodds, Dantas, Kern, et al., 1989; Cook, Dodds, Dantas, Massey, et al., 1989; Dantas, Kern, et al., 1990; Jacob et al., 1989), longer laryngeal elevation and closure (Kahrilas et al., 1988; Logemann et al., 1992), and longer and greater extent of upper esophageal sphincter opening (Castell, Dalton, & Castell, 1990b; Cook, Dodds, Dantas, Massey, et al., 1989; Cook, Dodds, Dantas, Kern, et al., 1989; Dantas, Kern, et al., 1990; Jacob et al., 1989; Kahrilas, Dodds, Dent, Logemann, & Shaker, 1988). In addition, bolus movement velocity or acceleration, measured in the pharynx, was greater for larger- than for smaller-volume swallows (e.g., from 15 to 50 cm/sec in velocity for 1-20 cc boluses, or from 460 to 680 cm/s² in acceleration for 10-20 cc boluses) (Kahrilas & Logemann, 1993; Ku et al., 1990). Volume variations, however, did not affect the velocity and magnitude of propagated pharyngeal contraction, or the extent of constrictor contraction pressure (Ekberg, Olsson, & Sundgren-Borgström, 1988; Kahrilas et al., 1992, 1993; Kahrilas & Logemann, 1993). Furthermore, findings were inconsistent on the relationship between bolus volume and the magnitude of hyoid excursions (Jacob et al., 1989 vs. Dodds, Man, Cook, Kahrilas, Steward, & Kern, 1988) with a suggestion of large intersubject variability (Ekberg et al., 1988).

Past data concerning the effects of bolus volume on lingual kinematics are not completely unequivocal. Using X-ray microbeam, Hamlet (1989) found no significant differences in the starting tongue posture, lingual movement direction, extent of grooving, peak velocity, and movement sequence as a function of varying volumes (5, 10, and 15 cc of water). Martin's X-ray microbeam study (1991), on the other hand, reported differences in lingual fleshpoint trajectories between 2-cc and 10-cc water swallows.

Specifically, the smaller volume had a more anterior and superior starting tongue position and a smaller range of tongue dorsum displacement, although the overall pattern of tongue action during swallowing was essentially the same regardless of the volume ingested. A recent study by Kahrilas et al. (1993), using simultaneous biplane videofluoroscopy and pharyngeal manometry, examined tongue contour changes as well as the pattern and timing of lingual movement during barium liquid swallows (1, 5, 10, and 20 cc). They found that larger volume swallows induced earlier onset of lingual propulsion, deeper central tongue grooving, and greater extent and duration of centripetal movement of the posterior tongue and tongue base. In addition, the depth, width, and duration of glossopalatal sphincter opening were greater with larger boluses, and bolus expulsion from the oropharynx more vigorous. Similarly, Dantas, Kern, et al. (1990) demonstrated that graded volume increases in both barium liquid and paste induced a progressively earlier onset of anterior movement of the tongue base.

Consistency. The effects of bolus consistency³ have been extensively documented, but mostly for esophageal function. With respect to the oral and pharyngeal stages of swallowing, some studies showed that viscous or thick barium, in contrast to thin liquid barium, increased the duration and magnitude of submental and infrahyoid muscle activity, and prolonged hyoid movement, oral and pharyngeal transit, pharyngeal peristalsis, and

³“Consistency” in layman’s terms refers to texture, thickness, and firmness. Technically, the definitions include density and viscosity. Density, the thickness of consistency, may be measured in weight per unit volume (i.e., g/cm³). Viscosity, expressed in centipoise (cp), refers to the degree of resistance to flow when pressure is applied. Water, for example, typically is 0.89 cp in viscosity, while the viscosity of syrup used in different clinical swallowing investigations may range from 48 to 1100 cp, depending on the thickness of the preparation.

upper esophageal sphincter opening (Dantas & Dodds, 1990; Dantas, Dodds, Massey, & Kern, 1989; Dantas, Kern, et al., 1990; Gramiak, Kelley, & Gravinia, 1967; Ingervall, Bratt, Carlsson, Helkimo, & Lantz, 1972; Ingervall & Lantz, 1973; Robbins, Hamilton, Lof, & Kempster, 1992). However, a recent scintigraphic study (Hamlet et al., 1996) found shorter “oral discharge time” with a viscous material (10 cc of apple juice thickened to 1100 cp) than with water (10 cc), and no significant difference between the two in pharyngeal transit times. Methodological variations may account for the inconsistencies in these results (see Hamlet et al., 1996 for explanations). Findings from comparisons of solids/semisolids with water also appeared equivocal. While there was evidence that solids/semisolids induced longer pharyngoesophageal contractions (Wilson, Pryde, Macintyre, & Heading, 1989) and slower opening but faster closing of the upper esophageal sphincter (Castell et al., 1990b) than did water, there was also a report of no significant differences in the degree of pharyngeal and laryngeal elevation, pharyngeal transit time, and the width and cross-sectional area of the upper esophageal sphincter (Ekberg, Liedberg, & Öwall, 1986).

In reference to the effect of bolus viscosity on lingual action, a recent investigation reported that barium paste induced a longer period of tongue-base contact to the posterior pharyngeal wall in normal subjects than did barium liquid (Lazarus et al., 1993). In addition, a study of tongue force indicated that viscous materials (pudding and mashed potato), in contrast to water, increased both the force amplitude during bolus propulsion and the pressure amplitude during pharyngeal residue clearance (Pouderoux & Kahrilas, 1995).

As part of the consistency issue⁴, saliva (dry) and liquid (wet) swallows have been compared from multiple aspects of deglutition. During the oral and pharyngeal stages of swallowing, dry swallows tended to induce: (a) a higher position of velopharyngeal contact and a more pronounced levator eminence (Shprintzen, Lencione, McCall, & Skolnick, 1974); (b) a longer duration of hyoid movement (Sonies, Parent, Morrish, & Baum, 1988); (c) faster and shorter pharyngeal contractions (Castell, Dalton, & Castell, 1990b); and (d) shorter upper esophageal sphincter relaxation (Castell, Dalton, & Castell, 1990a). In reference to the tongue, dry swallows were associated with: (a) longer genioglossus muscle activities (Cunningham and Basmajian, 1969; Hrychshyn and Basmajian, 1972); (b) a higher and more anterior starting tongue position and a shorter period of initial tongue tip elevation (Cleall, 1965); and (c) more angular lingual movement trajectories, lower peak velocities for tongue blade and dorsum, slower sequence of blade-to-dorsum movement, and smaller overall range of motion (Hamlet, 1989). In most of the above-cited studies, water was the type of wet material used, and the amount consumed per swallow ranged from small (unspecified) to 15 cc. Despite these reports of dry-wet contrast, a recent study by Shaker et al. (1990) found through simultaneous videoendoscopy, videofluoroscopy, pharyngeal manometry, and submental surface EMG that saliva and 5-cc liquid barium did not differ significantly in a number of

⁴The classification of dry swallow is difficult, because saliva is a complex solution apparently different in constituents from water or liquid barium (Baum, 1987; Kaplan & Baum, 1993). In some studies a dry swallow is considered volume-related, and assigned a "0" or a small, unspecific quantity on a continuum of graded volumes (cf. Dodds, Man, Cook, Kahrilas, Stewart, & Kern, 1988, and Kahrilas, Dodds, Dent, Logemann, & Shaker, 1988). The present study includes the dry swallow under consistency with recognition of the possibility for consistency-volume interaction in comparisons of dry and wet swallows.

lingual, submental, pharyngeal, and laryngeal timing measurements (e.g., the interval between the onset of vocal cord adduction and that of tongue base movement).

Effects of Task Demands

It is generally known that flexible motor systems are capable of adjusting the parameters of their activities in accordance with changing task demands. The human speech and limb motor systems are among those possessing such flexibility. The act of movement parameter adjustment is sometimes referred to as “response scaling” which may be accomplished using different kinematic strategies (Bermejo & Zeigler, 1989; Milner, 1986). When a complex, discrete motor task is repeated sequentially, parameter adjustment conceivably occurs due to the additional requirements for sequentialization and possible changes in movement coordination. In continuous speech, for example, there are ubiquitous instances of coarticulation where the articulatory movements for discrete sounds co-occur in space or overlap in time under the principal of motor economy (see Borden and Harris, 1984, Browman and Goldstein, 1990, and Lindblom, 1983).

To characterize gestural interactions during speech, Browman and Goldstein (1990) have proposed a linguistic gestural model in which task-specific vocal tract variables are grouped into gestures, and gestures are represented on different articulatory tiers. To produce an utterance, articulators on three different tiers of the oral tract--lips, tongue tip, tongue body--as well as those on the glottal and the velic tiers execute functionally specific labial, lingual, laryngeal, and palatopharyngeal gestures that reflect independent vocal tract variables (e.g., lip aperture, tongue tip constriction location and

degree, glottal aperture). Gestures within the same articulatory tier may blend, and those on different tiers may overlap in time, resulting in different types of changes in the movement output and the acoustic consequences. An example of within-tiers gestural interaction is the changing of /s/ to /ʃ/ in “this ship” (uttered as /ðɪʃʃɪp/; cited from Catford, 1977 in Browman & Goldstein, 1990), reflecting the smooth blending of an alveolar fricative with a palatoalveolar fricative. An example of across-tiers gestural interaction is the lowering of the anterior tongue for /a/ during tongue dorsum elevation for /k/ in the syllable-utterance /skɑ/, as observed on cinefluorography (Borden & Gay, 1979). This particular example, illustrating the temporal overlap of lingual gestures for a vowel with those for a consonant in a speech motor sequence, supports Öhman’s hypothesis (1966) that functional tongue segments exist and can act relatively independent of each other during articulation.

There is yet another set of examples in the speech literature that illustrates the differences between discrete and sequential articulatory movements. These examples are found in the vocalization of infants. As Kent and Murray (1991) pointed out, the monosyllabic utterances (e.g., /bɑ/) of infants represent unidirectional articulatory movements in which one or more articulators move from a constricted to an unconstricted vocal-tract position. In babbling, the monosyllabic utterances are reduplicated, resulting in multiple, sequential, reciprocal articulatory movements that “are motorically similar to rhythmical stereotypies” (p. 411). Examples of rhythmical motor stereotypies can be found in the repetitive movements of the limbs, fingers, torso, and head in normal infants (Thelen, 1981).

Closely related to the issue of discrete versus sequential motor tasks in both speech and limb motor systems is the issue of increased movement speed. Multiple empirical examples exist, indicating that when tasks are performed at a faster rate and consequently shortened duration, there are corresponding modifications in movement amplitude and velocity (Abbs, 1973; Cooke, 1980; Freund & Büdingen, 1978; Gay, 1981; Hughes & Abbs, 1976; Milner, 1986; Munhall, Ostry, & Parush, 1985; Ostry, Cooke, & Munhall, 1987; Ostry, Keller, & Parush, 1983; Stone, 1981; Tuller, Harris, & Kelso, 1982; Wieneke, Janssen, & Belderbos, 1987). While the common strategy is to modify peak velocity and amplitude in a tightly coupled linear manner, findings on the details of the kinematic adjustments are not all consistent, especially in speech (see concise review in Ostry & Munhall, 1985). Descriptively, a simple yet explicit account of the effect of speed on articulation is that from Stetson (1951, p. 71): "At a rapid rate the movements tend either to get into step or to drop in order to simplify the coordination".

Within the deglutition motor system, the issue of discrete (single) versus sequential swallows and the issue of normal versus fast drinking have not been well addressed. A few studies examined the effect of rate on jaw movements during mastication and found equal acceleration and deceleration durations for fast jaw opening but longer deceleration than acceleration for movements at normal speed (Morimoto, Inoue, Nakamura, & Kawamura, 1984; Plesh, Bishop, & McCall, 1987; Ostry & Flanagan, 1989). A few other studies examined the effect of multiple swallows, but only with respect to esophageal responses. They reported that repeated swallows of liquid, separated by short intervals, could dramatically change esophageal motility patterns; for example, the second swallow

could reduce or interrupt the peristaltic wave of the first swallow, and the residual wave of the first swallow could also depress or inhibit the subsequent swallow wave (Ham, Georges, Froideville, & Piepsz, 1985; Meyer, Gerhardt, & Castell, 1981; Vanek & Diamant, 1987).

Swallowing in normal infants during feeding is typically described as a part of the suck-swallow cycle which is repeated successively with a brief between-cycle pause for breathing (Bosma, Hepburn, Josell, Baker, 1990; Newman, Cleveland, Blickman, Hillman, & Jaramillo, 1991; Selley, Ellis, Flack, & Brooks, 1990; Selley, Ellis, Flack, Curtis, Callon, 1986; Weber, Woolridge, & Baum, 1986). Given the added breathing pauses and the variable suck-swallow ratios (from 1:1 to 3:1), infant swallows do not occur in the same “sequential” manner as those performed on one breath during adult continuous drinking. In addition, since the tongue must conform to and interact with the nipple for sucking, lingual behaviors during infant swallowing are not comparable to those during mature, nonstop cup-drinking. Interestingly, the radiographic investigation by Newman et al. (1991) showed that the activity of suck-oral transit overlapped with pharyngeal transit in all of the infants studied. Oral and pharyngeal transit overlap conceivably can also occur during adult continuous drinking, although the extent of the overlap remains unknown.

Little is known about the effects of task demands on the oral and pharyngeal kinematics of swallowing. As described earlier, past studies (Kahrilas et al, 1993; Martin, 1991) have emphasized that the overall pattern of deglutitive tongue action contains invariant features. This impression is based solely on the experimental model of single

swallows. Are these invariant features carried over to the sequential swallows in continuous drinking which is a common event in everyday eating? That is, is sequential swallowing during continuous drinking performed by merely concatenating single swallows? Does fusing or dropping of movement components occur as a function of the inherent rate increase? Most models of voluntary human limb movements describe a trade-off between movement speed and accuracy, that affects movement control (Hancock & Newell, 1985; Meyer, Smith, & Wright, 1982; Schmidt, Sherwood, Zelaznik, & Leikind, 1985). Swallowing, on the other hand, is a motor behavior that presumably cannot afford much latitude, if any, for movement inaccuracy due to the need for maximal airway protection. How, then, does the lingual motor system accommodate the added task demands and achieve a balance between continuous motion at an increased rate and swallowing safety? All of these questions required answers. Conceivably, when additional demands are superimposed onto a basic task, the reaction of a motor system would reflect the nature, strategies, and fundamental flexibility of the underlying movement control processes.

Tongue-Palate Interaction and Electropalatography

However mobile and biomechanically unique, the tongue cannot accomplish most of its functions by itself. To perform its rudimentary tasks during swallowing, it must interact with other oral structures, most importantly the hard palate. Tongue-palate interaction provides not only the primary means for bolus formation but also the anterior and lateral seals necessary for bolus containment. Furthermore, it is a dynamic source

from which the tongue gains stability, expands its freedom of movement, alters its surface contours, and derives the force needed for bolus propulsion. Linguopalatal relationship is not exclusively biomechanical, as there is also empirical evidence for sensorimotor connections between the two structures (see Hellstrand, 1982b for review). For example, mechanical stimulation of the hard palate in cats, such as the application of long-lasting pressure, produced intermittent activities in the genioglossus muscle and the motor consequence of rhythmic tongue flapping (Hellstrand, 1982a).

A safe and noninvasive technique, electropalatography (EPG), is available for studying the details--location, pattern, and timing--of linguopalatal contact. The usefulness of EPG has been well established in linguistic research and speech therapy. Linguistic research has studied phoneme-specific contact characteristics in different languages (Fujimura, Tatsumi, & Kagaya, 1972; Hoole, Ziegler, Hartmann, & Hardcastle, 1989; Mizutani & Hashimoto, 1988; Nihalani, 1974; Palmer, 1973), the effect of palatal shape on lingual articulation (Hiki & Itoh, 1986), speech motor adaptation and compensatory articulatory movements (Hamlet & Stone, 1978), the relationship between cross-sectional tongue shape and linguopalatal contact patterns (Stone, 1991; Stone et al., 1992), and lingual coarticulatory effects in connected speech (Butcher, 1989; Farnetani, Vaggies, & Magno-Caldognetto, 1985; Marchal, 1988; Miyawaki, Kiritani, Tatsumi, & Fujimura, 1974; Recasens, 1991; Wright & Kerswill, 1989). In speech therapy, EPG has been used as a biofeedback tool to facilitate the remediation of articulatory defects (Fletcher, 1985; Fletcher, Dagenais, & Critz-Crosby, 1991; Suzuki, 1989). (For detailed reviews of EPG applications, see Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989

and Hardcastle, Gibbon, & Nicolaidis, 1991). In recent years, increasingly more methods have been proposed for the reduction and quantification of speech-related EPG data, among which are the percent contact analysis, the contact index method, the center of gravity index, and the coarticulatory index (Byrd, Flemming, Mueller, & Tan, 1995; Fontdevila, Pallarès, & Recasens, 1994; Gibbon, Hardcastle, & Nicolaidis, 1993; Hardcastle, Gibbon, & Nicolaidis, 1991).

In contrast, there has been minimal utilization of EPG in swallowing research. The preliminary observations of a recent single-subject study (Jack & Gibbon, 1995) showed that EPG had potential usefulness and limitations in the investigation of swallowing and eating. As reported, liquid (milk) and semi-liquid (yogurt) were more appropriate than bulky or sticky materials (jelly) to use with EPG, since the latter prevented tongue-palate contact. While there was some indication that consumption duration varied with bolus consistency (longest for jelly), no specific kinematic issue was addressed in that study. There remained a need for a detailed investigation on the spatial and temporal characteristics of tongue-palate coordination during swallowing.

A major weakness of EPG is that it provides data on only tongue-hard palate contact. Information on the actual movement of the tongue or the bolus is missing. As a compensatory measure, the present study combined EPG with ultrasonography for cross-referencing of contact patterns to lingual actions. Real-time ultrasound imaging is a noninvasive technique widely applied in medical diagnostics, speech studies, as well as swallowing evaluation and research. For swallowing research, in particular, ultrasound has proven to be useful in examining lingual motility, tongue surface contour changes,

tongue-hyoid interactions, and the effects of different clinical conditions on oral bolus management and transport (Hamlet, Stone, et al., 1988; Shawker et al., 1983, 1984; Sonies, 1991; Stone & Shawker, 1986; Weber, Woolridge, & Baum, 1986; Wein, Böckler, & Klajmans, 1991).

A Theory of Swallowing Motor Control

Based on the literature reviewed, a plausible theory of swallowing motor control would include both central and peripheral mechanisms, and a general deglutitive motor program that provided some but not extensive flexibility in performance. Because swallowing is a complex motor act with involuntary as well as voluntary components, its successful execution is likely to rely on not only a pattern generator in the brainstem but also modulation processes at the suprabulbar/cortical levels and sensory input from the periphery. That is, the brainstem control mechanism dictates the basic response patterns, while the suprabulbar and peripheral mechanisms exert modulatory influences based on changes in task nature and demands. However, swallowing, like walking, is not a highly skilled motor behavior that requires extensive learning to perfect. Moreover, the persistent, stringent requirement for airway safety mandates certain fixed relationships and coordinations among many, if not all, of the deglutitive motor participants. These factors indicate that the degree of flexibility in swallowing motor control and performance does not need to be as extensive as that for expert skills such as playing tennis or piano.

This research proposes that the master motor program for swallowing must consist of both invariant and variant parameters. An example of invariance is the unidirectionality

of bolus translocation through the mouth and of the deglutitive action sequence of the tongue. In contrast, an example of variability is the duration of swallowing events. Duration adjustments may be made as a function of the motor goals, tasks, and physical conditions at hand so that optimal lingual movement execution may be maintained. In general motor physiology, timing and force have been shown to be variable parameters in the general motor programs for behaviors such as wrist movements and writing (see Gentner, 1987 for concise review). It is reasonable that these parameters would vary with task demands in swallowing as well.

The precise neurophysiological interaction between the central and peripheral mechanisms during deglutition remains obscure; however, the invariance and variability in swallowing motor control can be explored by investigating movement characteristics. Because motor performances are dependent on tasks, by examining the effects of bolus properties and task demands on specific peripheral parameters of deglutitive tongue action, the fixed and variable aspects of the lingual motor system are likely to be revealed. In turn, a better understanding of the degree of flexibility in the general motor program for swallowing would be gained.

Why is this type of research important clinically? First, there is a need for better knowledge about the variable aspects of swallowing, especially those under voluntary control, to improve the theoretical basis for treatment decisions. Second, information is also needed on the actual tongue modifications used by the swallowing motor program in adapting to bolus/task changes for more insight into patient management strategies (e.g., when to apply thicker consistency, what type of tongue exercises to use).

Summary

It has been well established that the tongue plays a vital role in the biomechanical events of swallowing, including bolus formation, containment and propulsion, and must coordinate perfectly with other structures of the aerodigestive tract to execute a complete and safe swallow. Multiple descriptive accounts exist on the radiographic and ultrasonographic characteristics of lingual movements during swallowing. In addition, there is an abundance of evidence for peripheral modulation of different elements of swallowing. Yet, minimal data are available on deglutitive lingual motor strategies or how tongue movements adapt to different swallowing tasks.

The tongue relies extensively on interacting with the hard palate to fulfill its deglutitive functions. The details of swallow-related linguopalatal coordination, however, remained obscure. Whether linguopalatal contact activities would reflect the effects of peripheral modulation, especially those resulting from changing bolus properties and task demands, also remained undetermined. The technique of EPG offers an avenue to examine these issues and this theory. Information on the spatial and temporal characteristics of tongue-palate interaction may further our understanding of deglutitive lingual motor strategies and provide insights into the underlying control mechanisms for swallowing.

Research Purpose and Questions

The overall objective of the present study was to document any flexibility that might exist in deglutitive lingual motor performance. The direct goal was to examine in

detail the timing and patterns of tongue-palate contact with associated changes in tongue shape as a function of different bolus properties and swallowing task demands.

Specifically, the following questions were addressed:

1. Does linguopalatal contact vary in pattern and/or timing as a function of bolus properties (volume and consistency)?
 - a. Is there evidence for regional specificity in tongue-palate contact during a discrete swallow? If yes, does such specificity change when the bolus changes in volume and/or consistency?
 - b. Are there functionally distinct stages in the EPG series of a discrete swallow? If yes, how are the stages affected by changing bolus properties, and how do they compare to those well established for radiographic swallowing analysis?
2. Is there evidence for spatial and/or temporal adjustment of movements as a result of changing task demands (discrete swallowing vs. sequential swallowing at normal and fast rates), or is continuous drinking performed by simply concatenating single swallows?
3. Are time-varying changes in tongue shape and tongue-palate contact related systematically?
4. Are there bolus- and/or task-induced differences in the patterns of instantaneous lingual velocities across time?

CHAPTER II. METHOD

The present investigation consisted of two experiments. Experiment 1 focused on discrete swallowing (single swallows), and Experiment 2 on sequential swallowing during continuous drinking. Simultaneous electropalatography and ultrasound imaging were conducted in both.

Subjects

Six healthy adults, three males and three females between the ages of 23 and 47 years, served as subjects. They had no history of swallowing disorders. All passed a swallowing screening and an oral motor examination. All were informed of the purpose, procedures, risks, and benefits of the study, and signed the required consent forms.

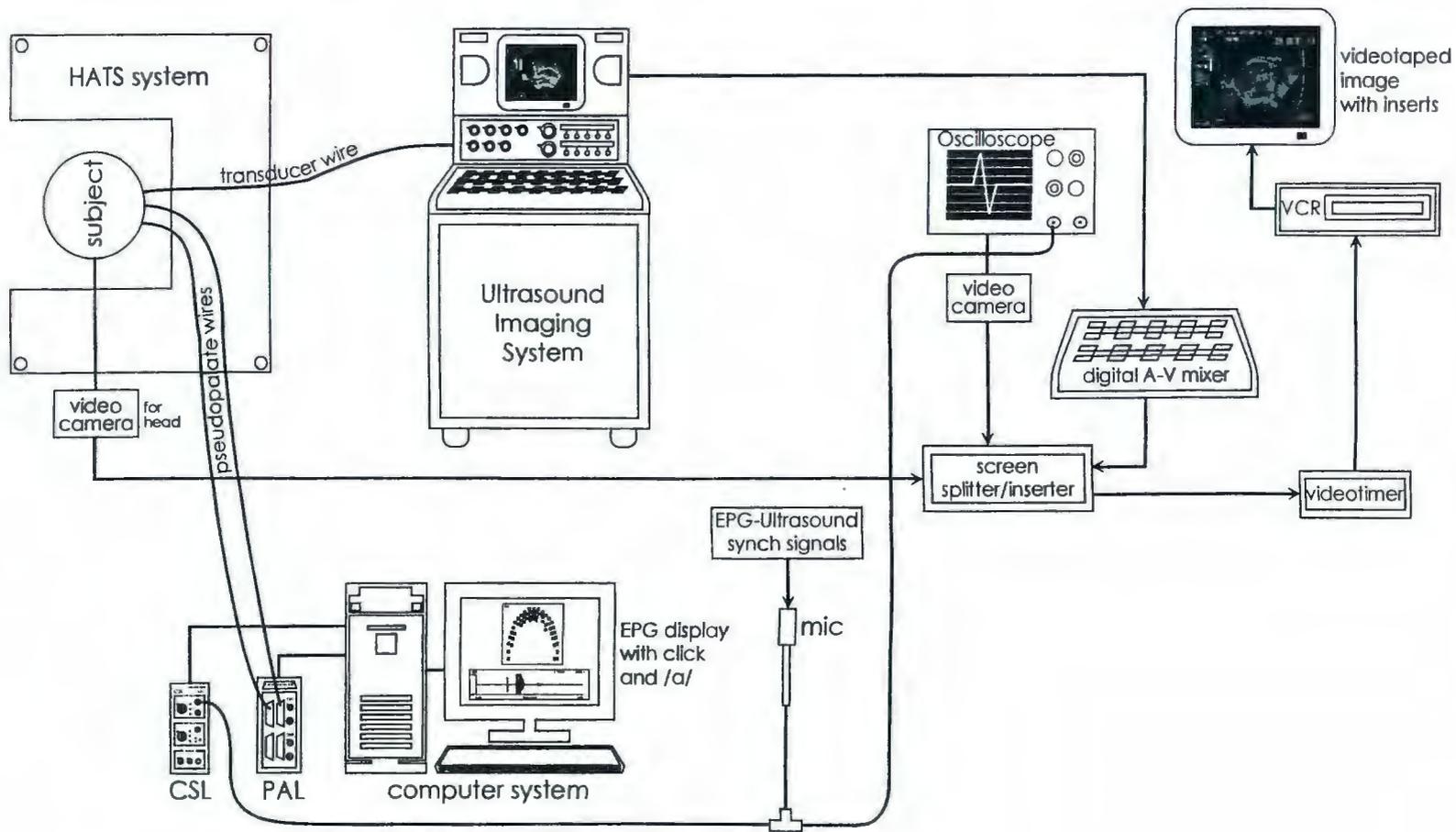
Instrumentation

A diagram of the instrumental setup for this study is presented in Figure 2.1.

Electropalatography

EPG data were collected using a Kay Elemetrics Palatometer (Lincoln Park, NJ, Model 6300). The Palatometer is a computer-assisted system that senses and displays tongue-palate contact in real time during oral motor activities such as speech and swallowing. The system consisted of an external input/output (I/O) module, a PC-based

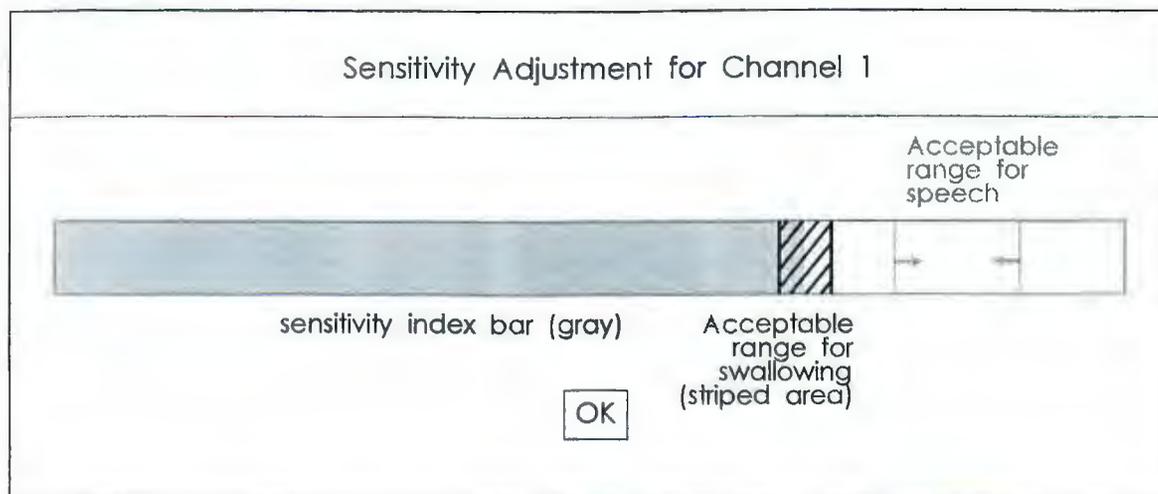
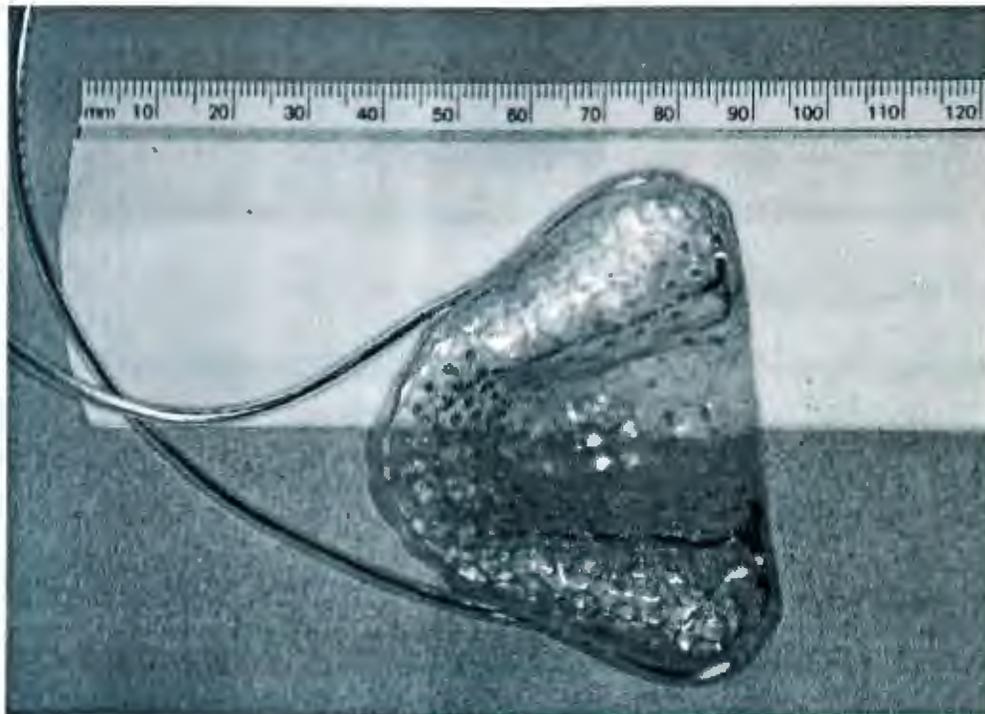
Figure 2.1. Schematic diagram of instrumental setup. HATS = head and transducer support; PAL = Palatometer; CSL = Computerized Speech Lab.



printed circuit card, connecting cables, and software. A pseudopalate and a ground electrode that introduced a high frequency, low amplitude, harmless current to the wrist were worn by the subject. Each pseudopalate (Figure 2.2, upper panel) was a 0.5-mm-thick, acrylic plate, molded according to a custom stone cast to ensure a snug fit. Embedded in the pseudopalate were 96 gold-plated contact sensors, each about 1 mm in diameter, which were symmetrically placed along the medial surface of the teeth and across the plane of the hard palate. Pseudopalate length was maximal for each subject, extending 5-10 mm beyond the third molars, but short of the gag reflex mechanism. The distance between the electrodes was normalized across palates relative to the subject's dentition and palate size. Extending from each electrode was a fine wire (42 gauge), and the wires were gathered at the back of the pseudopalate in left and right bundles. The bundles were routed around the third molars and anteriorly along the lateral teeth to exit the mouth at the front. They were then housed in polyethylene tubing and affixed to the Palatometer I/O box via connectors.

With the Palatometer activated, a nondetectible DC current was sent through the fine wires to the electrodes which registered tongue-palate contact at a sweep rate of 100 samples per second. The contact information was relayed to the computer and displayed on the monitor in a pattern closely resembling the actual electrode layout on the pseudopalate. The uncontacted, individual electrodes appeared on the screen as pale-gray dots, while the contacted electrodes appeared as small, red squares. The overall electrode threshold was adjusted for the individual subjects to a range determined in multiple pilot

Figure 2.2. A subject's acrylic pseudopalate (upper panel), and the Palatometer electrode sensitivity adjustment screen (lower panel) with the suitable range for swallowing superimposed (striped area).



studies to be sensitive to tongue contact but insensitive to the bolus itself (see Figure 2.2, lower panel). For each swallowing event, the contact information was stored at 10-msec intervals in a 4-sec record on a hard disk. The stored EPG records were then reviewed using specially developed software.

Ultrasound Imaging

Real-time, sagittal and coronal (cross-sectional) images of the tongue during swallowing were collected via an Acoustic Imaging Open Technology Ultrasound System (Phoenix, AZ, Model AI5200S) at the Ultrasound Division, Department of Radiology, Johns Hopkins University Hospital. A 3.5-MHZ convex curved linear array transducer was used. Focal depth was set at 8.6, 10.3 or 12 cm, depending on the subject's tongue size, thus producing 26-30 scans per second. Scan angle was 70°.

A specially designed head and transducer support (HATS) system was used to stabilize the subject's head during data collection (see Figure 2.3, upper panel). The HATS unit was built at the Department of Electrical and Computer Engineering, Johns Hopkins University. (For a technical description of the system and its validation, see Stone & Davis, 1995.) As part of this system, four well-padded clamps secured the head at the front, back, and sides. The transducer was housed in a transducer holder and positioned under the subject's chin in fixed relation to the head. An acoustic standoff pad (Kitecko, 3M), coated with transmission gel on its superior and inferior surfaces to prevent air bubbles, separated the mandible and the transducer. This permitted jaw movement without translation of motion to the scanner.

Figure 2.3. The head and transducer support (HATS) system (upper panel) and transducer placement calibrations (lower panel). The subject's head is stabilized by four well-padded clamps from the circular ring of the head holder. The head holder is suspended by vertical bars from an H-frame at top. The transducer is positioned under the subject's chin in fixed relation to the head. The eye-glass frame, the tongue depressor marking the occlusal plane, and the long bone of the mandible were used to measure the transducer angle. (From Stone and Davis, 1995.)



Transducer placement calibrations (details in Stone & Davis, 1995) were performed on each subject prior to data recording, after each break, and whenever changing imaging plane. The subject's jaw length was measured with calipers from the posterior angle to a tongue depressor held flat against the mental symphysis. For sagittal scanning, since the emphasis was on acquiring optimal images of the full length of the tongue, the transducer was placed 2.5-3.3 cm (31-40% of the individual jaw lengths) behind the mental symphysis at a 6-8° angle posterior to vertical. For the coronal scans, the transducer was positioned 2.7-3.2 cm (33% of the individual jaw lengths) back from the mental symphysis at an 11-14° angle. (Information on jaw length and transducer placement for the individual subjects is presented in Appendix A.) "Midline" was determined by the space between the maxillary central incisors and aligned with the pre-marked midline of the transducer. The ultrasound beam angle was measured relative to the body (long bone) of the mandible, the occlusal plane, and an eyeglass frame with two pre-marked crosses on its side bar (see Figure 2.3, lower panel). The occlusal plane was determined by having the subject bite down on a tongue depressor with the molars. Worn by the subject, the crosses on the eyeglass frame defined an additional plane, consistent across subjects, relative to which the transducer angle could be measured. All transducer calibrations were done from the subject's right side.

With the ultrasound imaging system activated, a beam of ultra high-frequency sound wave, emitted from the piezoelectric crystals of the transducer, was directed through a 1.9-mm thick section of the lingual soft tissue. The beam was reflected at

various places within the tongue and especially at its superior surface where the mucosa interfaced with air. The reflections were received by the transducer crystals and electronically processed. Within the ultrasound instrument a computer converted the returning echoes into a video image in which stronger echoes were displayed as brighter regions. The sector scanner contained a curvilinear array of 96 crystals that fired sequentially, forming a 90° wedge-shaped image. (For technical descriptions of ultrasound imaging, see Hedrick, Hykes, & Starchman, 1995; for information on lingual ultrasonography, see Stone, 1996). On the video screen, the tongue surface appeared as a white curve, while two black cone-shaped shadows--one anterior and one posterior--were cast by the jaw and the hyoid bone. Bone refracts the ultrasonic beam. The sharpness of the tongue-surface outline varied across subjects and appeared to depend somewhat on the subject's lingual tissue (e.g., amount and distribution of fat, oral moisture, tongue size).

The ultrasound data, collected simultaneously with the EPG data, were recorded on videotape with voice commentaries. A digital audio-visual mixer (Panasonic, Model WJ-MX30) was used to control the input signals. The subject's head was also videotaped throughout data collection, and the image was inserted at the lower left corner of the screen via a screen splitter (American Dynamics, Orangeburg, NY, DigiSplit Model AD1479) to enable monitoring of head position and movements. Each frame of the videotape was encoded with a digital timing signal in hundredths of a second using a video timer (FOR-A, Natick, MA, Model VTG-33).

EPG-Ultrasound Recording Synchronization

Synchronization of EPG and ultrasound recordings was accomplished by introducing two trigger signals: a click from a noise maker and a glottalized /a/ uttered by the experimenter. The choice of two signals was for double-checking. These audio signals were transmitted through a microphone to the Kay Elemetrics Computerized Speech Lab (CSL; Lincoln Park, NJ, Model 4300) and recorded on a second channel simultaneously with the EPG data. The Palatometer is designed to use the CSL hardware, input device, and powered speaker for the acquisition and playback of acoustic signals. The computer-stored EPG record for each swallowing event, therefore, contained both the contact data and the trigger signals. Through the Palatometer software the acoustic waveform of the trigger signals was displayed in a time-linked fashion with the contact information.

The audio trigger signals were also sent to and displayed on an oscilloscope. The oscilloscope screen was continuously videotaped with a separate camera, and the image inserted at the lower right corner of the video screen for ultrasound data via a screen splitter. Thus, the acoustic waveform was displayed on the ultrasound video frames to an accuracy of ± 15 msec.

Procedure

Preparatory Activities

Subject Preparation

Each subject underwent a pilot session two days to three weeks prior to the experiment. Only the Palatometer was used in this session. The primary purpose was to have the subject test-wear the pseudopalate for at least an hour while performing selected swallowing tasks. A second reason was to determine if the 30-cc bolus size would present any problem. All subjects completed the session without difficulty. They were also required to wear their pseudopalates for one to two hours the evening before the experiment.

On the day of the experiment, subjects wore their pseudopalates for at least 30 minutes during setup and calibrations prior to performing experimental swallowing tasks. This allowed adaptation to the palate's presence and to the loss of palatal sensory feedback. Previous research indicated that thin (1-mm thick) artificial plates did not affect normal articulation after only a few minutes of acclimatization (Allen, 1958). No research has investigated the effects of sensory-feedback loss due to an acrylic pseudopalate. In the present study subjects were queried before and throughout data collection about palatal comfort and swallowing ease. No discomfort or difficulties were reported, although it is possible that the pseudopalate had a minimal effect on swallowing.

Pseudopalate Landmark-Marking on Ultrasound

Subjects performed non-swallow lingual tasks prior to the swallowing experiments for the purpose of identifying the general physical landmarks of the pseudopalate in mid-sagittal view on ultrasound. Specifically, guided by the experimenter who had visual feedback from the Palatometer display, the subject positioned the tongue tip at three locations on the pseudopalate, namely, the front, mid, and posterior rim at midline. These tongue-tip maneuvers, recorded on videotape, allowed the extraction of three midsagittal ultrasound images, each with a matching EPG frame, for use as references during data analysis. A representative set of the ultrasound images and corresponding EPG frames is illustrated in Figure 2.4. The image in the left upper panel shows the tongue surface as a bright white line beginning at the arrow (which marks the approximate point of contact between the tongue tip and the pseudopalate) and continuing back and down into the pharynx. This particular midsagittal tongue shape corresponds to two rows of front contact on the EPG (right upper panel). In the left middle and lower images, a discontinuity appears in the tongue surface where the tongue tip (again identified by arrows) is angled upward and backward to contact the mid portion and the posterior rim of the pseudopalate.

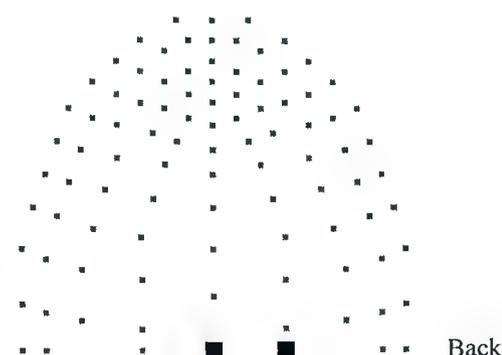
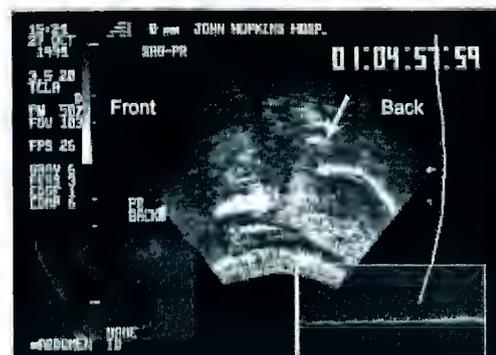
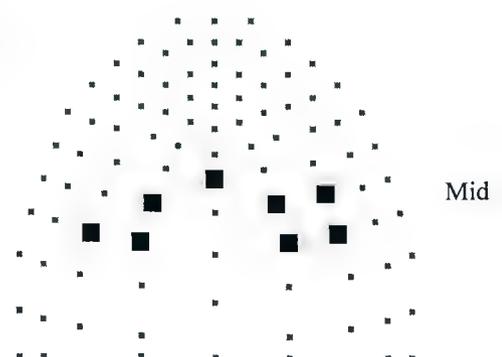
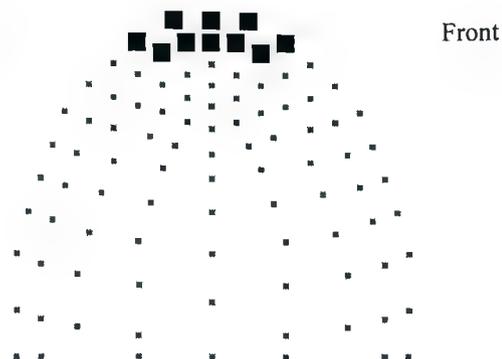
In addition, several speech tasks were performed for general linking of ultrasound tongue shapes with EPG activities. For sagittal imaging, the utterances included /ətətə/, /əsəsə/, and /əkəkə/; for coronal imaging, /əjajə/ and /əsəsə/. Each utterance-string was repeated three times.

Figure 2.4. Physical landmarks of a subject's pseudopalate on mid-sagittal ultrasound (left) and corresponding EPG displays (right). Arrows in left upper, middle, and lower panels mark, in order, the approximate locations of front, mid, and posterior rim of the pseudopalate. All landmarks were identified with tongue-tip movements. In left middle panel, tongue tip is retroflexed and positioned high in palatal vault; in left lower panel, more pronounced retroflexion is used to reach the posterior target sensors. Discontinuity in tongue surface contour occurs because the tongue blade is parallel to the ultrasound beam.

Mid-Sagittal Tongue Contour
on Ultrasound



Tongue-Palate Contact
on EPG



Experiment 1. Discrete Swallowing

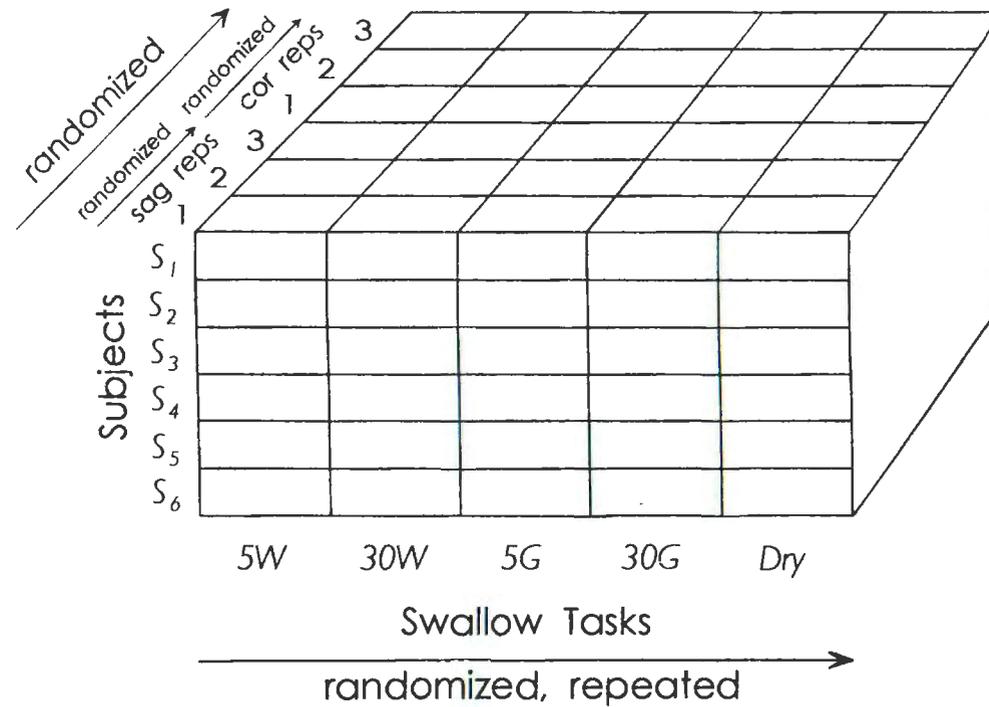
Tasks and Design

Tasks for the discrete swallowing experiment incorporated two bolus volumes and three bolus consistencies. Specifically, they were: (a) 5-cc water, (b) 30-cc water, (c) 5-cc gelatin, (d) 30-cc gelatin, and (e) dry (saliva) swallow. Although it has been shown that the average size of a thin liquid bolus is 21 cc (Adnerhill, Ekberg, & Groher, 1989), the quantity of 30 cc was chosen in this study to maximally contrast volume difference. This decision was further supported by Hamlet's X-ray microbeam study of swallowing (1989) in which inconsistent effect of water-bolus size (5, 10, 15 cc) on tongue position, grooving and velocity was attributed to the small volume differences. In the present study 30-cc water was handled successfully by all subjects, but two subjects reported during the post-experiment interviews that the 30-cc gelatin, though manageable, "felt large" or "kind of clumsy" when swallowed at once.

Each swallowing task was repeated six times--three each during sagittal and coronal ultrasound scanning. Thus, the experiment was of a subject-by-task, repeated measures design (see Figure 2.5). Presentation sequences for tasks and repetitions were completely randomized, as was the order of sagittal versus coronal imaging.

Dry swallows were accomplished by swallowing the saliva present in the mouth at the time. In the event of two successive dry swallows, a between-task delay of at least 15 seconds was introduced. Water and gelatin were presented in syringes. Jello-like boluses were prepared with unflavored gelatin (Knox), sugar, water, and red food coloring. The

Figure 2.5. Subject-by-task repeated measures design for the discrete swallowing experiment. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin; sag reps = repetitions during sagittal ultrasound imaging; cor reps = repetitions during coronal ultrasound imaging.



use of plain gelatin was necessary to avoid acid-induced activation of electrodes⁵. For the gelatin swallows, the syringes were pre-treated by removing the protruded tips and creating a hole (6 mm in diameter) at the center of the flat, sanded head. This allowed the gelatin to be coarsely mashed while being squirted into the mouth, thus eliminating mastication. All gelatin-filled syringes were stored in a cooler with a cooling pack and estimated to be 6-10°C in temperature. All water boluses were at room temperature (23-26°C). Pilot studies indicated no temperature effect⁶.

For each swallow, the subject was instructed to keep the tongue in the lowest possible position, hold the bolus anteriorly in the mouth without movement, clear the entire bolus in one swallow upon hearing the trigger click, and open the mouth slightly after swallowing. These prerequisites ensured stable, minimal tongue-palate contacts at the start and the finish so that activity onset and termination could be identified without ambiguity. Thus, by the requirements of the experimental protocol, the discrete swallowing task of the present study consisted of two components: the swallow and the post-swallow gesture of mouth opening with tongue lowering.

⁵Pilot studies were conducted on three subjects to determine if “taste” could be included as one of the variables. The material used included sour (lemonade), sweet (sugar water), and plain (tap water) liquid in 5-cc volume and at room temperature. Results showed spontaneous, random activation of EPG sensors by the sour bolus. Due to this pseudopalate constraint the “taste” variable was excluded from the present study, and plain gelatin was used to prepare the jello-like boluses.

⁶Pilot studies were conducted on two subjects to determine the effect of temperature on tongue-palate contact. The material used included 5 cc and 30 cc of water at room temperature and at 4°C. Results showed no apparent differences in contact timing or pattern for each volume tested.

Data Analysis

A total of 30 single swallows were collected from each subject. However, the data from one male subject had to be discarded due to an experimental mishap (undetected, accidental change in electrode sensitivity setting on the Palatometer). Therefore, only the data from the remaining five subjects (S1 to S5) were analyzed. One 30-cc gelatin swallow from S5 was also excluded, because the subject cleared the bolus in two swallows.

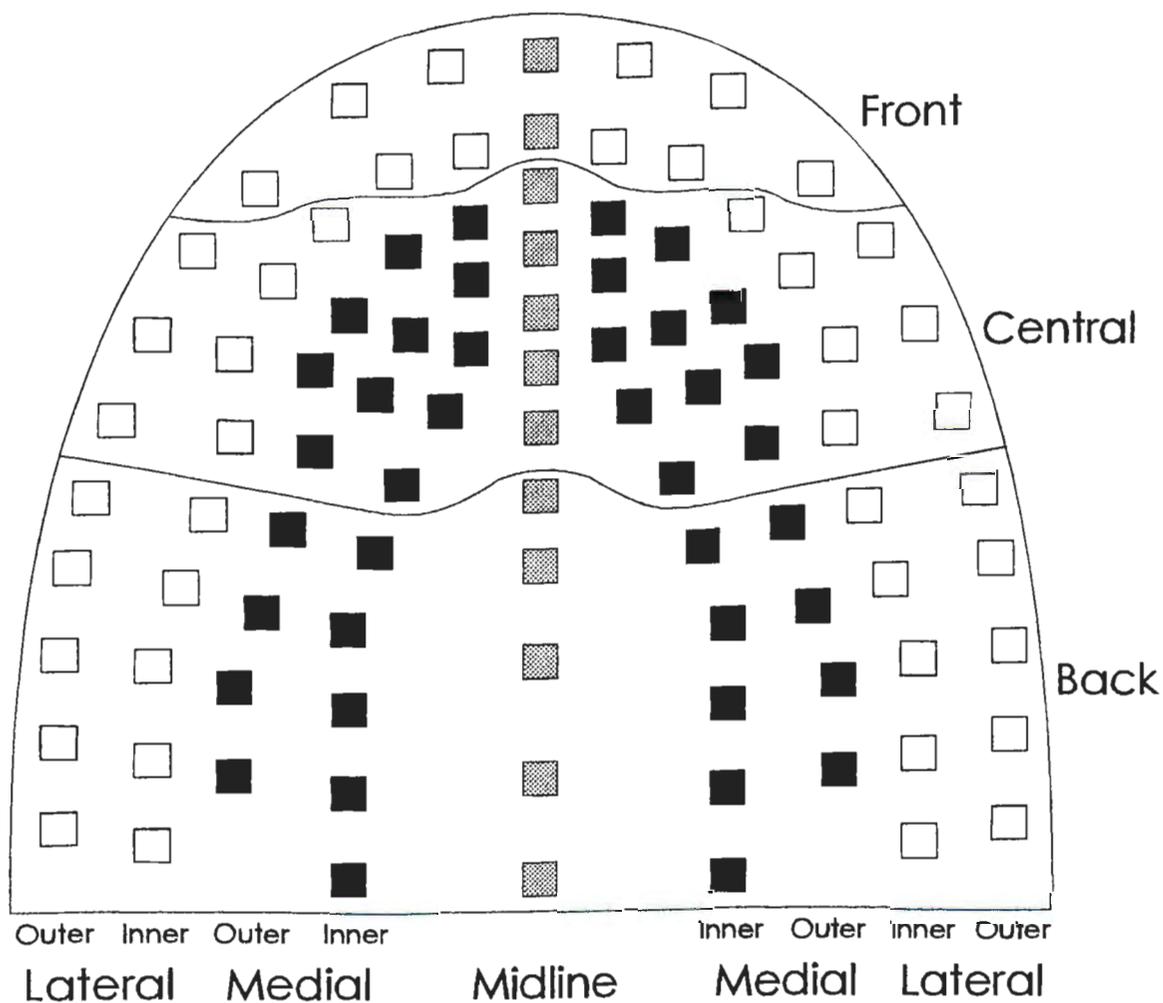
All statistical analyses were performed using the SAS System for Windows, Version 3.95, Release 6.08 (SAS Institute, Inc., 1992). Unless specified otherwise, the α level was set at .05.

EPG Data

Overall analysis framework. A system of analysis was devised, which consisted of two aspects: palatal bins and swallowing stages. They were the results of multiple pilot studies and provided the spatiotemporal bases for detailed examination of EPG data.

Preliminary examination showed systematic, time-varying regional differences in tongue-palate contact activity during swallowing. Based on those differences, six primary regions or bins were defined across the electrode array of the pseudopalate, so as to capture the salient contact features. They were named: front, central, back, lateral, medial, and midline (Figure 2.6). These bins formed two continua: front-to-back and lateral-to-midline in a horseshoe configuration. For descriptive purposes, the medial and the lateral bins were each subdivided into inner and outer columns. In addition, two

Figure 2.6. Compartmentalization of the pseudopalate into six primary bins: front, central, back, midline (shaded squares), medial (black squares), and lateral (white squares). The lateral and medial bins are each further divided into outer and inner columns.



secondary bins were extracted by dividing the pseudopalate into left and right halves, excluding the midline. These bins enabled the observation of symmetry.

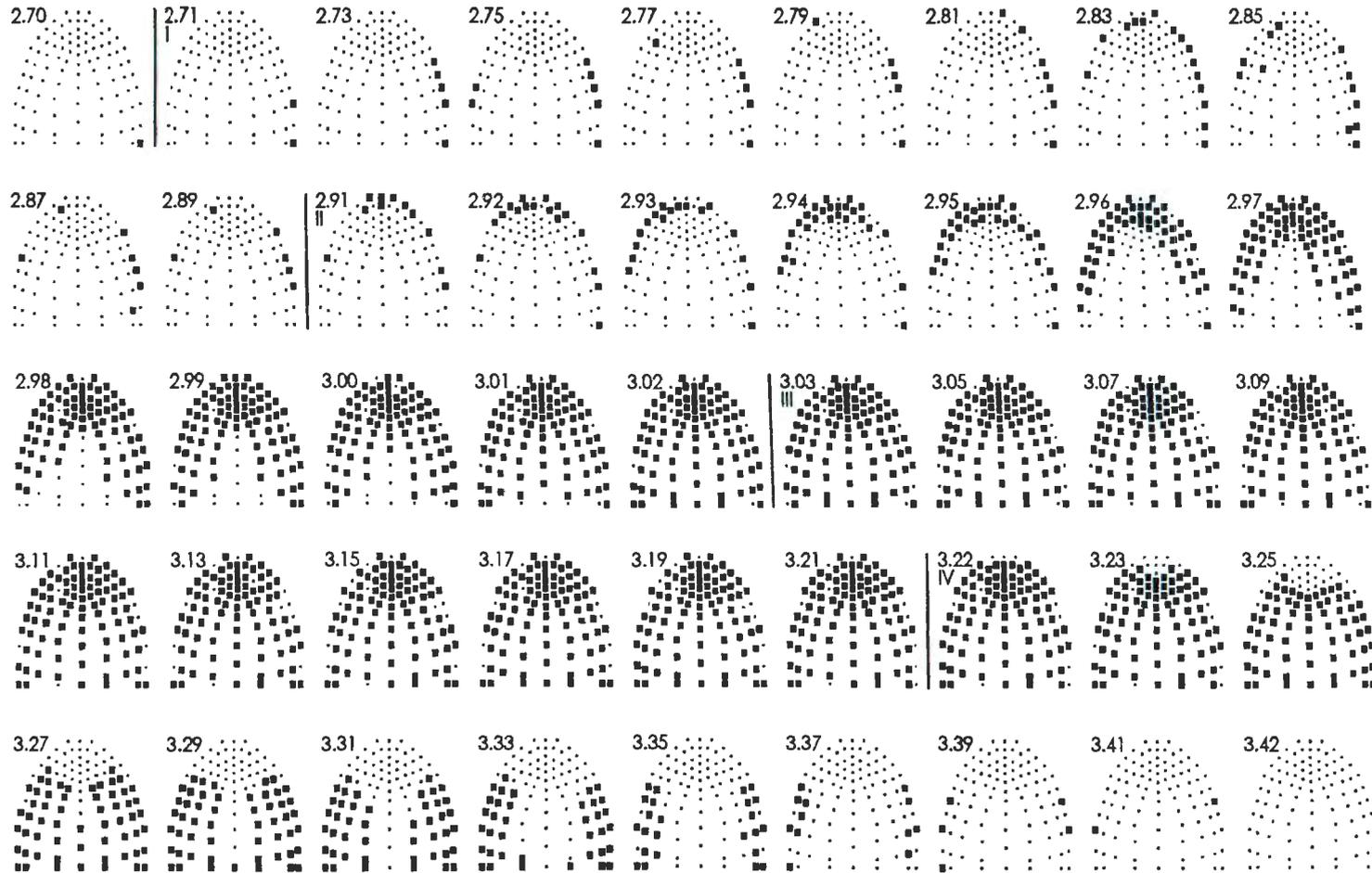
Preliminary examination also showed that the EPG time-series for the discrete swallowing task, though representing a continuous physiological event, contained four distinct stages that could be distinguished by their time-varying contact patterns. Boundary frames for each stage were extracted through visual inspection (intrajudge test-retest reliability = 95.1%). These boundary frames showed specific, repeatable features, and represented a change from the preceding pattern.

The four successive stages were named, in order, prepropulsion, propulsion, full contact, and withdrawal. The first three stages reflected the swallow component of the task performed, while the fourth stage presumably reflected the post-swallow mouth-opening component. Figure 2.7, a time-series display of the raw EPG data for a representative task at 10-20 msec increments, illustrates the delineation of the four stages. The criteria used for their identification were:

1. Stage I - prepropulsion. The boundary frame marking the onset of prepropulsion had to show a change in tongue-palate contact and be preceded by a steady-state period of stable or no contact. Subsequent frames in this stage must show continuous changes in tongue-palate contact location and number. The changes did not have to be systematic.

2. Stage II - propulsion. The boundary frame marking the onset of propulsion began a sequence of progressive, front-to-back activation of a steadily increasing number of electrodes until maximum contact was reached. The onset frame had to have a

Figure 2.7. Raw EPG time-series in 10-20 msec increments for a representative discrete swallowing task (including the swallow and post-swallow mouth opening gesture). Temporal boundaries for the four stages are: prepropulsion (I) 2.71-2.90, propulsion (II) 2.91-3.02, full contact (III) 3.03-3.21, and withdrawal (IV) 3.22-3.41. Black squares are activated electrodes. The contact seen in Frame 2.70 had been unchanged for the preceding 270 msec.



minimum of three adjacent contacts within two successive rows in the front or central bins, since the activation of one or two electrodes might not begin the continuous propulsive motion. This stage ended with activation of the posterior-most electrodes in the midline bin or the medial bin (inner column), whichever occurred later (see Figure 2.6 for bins).

3. Stage III - full contact. This stage consisted of a period of maximal, essentially stable palatal contact. The full contact stage did not require activation of all electrodes or extreme stability⁷.

4. Stage IV - withdrawal. The boundary frame marking the onset of withdrawal began a sequence of progressive, front-to-back deactivation of a steadily increasing number of electrodes. The end of withdrawal was defined as the first frame with a stable, minimal number of contacts that lasted at least 60 msec, irrespective of subsequent, additional deactivation. These criteria were set to establish a common reference across bolus conditions and subjects.

Measurements and statistics. Two sets of timing measurements were made:

1. Total duration. Operationally, the total duration of the discrete swallowing task was the interval from the onset of prepropulsion to the end of withdrawal on EPG. Analysis of variance (ANOVA) was performed on the total durations of 149 task responses, using a random effect approach (where “subject” and “subject-by-task interaction” were specified as naturally random effects). Post hoc contrasts were done

⁷Flickering (transient on and off) of some electrodes, mostly in the front and the lateral bins, was noted occasionally during this stage, probably as an instrumental artifact.

with the least-squares means, using the Scheffé method. The specific contrasts included: pairwise comparisons of all five swallowing tasks, comparisons between the two sizes (5 cc vs. 30 cc), and comparisons among the different consistencies (water, gelatin, and dry).

2. Stage duration. Based on the boundary frames described earlier, the duration of each stage was calculated for all task responses, and the raw data were collapsed by stage into mean durations for different boluses. The collapsed data were then subjected to a multivariate analysis of variance (MANOVA), using $\alpha = .05$. The multivariate approach was applied to be consistent with the repeated measures design of the experiment. However, MANOVA of bolus-by-stage interaction could not be performed due to insufficient error degrees of freedom; therefore, univariate tests of interaction were conducted. Planned comparisons of the task means were carried out for Stages II and III, using $\alpha = .01$. The α level was more stringent because of conducting multiple contrasts for each of these stages. Stages I and IV were examined visually but not analyzed statistically. This was due to concerns over the potential artificiality added to these stages by the required starting and ending tongue postures. That is, normally the tongue may not assume a low position at the start of a swallow and may remain elevated at the end of a swallow.

To extract contact patterns, two data reduction processes were used:

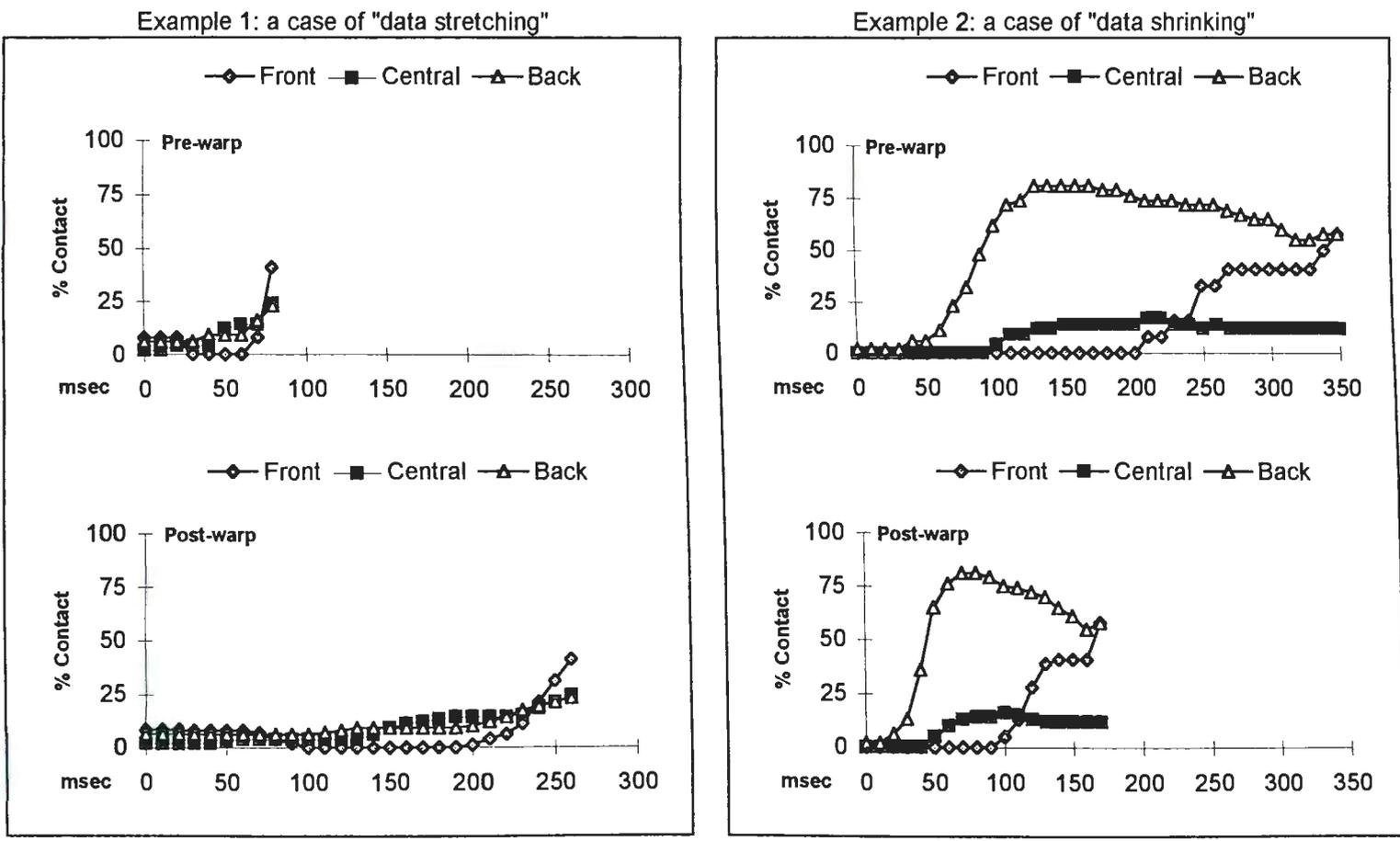
1. Percent-contact computation. The percentage of tongue-palate contact (% of electrodes on) in each palatal bin was tallied at 10-msec intervals over time for each task response, using software developed for the Department of Linguistics, University of

California, Los Angeles (Mueller, 1992). The data for each stage were then transformed into a waveform displaying percent-contact per bin as a function of time.

2. Time-warping and averaging. Because each subject repeated each discrete swallowing task six times, the repetitions must be averaged to extract the underlying patterns. Since no two swallowing responses ever can be of exactly the same duration (same number of frames), one cannot simply average the frames in one sequence with those in another. To create repetitions with the same number of frames, time-warping was performed. Time-warping, also referred to as time-aligning or time-normalizing, has been employed in speech research for similar purposes, and may be accomplished via different mathematical approaches. (For examples of some of the approaches and applications, see Cordaro, 1991, Fallside and Woods, 1985, Sakoe and Chiba, 1978; and Smith, Goffman, Zelaznik, Ying, and McGillem, 1995.) In the present study, the time-warping procedure was as follows: For each stage, mean durations were calculated for the six repetitions of each swallowing task. Next, the stage duration for each repetition was time-aligned against the subject's mean. That is, each repetition was either stretched or shortened in duration to match the mean duration. Piecewise linear interpolation was used to add or delete frames from the warped data, and to recompute the percent-contact for each new frame. This method was appropriate, because the raw data showed essentially linear frame-to-frame changes in contact.

Comparisons of pre- and post-warp waveforms showed satisfactory retention of percent-contact characteristics in virtually all cases. Two examples, presented in Figure 2.8, illustrate cases where the pre-warp data series were “stretched” (left panels) or

Figure 2.8. Examples of pre-warp (upper panels) and post-warp (lower panels) data conformity in two representative discrete swallows. All waveforms show percent-contact changes in the front, central, and back bins during Stage I. Left panels illustrate a case of "data stretching" (from 80 to 260 msec) in one swallow; right panels a case of "data shrinking" (from 350 to 170 msec) in a different swallow.



“shrunk” (right panels) considerably (by $>1/2$ of original durations) to achieve time-alignment. They represented about 15% of all cases, occurring mostly in Stage I. In 78% of the cases, the amount of time-warping was small ($<1/3$ of pre-warp durations). Time-warping amount for the remaining 7% of cases fell in between.

Subsequently, the time-warped percent data were averaged by frame for each bin and each stage to extract an underlying pattern for the six repetitions of a single swallowing task. Frame-by-frame standard deviations were also calculated. Waveforms of the averaged percent-contact data were examined in detail and compared across subjects and swallowing tasks. No statistical test was performed on the waveforms.

Two additional measurements were made, including:

1. Lateral percent-contact at Stage-II onset. Preliminary examination showed that some swallows differed in the extent of lateral contact at the end of prepropulsion or the start of propulsion. The underlying issue was whether a prominent lateral seal was present just before propulsive activity. Thus, measurements were made of the lateral percent-contact at Stage-II onset. Based on the computed percentages, the individual swallows were categorized into Patterns 1 and 2 (1 = $<65\%$, i.e., without prominent lateral seal; 2 = $>65\%$, with prominent lateral seal) and verified against the raw EPG time-series data. It should be noted that while the cutoff percentage was set at 65, the majority (95%) of the raw data displaying Pattern 2 had more than 70% of contact at Stage-II onset. Subsequently, the distribution of Patterns 1 and 2 was examined as a function of swallowing tasks. Chi-square analysis was planned but could not be successfully carried out due to exclusive distribution of one pattern or another to particular tasks.

2. Order of percent-contact peaks during Stage II. An additional measurement was made to assess task effects. This involved identifying the order in which the front (F), lateral (L), and back (B) bins reached their respective percent-contact peaks during propulsion. A percent-contact peak was defined as the first occurrence of the highest percentage in contact for a respective bin within the demarcated stage limits. The front, lateral, and back bins were selected for this analysis, as jointly they were most revealing of the general contact pattern observed during Stage II. All patterns of sequencing were tallied. Because the predominant pattern followed an F-L-B order, the individual swallows were classified into an "F-L-B" group and an "others" group. Chi-square analyses were performed to examine the distribution of these groups as functions of subjects and swallowing tasks.

Ultrasound Data

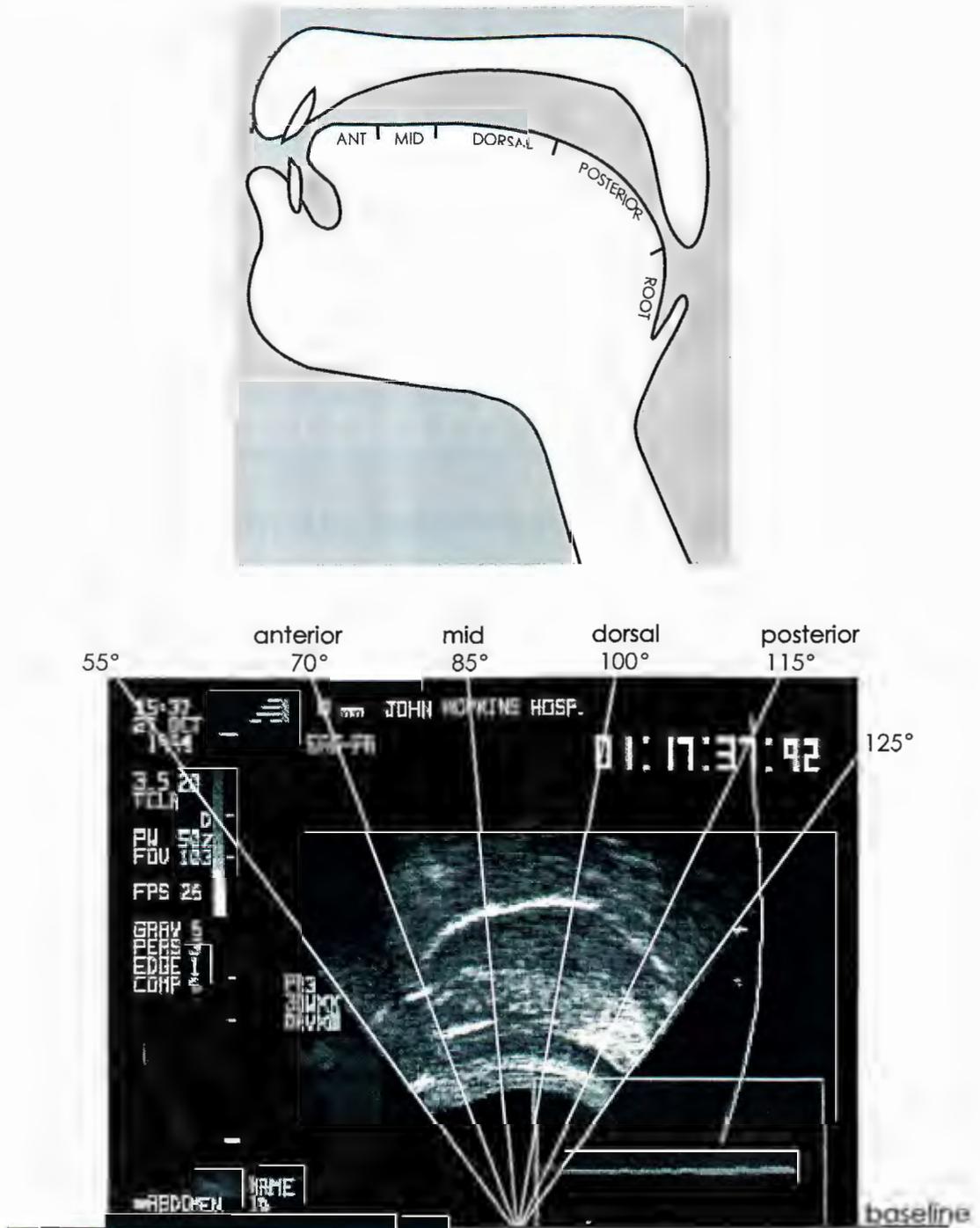
The videotaped ultrasound data were digitized in real time via a Macintosh-based image acquisition system (Scion Corp., Frederick, MD, Model 1200). Frame-by-frame examination of the digitized images was accomplished using the NIH Image software, Version 1.55 (Rasband, 1994). The midsagittal ultrasound scans were used for all of the observations and analyses described below. Unlike the midsagittal images that showed various movements of the tongue across its length, the coronal images showed repetitive and strictly upward-downward movements of a small crosswise tongue section. The latter offered no global illustration of swallow-related lingual actions and could not be used to cross-refer to the EPG data.

Overall analysis framework. A system of analysis was devised, which consisted of two schemes: functional segments and radial grid. These schemes provided the bases for describing ultrasound tongue movements and for cross-referring to the EPG data.

For convenience of descriptive analysis, the tongue was divided into five functional segments--anterior, mid, dorsal, posterior, and root (cf. Stone, 1990; see Figure 2.9, upper panel). The root of the tongue, not visible on ultrasound, was not included in the present study.

A transparent, radial grid was superimposed on the monitor screen over the ultrasound image (see Figure 2.9, lower panel; modeled after Stone, Sonies, Shawker, Weiss, & Nadel, 1983 and Morrish, Stone, Shawker, & Sonies, 1985). Once in place, the grid was not removed until all analyses were completed to ensure constant positioning over all frames. The grid consisted of a baseline plus six radii angled at 55, 70, 85, 100, 115, 125 degrees from left to right. For placement, the baseline where all radii converged was aligned with the scan vertex, and the two outside radii aligned with the scan borders. The angles of the four inside radii were set so that their intersections with the surface of a “neutral” tongue (resting without bolus in mouth) approximated the centers of the respective tongue segments. This grid setup permitted systematic observations and measurements of instantaneous radial displacement for the tongue segments. More specifically, for each tongue segment on each frame, the measured displacement was the x,y coordinates of a point where the tongue surface and a particular grid radius intersected.

Figure 2.9. Schematic of functional lingual segmentation (upper panel, modeled after Stone, 1990), and grid system for tracking radial displacement of the anterior, mid, dorsal, and posterior tongue segments (lower panel). The tongue root, not visible on ultrasound, was not measured. In the lower panel each inside radius of the superimposed grid intersects the approximate center of a tongue segment.



Observations and measurements.

1. Ultrasound lingual behaviors versus EPG contact activities. With the grid in place, swallow-related movements of the anterior, mid, dorsal, and posterior segments were visually tracked by advancing the ultrasound frames one at a time, and their characteristic patterns noted. Comparisons were then made between EPG contact activities and ultrasound lingual behaviors, and the similarities and differences described.

2. Task effect on tongue shape. To enable the examination of changes in sagittal ultrasound tongue shape as a function of swallowing tasks, criteria were set up to extract specific frames from each swallow for within- and between-subject comparisons. The frames selected included: the frame just before the onset of any lingual movement, which displayed the tongue in its resting posture with the bolus collected in front; the first frame showing the entire bolus on (i.e., no longer in front of) the tongue surface; and four successive frames (identified using the radial grid) showing the point of maximal displacement of the anterior, mid, dorsal, and posterior tongue segments. No subsequent frames were selected, because “task effect on tongue shape” became irrelevant when the bolus left the oral cavity.

3. Lingual velocity profiles. Using the same radial grid, frame-by-frame measurements of displacement were made for the four tongue segments from the swallow onset through the end of propulsion (i.e., the point of maximal displacement of the posterior segment). The displacement data derived from the grid were used to compute instantaneous velocities. Subsequently, a velocity profile--a waveform displaying changes in velocity over time--was plotted for each tongue segment in each swallow. However, it

should be pointed out that the accuracy of frame-by-frame displacement measurements depended greatly on the sharpness of the tongue surfaces imaged. Because of considerable variability in image quality across subjects accurate measurements could only be maintained with the images from Subject 5 (S5). Therefore, only the velocity data of this subject were included.

The velocity profiles of S5 were examined as a function of swallowing tasks. Means and standard deviations were calculated by tongue segments and swallowing tasks for the “positive peak velocity” and for the “interval from onset to positive peak velocity (OTP)”. Also computed were the differences in mean OTP values between tongue segments. No statistical test, however, was performed.

4. Correlation of EPG timing measurements with ultrasound activity. To ensure data accuracy, steps were taken to determine the general consistency between EPG timing measurements and corresponding sagittal ultrasound tongue shapes. They included mathematically aligning the measured EPG events to corresponding ultrasound frames, and comparing the tongue shapes depicted on those frames against the particular contact activities displayed on EPG. The extent of the “match” was noted.

5. Identification of unusual lingual behaviors. The ultrasound swallowing data of all subjects were screened independently of the EPG data for any unusual lingual behaviors such as “double swallows” or excess movements. In cases where the EPG data were questionable, the ultrasound images were examined in detail for elucidation. Questionable EPG data included task responses where the measured durations seemed unusually long or

short for one or more stages, and occasional cases where contact activities were not consistent with the typical observations.

Experiment 2. Sequential Swallowing in Continuous Drinking

Tasks and Design

Tasks for the sequential swallowing experiment included drinking 200 cc of water at normal and fast rates. No precise control was exercised over the speed of drinking. For the normal rate, subjects were instructed to drink normally upon hearing the trigger and swallow consecutively with no between-swallow pauses. For the fast rate, subjects were simply asked to “drink as fast as you can.” Water was measured and presented in a 400 cc plastic beaker with part of its wall cut off and sanded to enable tilting of the container without tilting of the head.

One trial at each rate was implemented in randomized order for both ultrasound imaging planes. In addition to drinking rate, a naturally present variable was swallow order. The starting tongue position for the first swallow was likely to be different from that for the subsequent swallows. Thus, Experiment 2 was of a two-level, randomized block design with respect to sagittal/coronal ultrasound data. With respect to the EPG data, the experiment was of a repeated measures design, as there were two repetitions for each rate.

Data Analysis

EPG Data

Data from Experiment 2 were examined across subjects and as functions of drinking rate (normal vs. fast) and swallow order (first vs. subsequent). In addition, they were compared with the discrete/single water swallows from Experiment 1. The analysis schemes and steps used here were essentially the same as those for the discrete swallowing experiment. However, time-warping and frame-by-frame data averaging were not performed due to limited sample size. For contact patterns, therefore, the raw EPG percent-contact waveforms were examined.

Measurements. For contact timing, the total duration of each component swallow or task response (up to three swallows due to instrumental limit) within a continuous drinking series was measured, using the same operational definition specified for discrete swallowing. That is, for Experiment 2, this measurement also included contact activities from prepropulsion through the end of contact retraction. Mean total durations were calculated for the first and the subsequent swallows at each rate, and ANOVA was subsequently performed on these means for the effects of “order” and “rate”. In addition to total duration, a measurement was made of the average total-duration ratios of sequential versus discrete water swallowing tasks for comparative analysis.

For contact pattern, in addition to the analyses on “lateral percent-contact at Stage-II onset” and “order of percent-contact peaks during Stage II” (see descriptions under Experiment 1), a third measurement was made of the “percent-contact ratios at maximal midline” to contrast sequential and single water swallows. The idea was derived

from preliminary examination of the data. The procedure involved: (a) extracting the percentages of electrodes-on in the front, back, and lateral bins at the time of maximal midline contact (i.e., end of propulsion); and (b) calculating the front:back and the lateral:back ratios in percent-contact. ANOVA was subsequently performed on each set of ratio data.

Ultrasound Data

Observations and measurements.

1. Swallow volume estimation. The sagittal ultrasound data of each subject were used to estimate the average bolus size for sequential swallows. The basic assumption was that the intake amount varied minimally from swallow to swallow within a continuous drinking series. The total amount consumed (200 cc) was divided by the number of swallows in a series to obtain an estimated swallow volume.

2. Lingual movement characteristics. Tongue movements during sequential swallowing were examined as functions of drinking rate and swallow order, and compared with the characteristics observed for the discrete water swallowing task. Similarities and differences were described. In addition, specific ultrasound frames were extracted for each component swallow (see criteria specified under Experiment 1) for the examination of task-induced tongue shape differences during continuous drinking.

3. Lingual velocity profiles. Procedures for velocity analyses on the sequential swallowing data were the same as those described for Experiment 1. However, the data set for each drinking series included values extracted from the first four sequential

swallowing responses. Descriptive comparisons were made between normal and fast drinking rate, between first and subsequent swallows, and between sequential and single water swallows. No statistical test was performed on the single-subject data.

CHAPTER III. RESULTS

Experiment 1. Discrete Swallowing

EPG Findings

Tongue-Palate Contact Timing

Total duration: task effect and subject variability. Average total durations of the 5-cc water, 30-cc water, 5-cc gelatin, 30-cc gelatin, and dry swallowing tasks for Subjects 1 to 5 (S1 to S5) are presented in Table 3.1. One of the six repetitions for the 30-cc gelatin swallow of S5 had to be discarded due to “double swallowing,” otherwise all averages were based on six replications. As shown in Table 3.1, intrasubject replication variability was small. In 84% of the cases, the coefficients of variation ($CV=SD/M$) were less than 0.20 (standard acceptable limit of CV in ratio = 2.00). In the remaining 16% of cases, the CV values ranged from 0.21 to 0.28.

Analysis of variance (ANOVA) on the total duration data showed a significant subject effect ($p = .0007$), a significant interaction ($p = .0001$), and a significant but weaker task effect ($p = .0488$). (The ANOVA table is presented in Appendix B, section B-1.) Post hoc tests did not isolate the effect of swallowing task to any pairwise comparisons or complex contrasts related to bolus size or consistency. The exact nature

Table 3.1. Mean total durations (in milliseconds) of tongue-palate contact during discrete swallowing for Subjects 1 to 5 (S1 to S5). Coefficients of variation (CV) were computed using the formula $[SD/M]$. Except for "30cc Gelatin" of S5, all values are based on six replications. Data for "30cc Gelatin" of S5 had one missing replication.

		Single Swallow				
		<u>5cc Water</u>	<u>30cc Water</u>	<u>5cc Gelatin</u>	<u>30cc Gelatin</u>	<u>Dry</u>
S1	<u>M</u>	922.30	816.44	1066.44	1055.18	1161.04
	<u>SD</u>	135.79	138.77	103.83	129.57	175.07
	<u>CV</u>	0.15	0.17	0.10	0.12	0.15
S2	<u>M</u>	1647.52	1233.11	2225.23	1388.52	1662.17
	<u>SD</u>	292.01	178.86	233.62	144.84	260.39
	<u>CV</u>	0.18	0.15	0.10	0.10	0.16
S3	<u>M</u>	1409.91	1208.17	1486.49	1377.25	1679.05
	<u>SD</u>	133.62	110.41	255.26	121.88	149.31
	<u>CV</u>	0.09	0.09	0.17	0.09	0.09
S4	<u>M</u>	1467.79	1449.50	1803.72	1848.65	1664.62
	<u>SD</u>	309.11	297.58	174.61	166.65	241.97
	<u>CV</u>	0.21	0.21	0.10	0.09	0.15
S5	<u>M</u>	1365.09	1378.55	1414.75	1944.32	1538.63
	<u>SD</u>	266.05	386.48	120.82	115.97	414.34
	<u>CV</u>	0.19	0.28	0.09	0.06	0.27

of the task effect was apparently masked by large intersubject differences. These differences as well as the strong subject-task interactions can be seen in Figure 3.1 (upper panel; crossed lines indicate interactions). As illustrated, total durations for S1 were considerably shorter than those of all other subjects. The lack of a consistent pattern across subjects was apparent. Nevertheless, a closer examination of the swallowing tasks as a function of subjects (Figure 3.1, lower panel) did reveal some task-based tendencies with respect to bolus consistency. That is, dry swallows were longer than water swallows of either size, and gelatin swallows were longer than water swallows of comparable size.

Stage duration: effects of task and stage, and subject variability. Average durations for the different swallowing tasks by stage are illustrated in Figure 3.2. Task-based differences were apparent for all stages, though less so for Stage IV. Statistics were performed for only Stages II and III, since they did not have an arbitrary beginning or end point.

Results of the multivariate analysis of variance (MANOVA) on stage durations showed a significant main effect of swallowing task, and a significant task-by-stage interaction. Post hoc comparisons of the task means for Stages II (propulsion) and III (full contact) revealed the following: For Stage II, with respect to bolus consistency, water had a significantly shorter duration than gelatin, and dry swallows were significantly shorter than 5-cc gelatin swallows. With respect to bolus size, 30-cc swallows were consistently shorter than 5-cc swallows. Thus, thinner consistency and larger volume were propelled faster through Stage II. For Stage III, the only significant duration effect

Figure 3.1. Least-squares mean total durations for Subjects 1 to 5 (S1 to S5) as a function of discrete swallowing task (upper panel) and for different discrete swallowing tasks as a function of subject (lower panel). 5W = 5-cc water, 30W = 30-cc water, 5G = 5-cc gelatin, 30G = 30-cc gelatin.

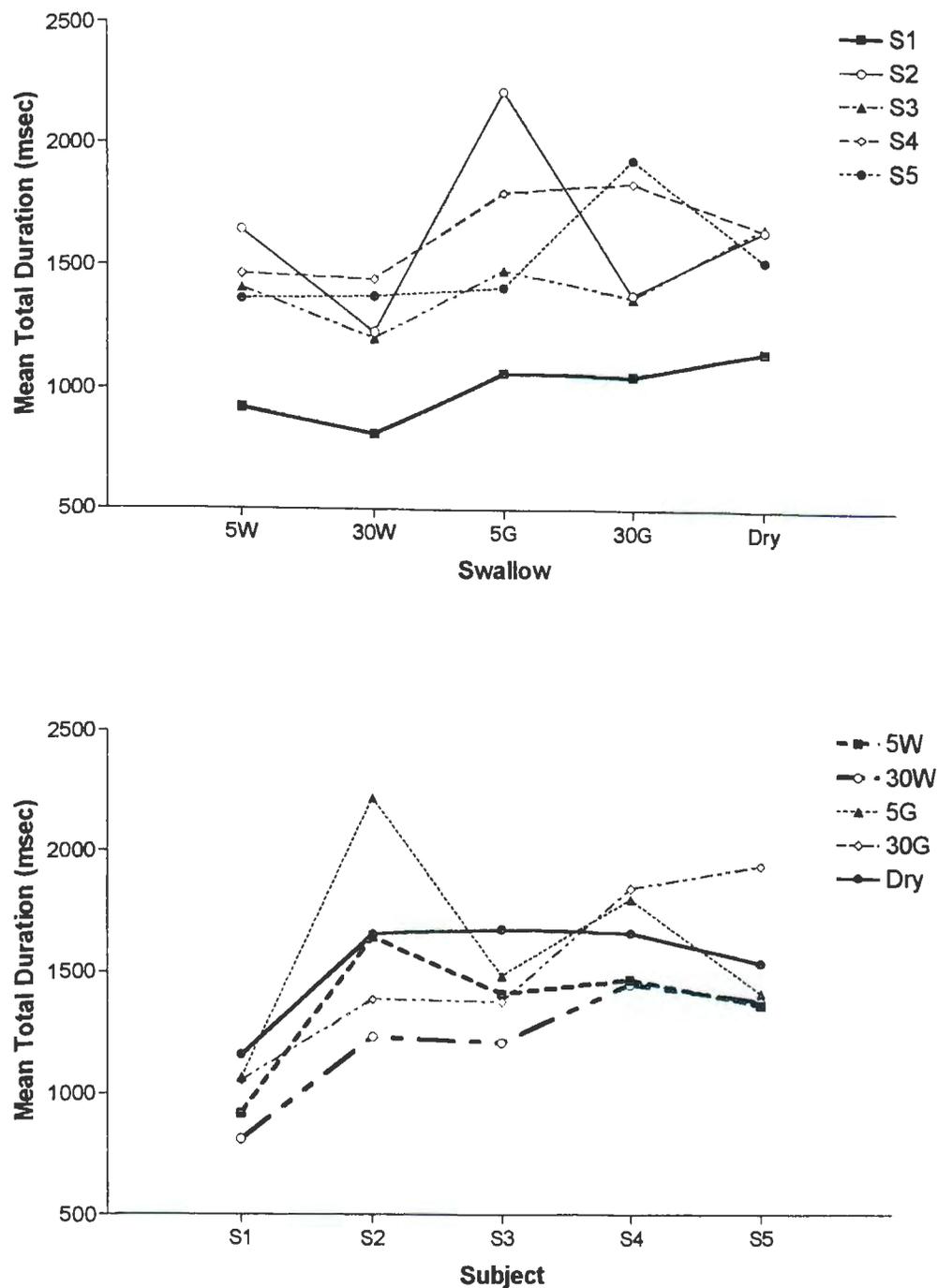
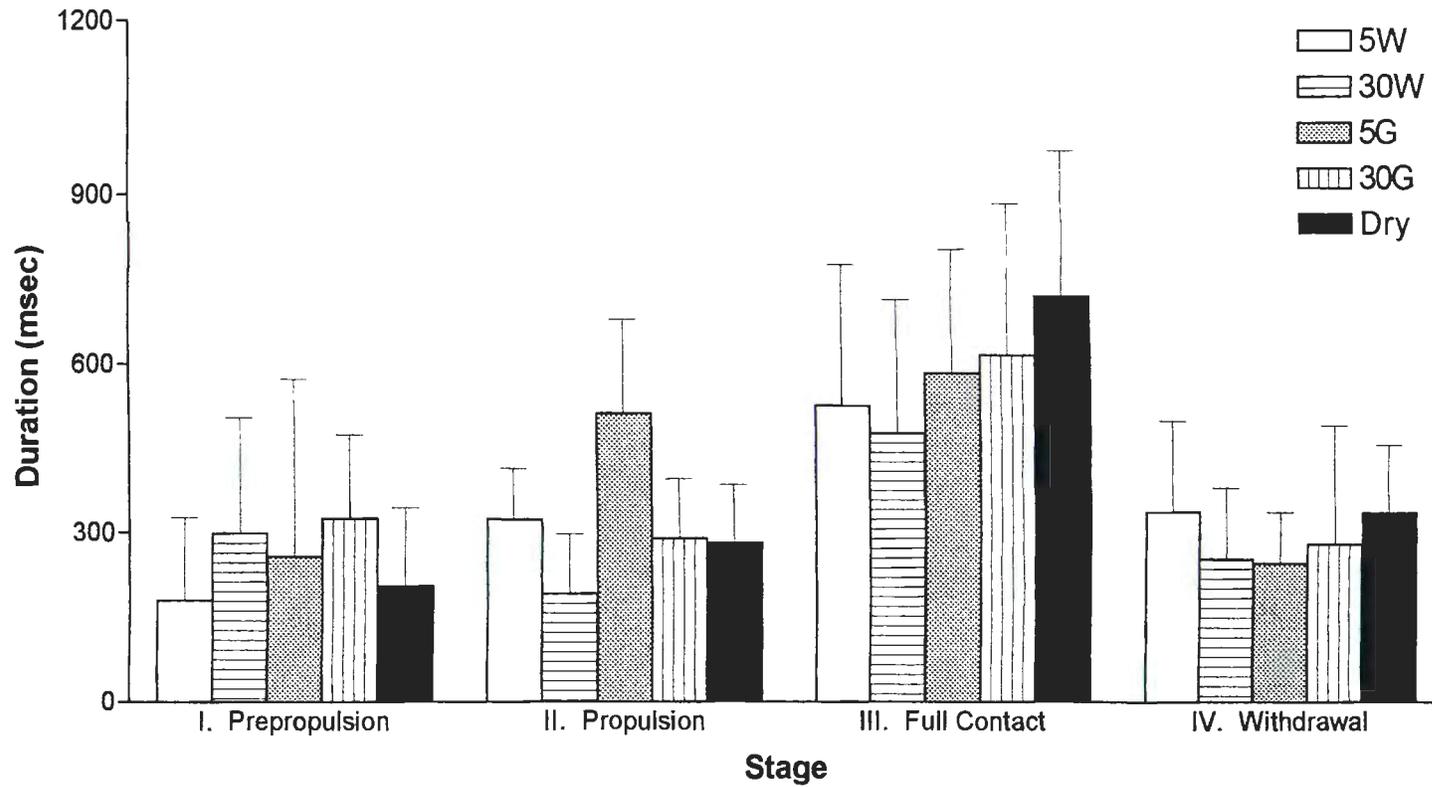


Figure 3.2. Mean durations (with error bars) of individual discrete swallowing tasks for the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 30-cc gelatin; 30G = 30-cc gelatin.



at the $\alpha = .01$ level was that the dry swallow was longer than either 5-cc or 30-cc water swallows. (Tables for the MANOVA tests of main effects and contrasts are presented in Appendix B, sections B-2 to B-4.)

The average duration (standard deviation) for each of the four stages, collapsed across swallowing tasks, was 251.33 (± 208.62), 320.03 (± 158.60), 585.13 (± 257.67), and 288.77 (± 150.90) msec, respectively. These means were not significantly different due to a large degree of variability in the measurement units, as reflected in their respective standard deviation values.

Averaged timing data from the different swallowing tasks for the individual subjects in Stages I to IV are illustrated in Figures 3.3 to 3.6, respectively. Intrasubject timing variability was greater on the whole for Stage I (overall coefficient of variation = .56) than for Stages II to IV (overall coefficients of variation = .20, .23, .31, in order). Intersubject timing variability for the individual swallowing tasks was expected in all stages. Specifically, in Stage I (prepropulsion, Figure 3.3), both S2 and S5 were noticeably different from the other subjects for the 5-cc gelatin swallow in that the former had the longest and the latter had the shortest duration. In addition, S2 was the only subject whose 5-cc gelatin swallows averaged considerably longer than the larger-volume swallows of the same consistency, whereas for all other subjects the opposite was true. In Stage II (propulsion, Figure 3.4), the subjects without exception took longer time to propel the 5-cc gelatin bolus than they did the other swallowing tasks. In Stage III (full contact, Figure 3.5), the dry swallow was the longest in three subjects (S1, S2, S3) and the second longest in the other subjects. Interestingly, S1 had considerably shorter

Figure 3.3. Average durations of Stage I (prepropulsion) as a function of discrete swallowing tasks for Subjects 1 to 5 (S1 to S5). 5W = 5-cc water; 30W = 30-cc waster; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

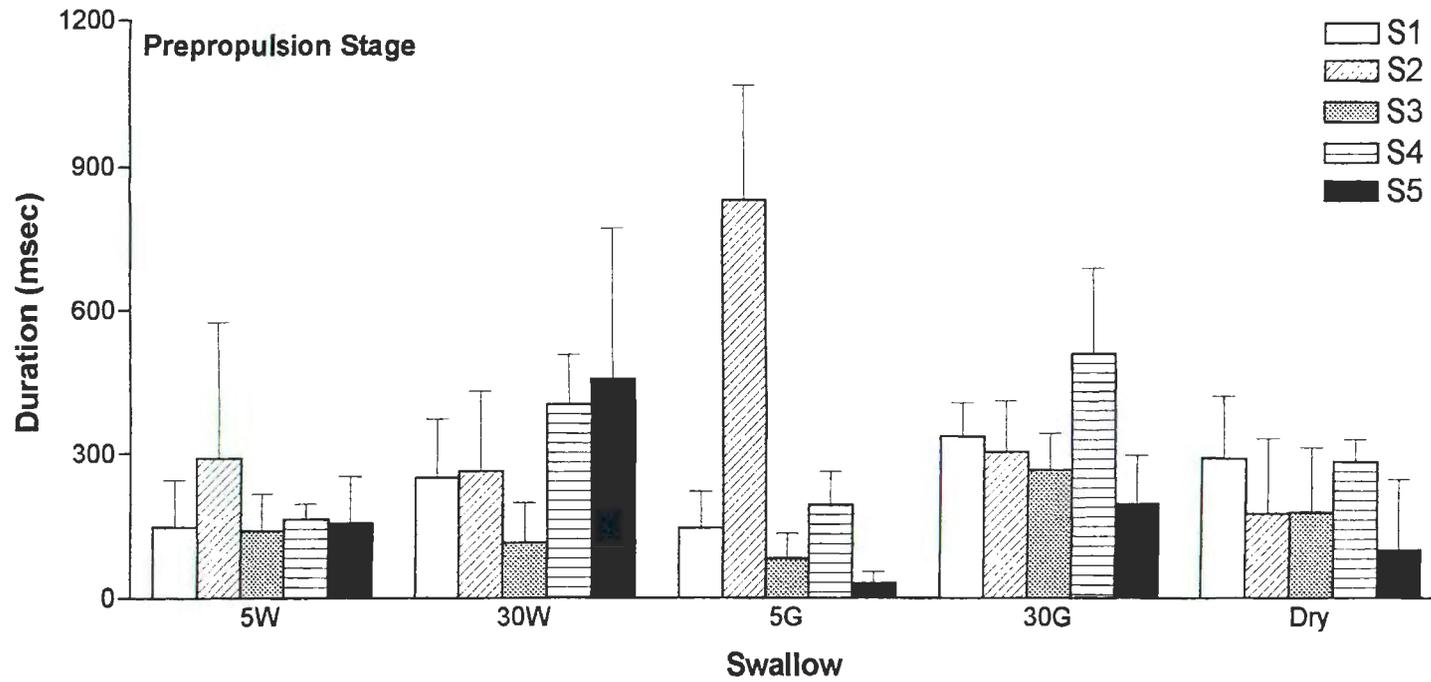


Figure 3.4. Average durations of Stage II (propulsion) as a function of discrete swallowing tasks for Subjects 1 to 5 (S1 to S5). 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

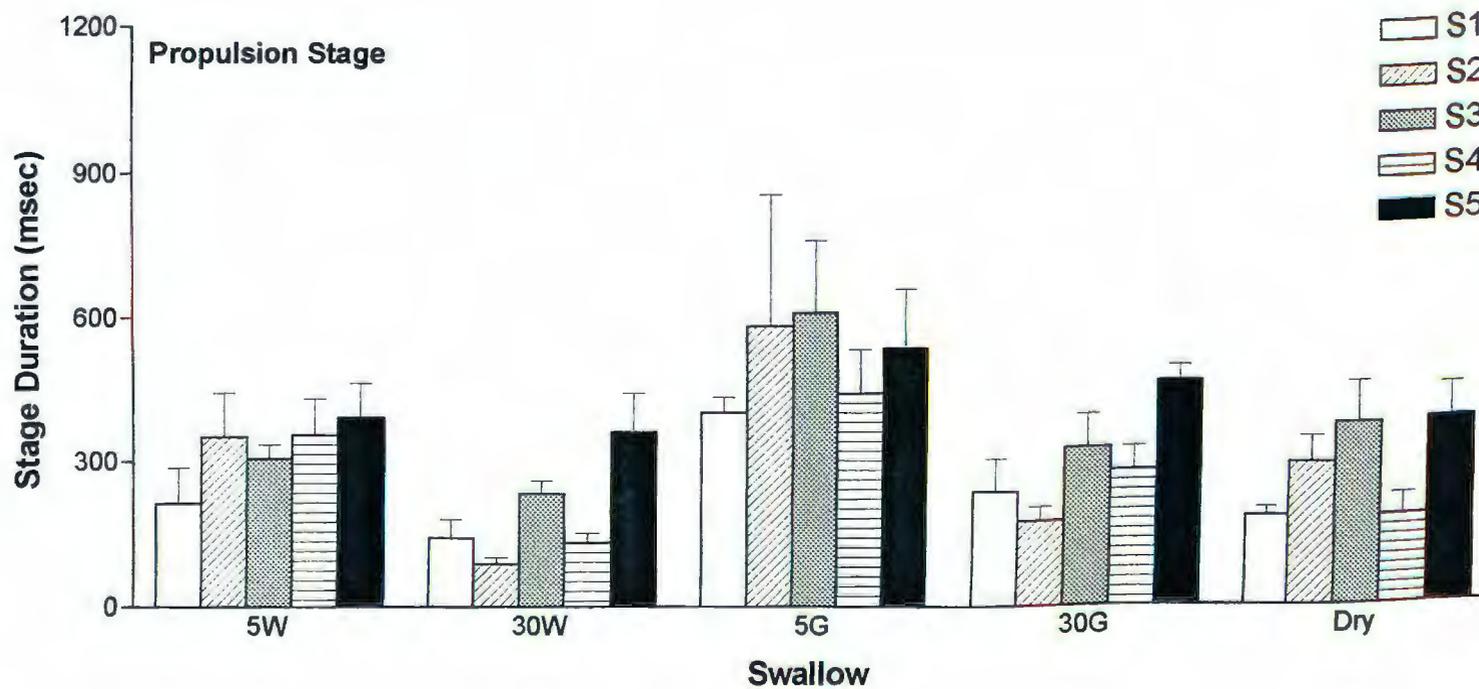


Figure 3.5. Average durations of Stage III (full contact) as a function of discrete swallowing tasks for Subjects 1 to 5 (S1 to S5). 5W = 5-cc water; 30W = 30-cc waster; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

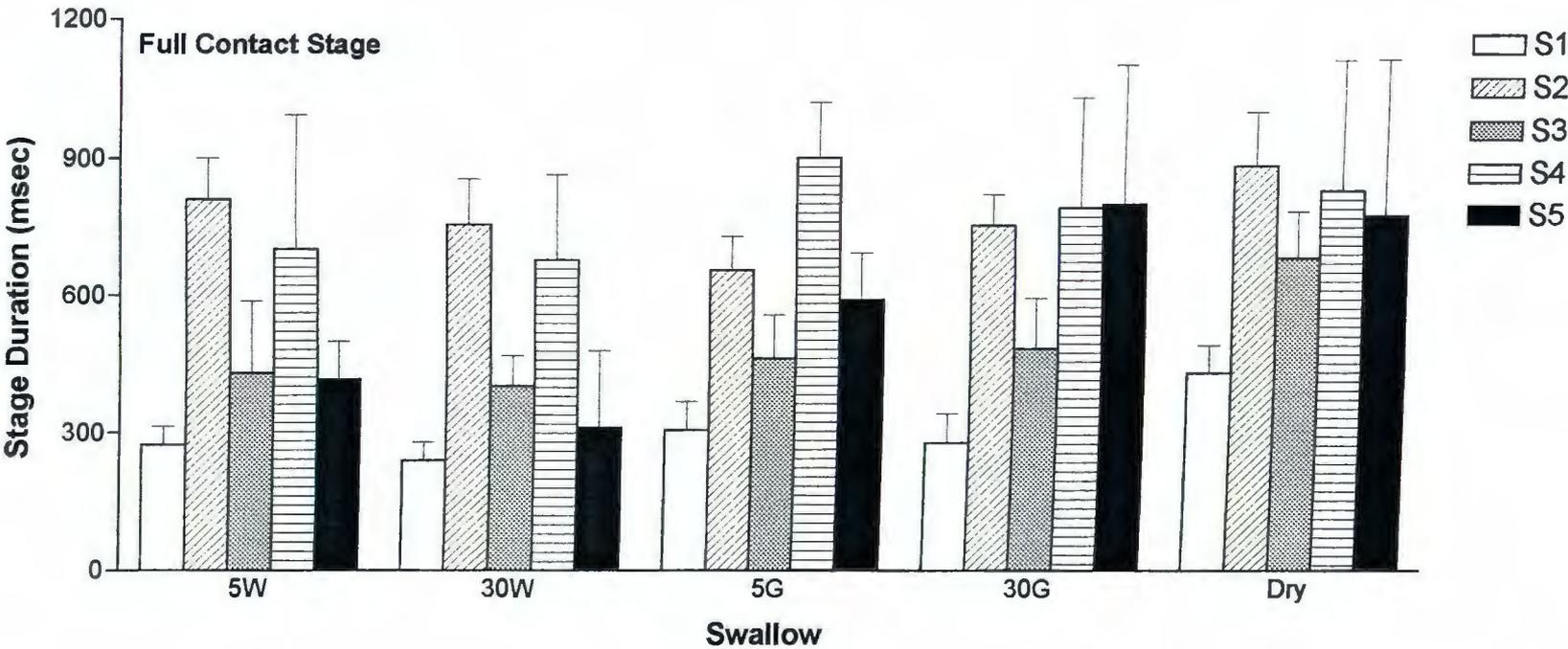
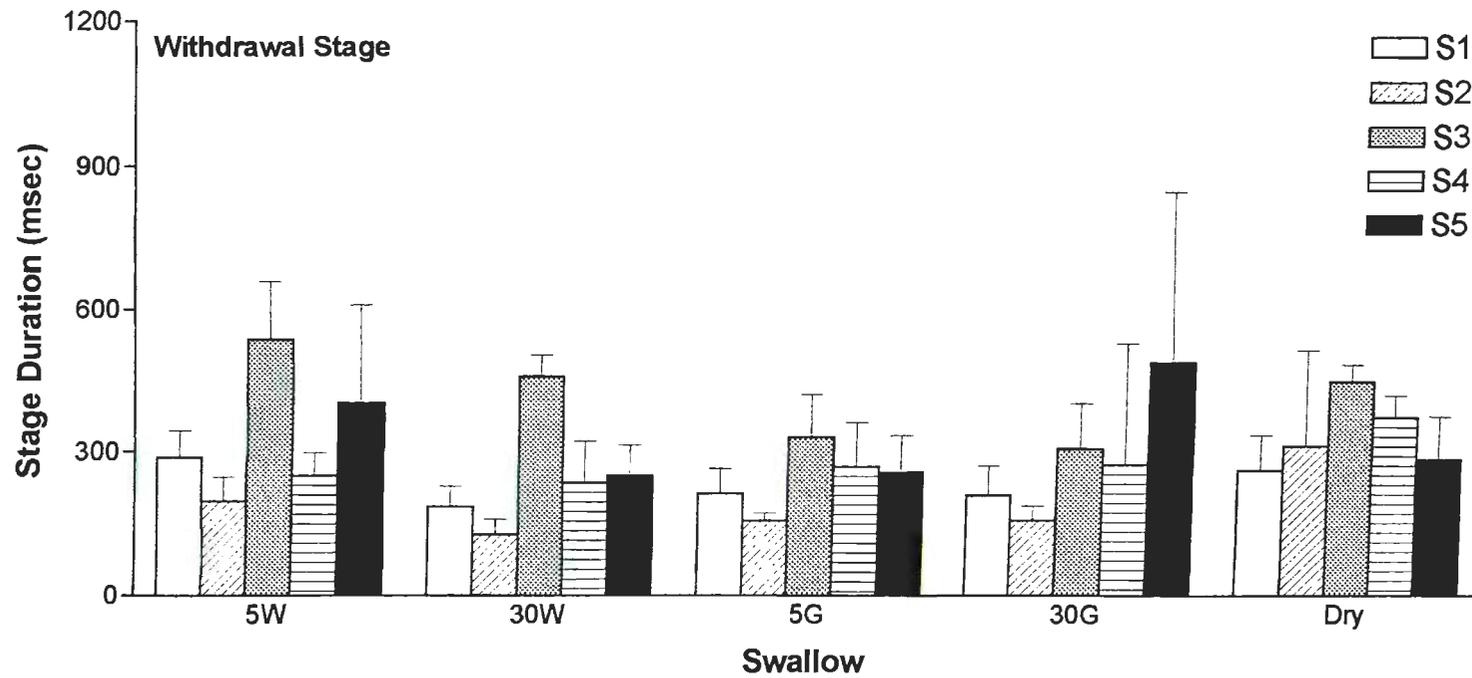


Figure 3.6. Average durations of Stage IV (withdrawal) as a function of discrete swallowing tasks for Subjects 1 to 5 (S1 to S5). 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.



Stage-III durations for all swallows than the other subjects, making this stage the primary source of the intersubject variability for the total swallow duration described in the previous section. In Stage IV (withdrawal, Figure 3.6), S3 had the longest mean durations for all swallowing tasks except 30-cc gelatin, and S2 had the shortest mean durations for all tasks except the dry swallow.

Tongue-Palate Contact Patterns

Contact patterns for individual stages. Average percent-contact profiles (time-series waveforms) from the different swallowing tasks for Subjects 1 to 5 are presented in Figures 3.7 to 3.11⁸, respectively. Each figure consists of two parts with Part (a) illustrating data for the front, central, and back bins and Part (b) illustrating data for the lateral, medial, and midline bins. Contact characteristics specific to each stage are as follows:

1. Prepropulsion stage. The prominent percent-contact pattern, Pattern 1, for this stage was characterized by small, scattered changes in contact over time, mostly in the lateral/back bins, resulting in lateral contacts of <30% by the end of the stage. This pattern occurred in 80% of the data. A variant of this pattern, Pattern 2, was observed in 20% of the data. It was characterized by activation of a greater number of lateral electrodes (>65%) as well as some outer-medial electrodes, resulting in an apparent lateral seal (see Figures 3.7b--5W and Dry, 3.9b--5W, and 3.10b--30W and Dry).

⁸In order to achieve optimal illustration of contact patterns, the X-axes in these figures are scaled uniformly within subjects (i.e., to the longest averaged swallow for each subject) but differently across subjects.

Figure 3.7a. Changes in average percent-contact over time in front (thick solid line), central (thin solid line), and back (dashed line) bins from different discrete swallowing tasks for S1 (female, age 47). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

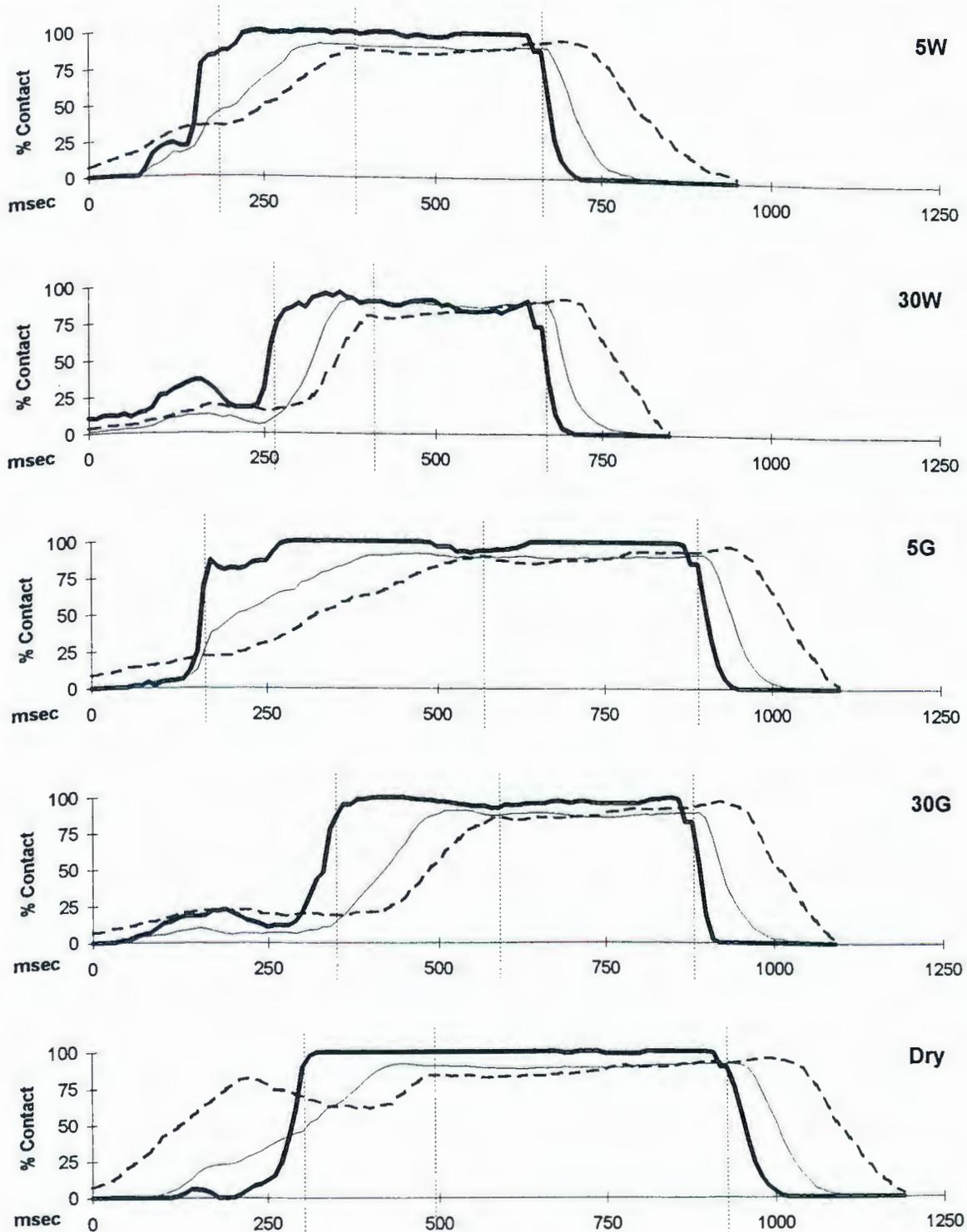


Figure 3.7b. Changes in average percent-contact over time in lateral (black solid line), medial (dashed line), and midline (gray solid line) bins from different discrete swallowing tasks for S1 (female, age 47). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

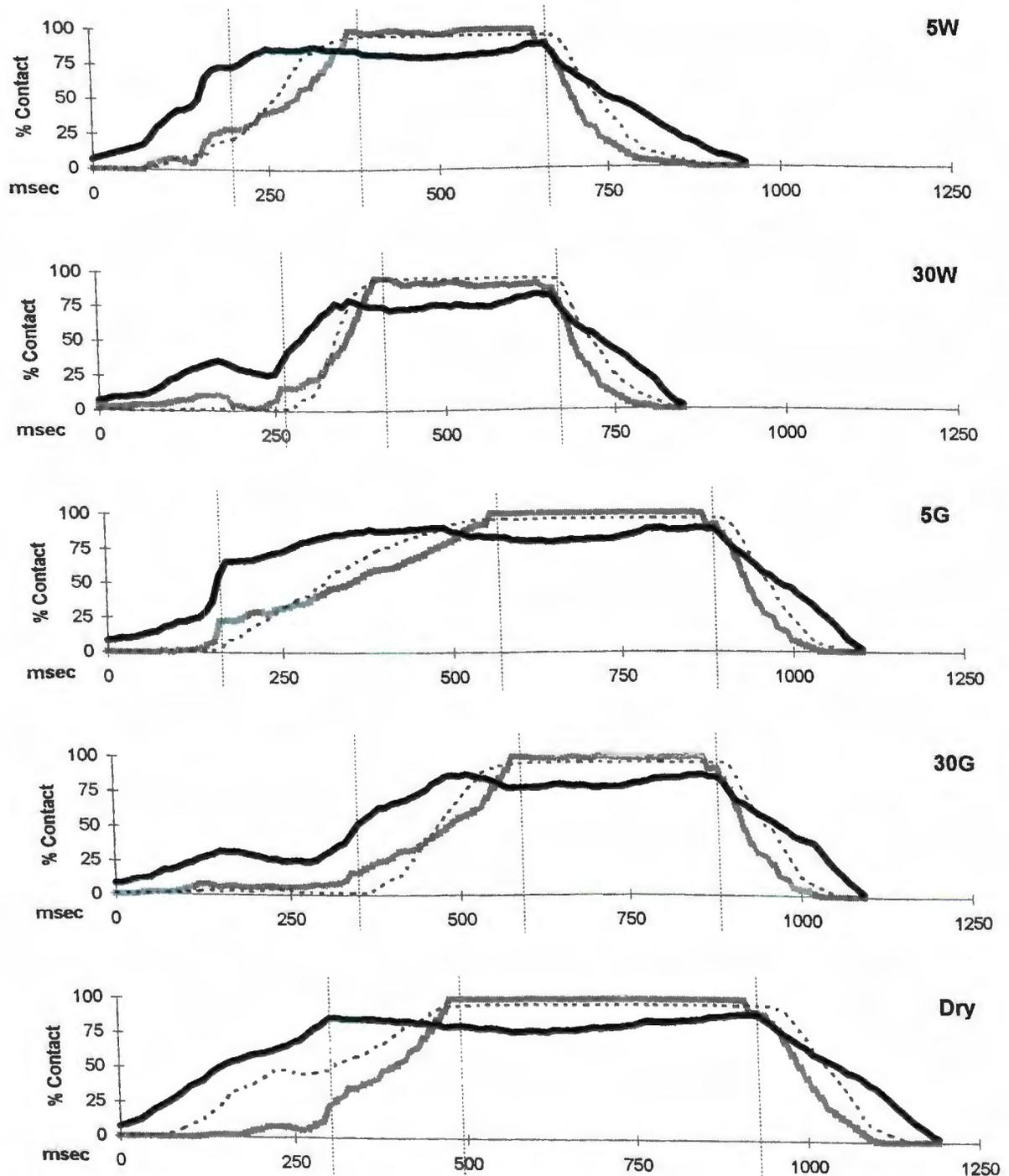


Figure 3.8a. Changes in average percent-contact over time in front (thick solid line), central (thin solid line), and back (dashed line) bins from different discrete swallowing tasks for S2 (female, age 46). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

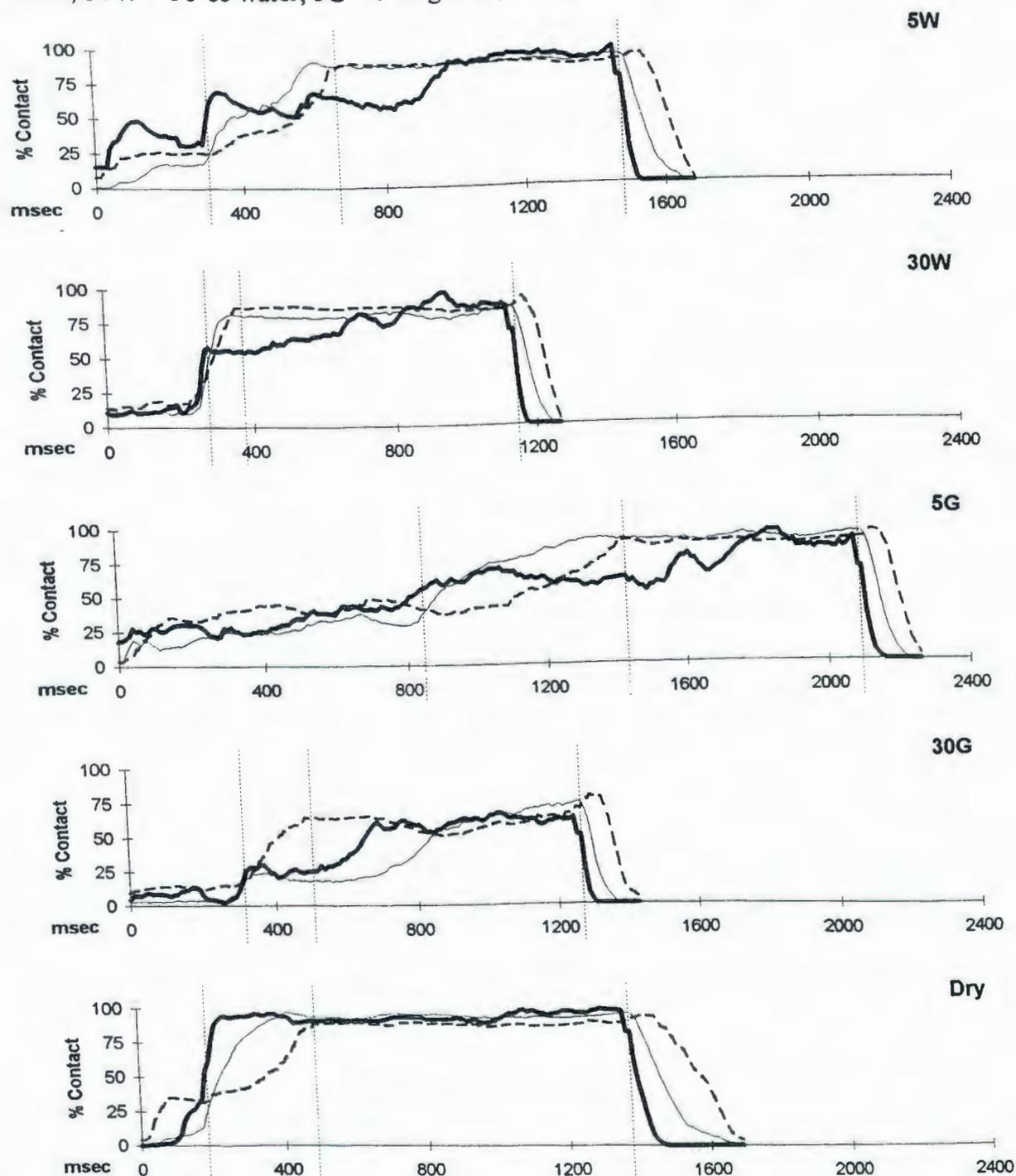


Figure 3.8b. Changes in average percent-contact over time in lateral (black solid line), medial (dashed line), and midline (gray solid line) bins from different discrete swallowing tasks for S2 (female, age 46). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

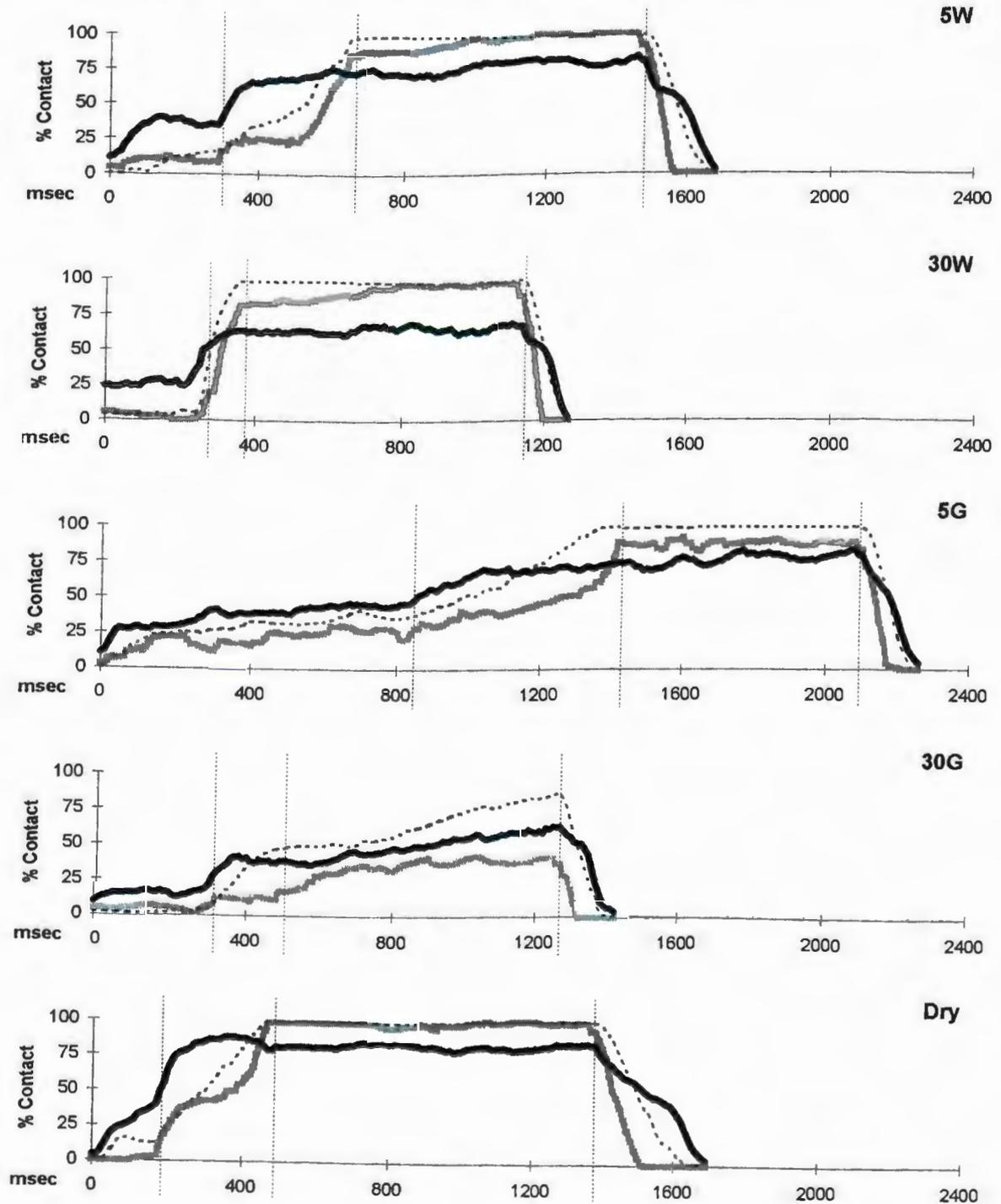


Figure 3.9a. Changes in average percent-contact over time in front (thick solid line), central (thin solid line), and back (dashed line) bins from different discrete swallowing tasks for S3 (male, age 23). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

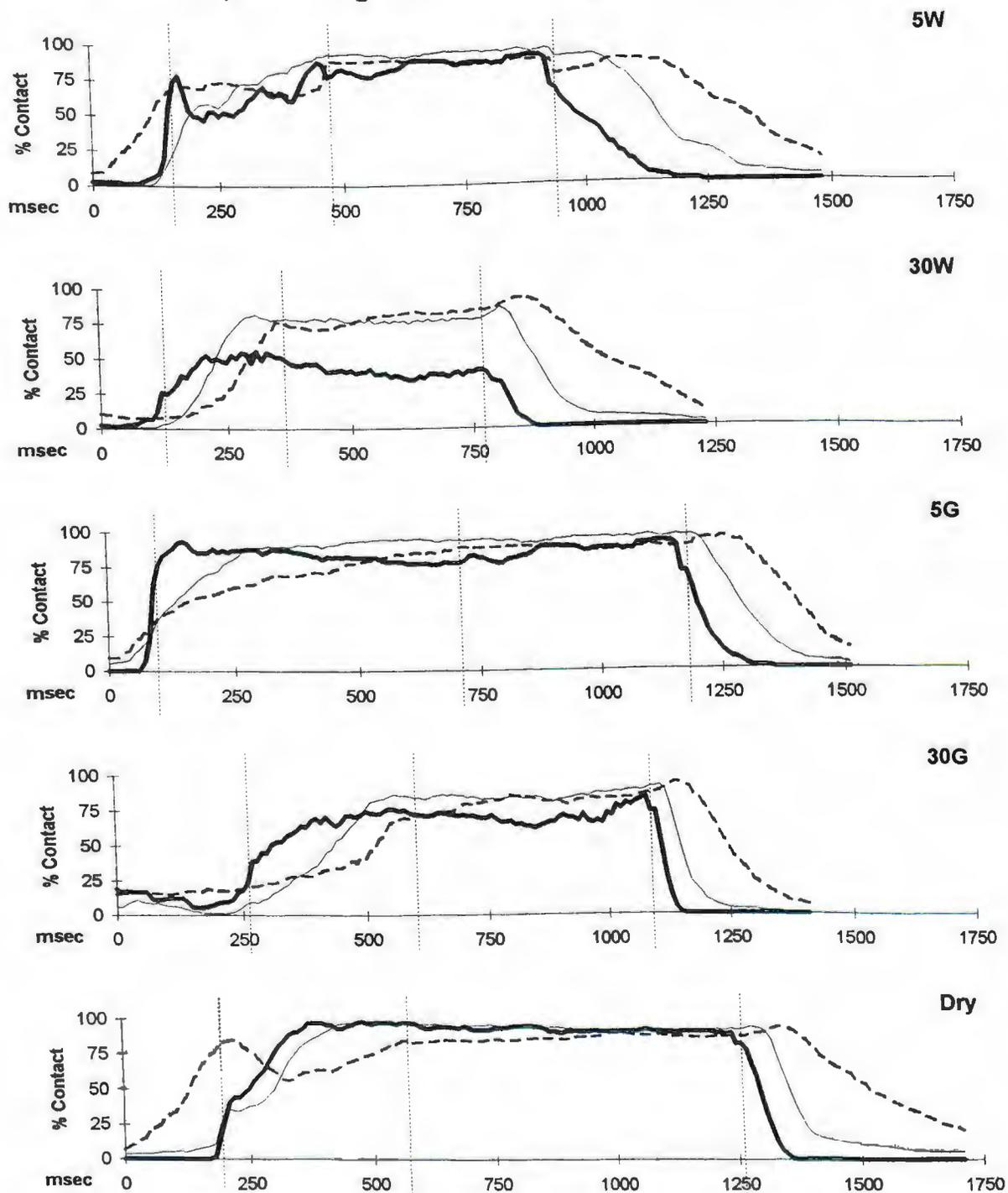


Figure 3.9b. Changes in average percent-contact over time in lateral (black solid line), medial (dashed line), and midline (gray solid line) bins from different discrete swallowing tasks for S3 (male, age 23). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

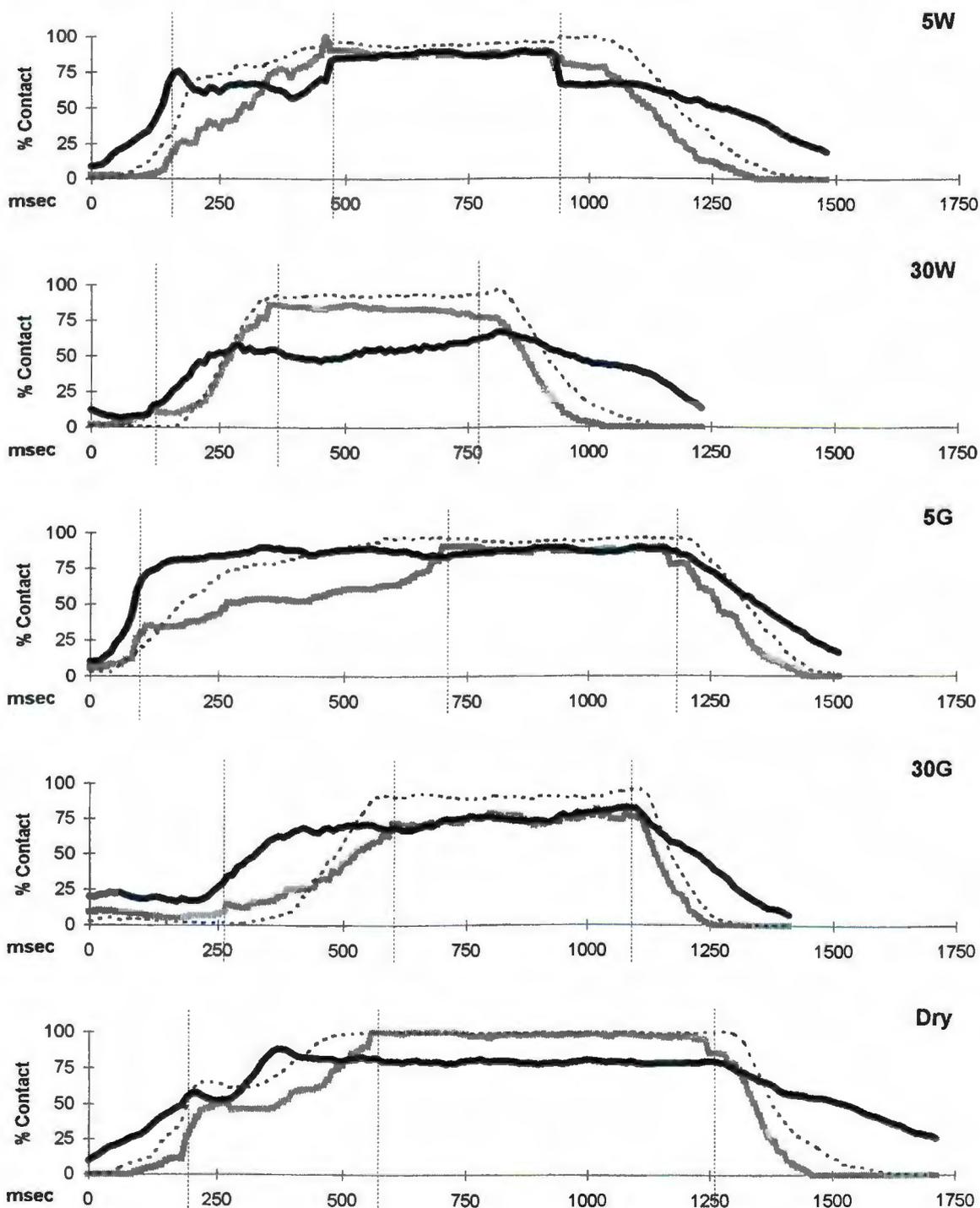


Figure 3.10a. Changes in average percent-contact over time in front (thick solid line), central (thin solid line), and back (dashed line) bins from different discrete swallowing tasks for S4 (male, age 37). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

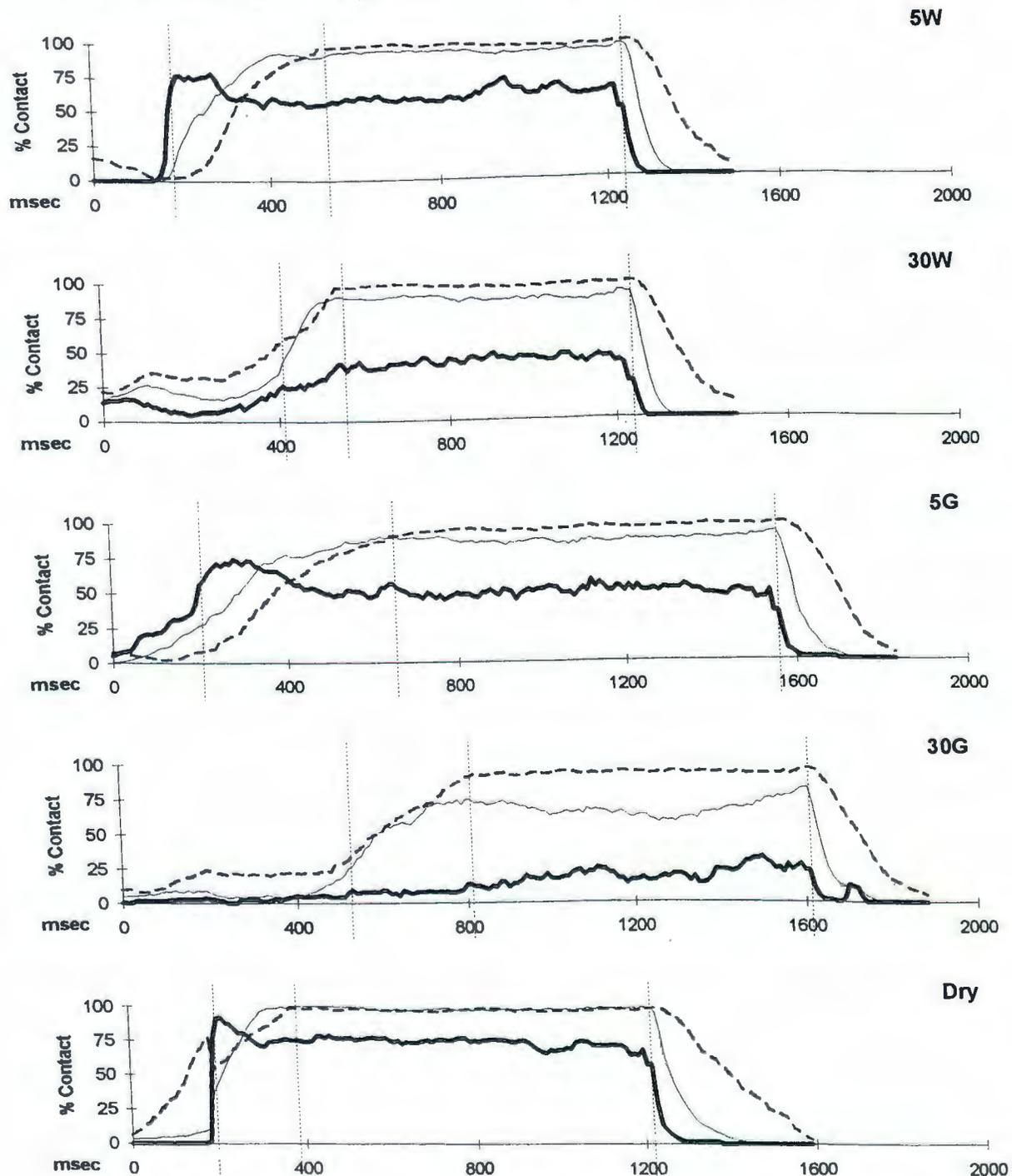


Figure 3.10b. Changes in average percent-contact over time in lateral (black solid line), medial (dashed line), and midline (gray solid line) bins from different discrete swallowing tasks for S4 (male, age 37). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

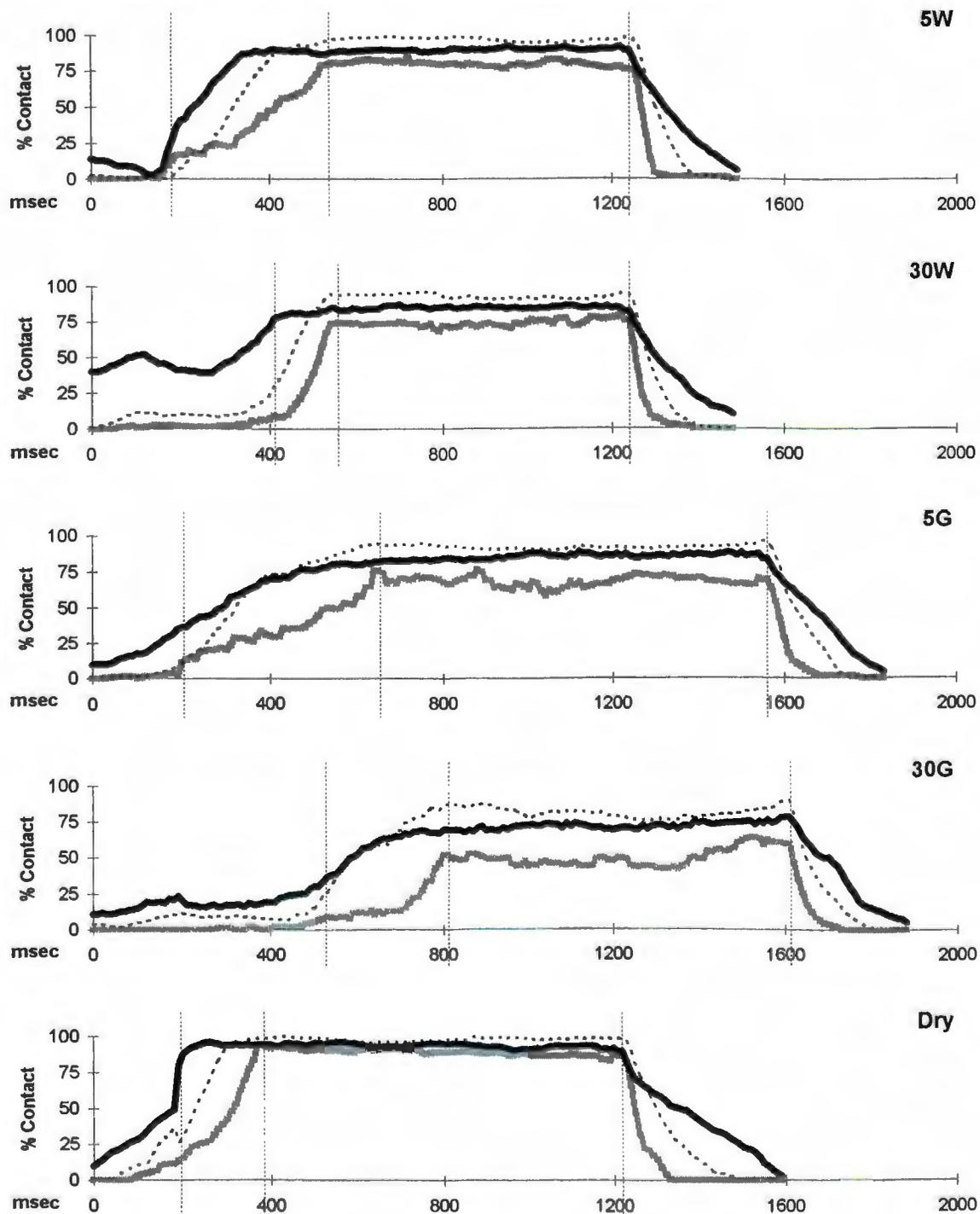


Figure 3.11a. Changes in average percent-contact over time in front (thick solid line), central (thin solid line), and back (dashed line) bins from different discrete swallowing tasks for S5 (female, age 23). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.

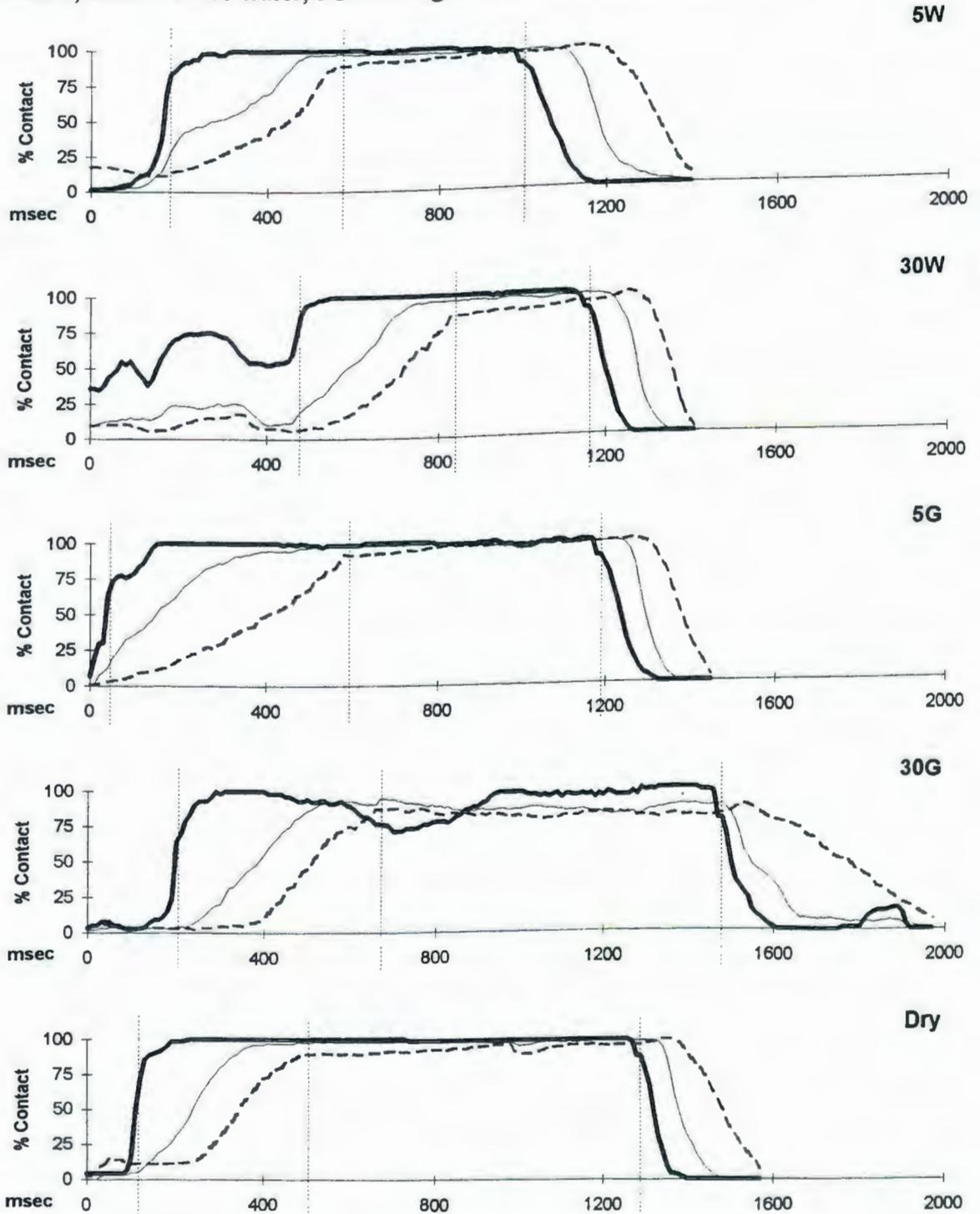
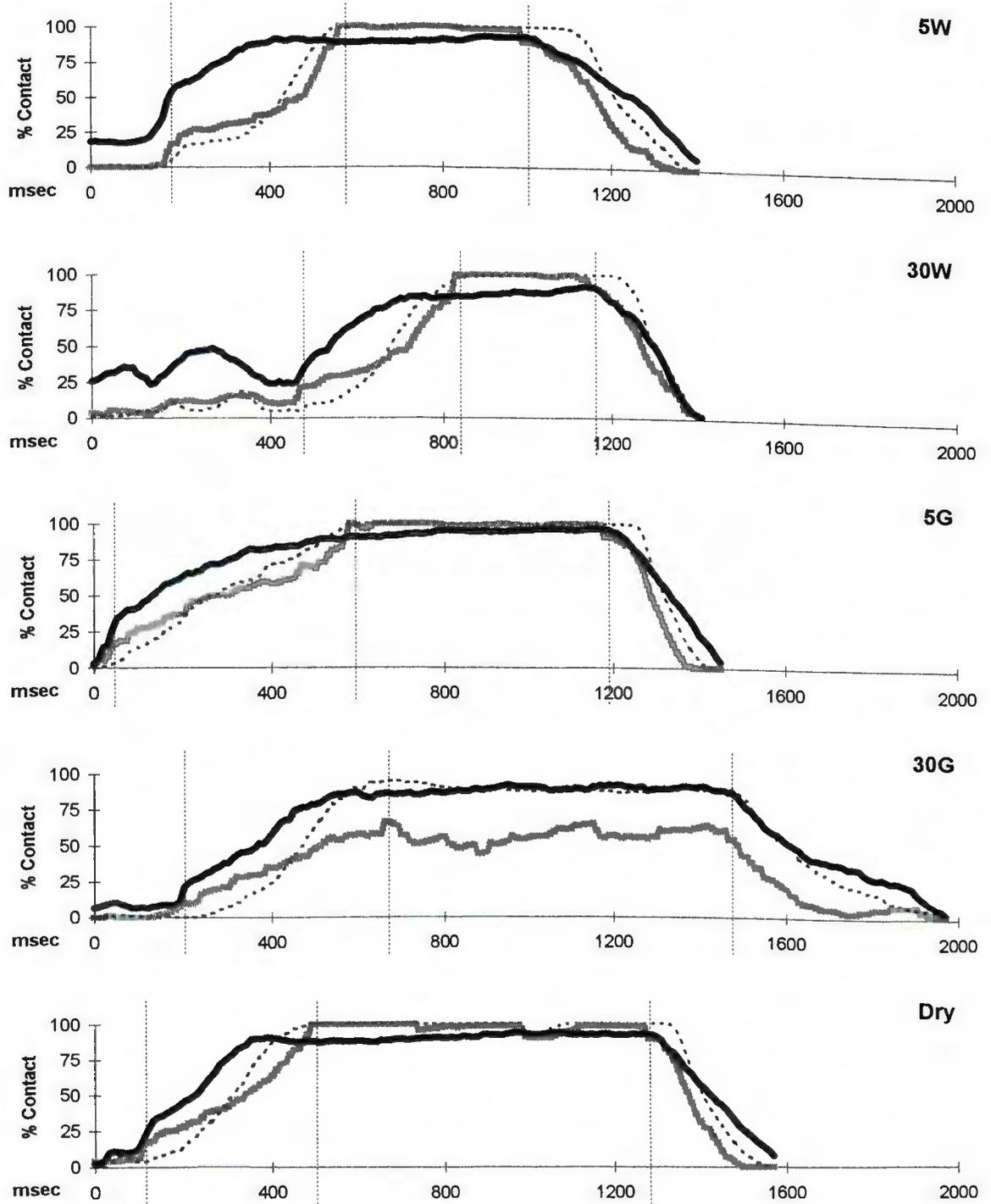


Figure 3.11b. Changes in average percent-contact over time in lateral (black solid line), medial (dashed line), and midline (gray solid line) bins from different discrete swallowing tasks for S5 (female, age 23). Vertical lines demarcate the four stages. 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc gelatin.



2. Propulsion stage. The predominant propulsion pattern, which followed the prepropulsion Pattern 1, began with an abrupt onset of front contact, followed by a steady increase in contact in both a front-to-back and a lateral-to-midline progression, ending with maximal contact for all bins (see Figure 3.12, top). This pattern, occurring in 80% of the data, created a lateral seal simultaneous with the backward propulsion of the bolus. Pattern 2, which followed Pattern 2 of prepropulsion, was seen in the remaining 20% of the data. This pattern was characterized by increasing contacts in a primarily front-to-back progression, occurring in the medial and midline bins (see Figure 3.12, bottom.)

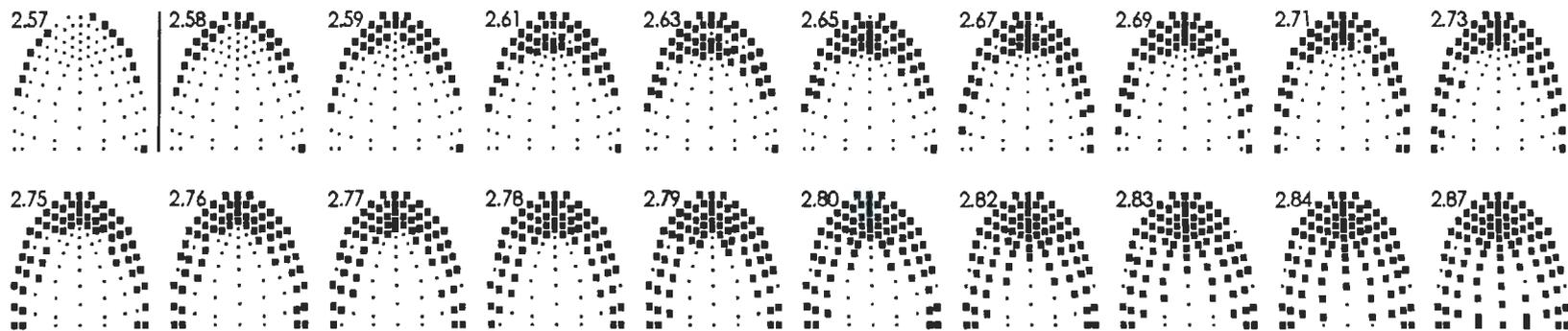
3. Full contact stage. This stage was characterized by stable, maximal contact. Such characteristic can be seen in all panels of Figures 3.7 through 3.11.

4. Withdrawal stage. The characteristic pattern for this stage was a progressive front-to-back and simultaneous midline-to-lateral withdrawal of contact (Figures 3.7-3.11). The pattern of percent-contact retraction was remarkably consistent within subjects and across swallowing tasks.

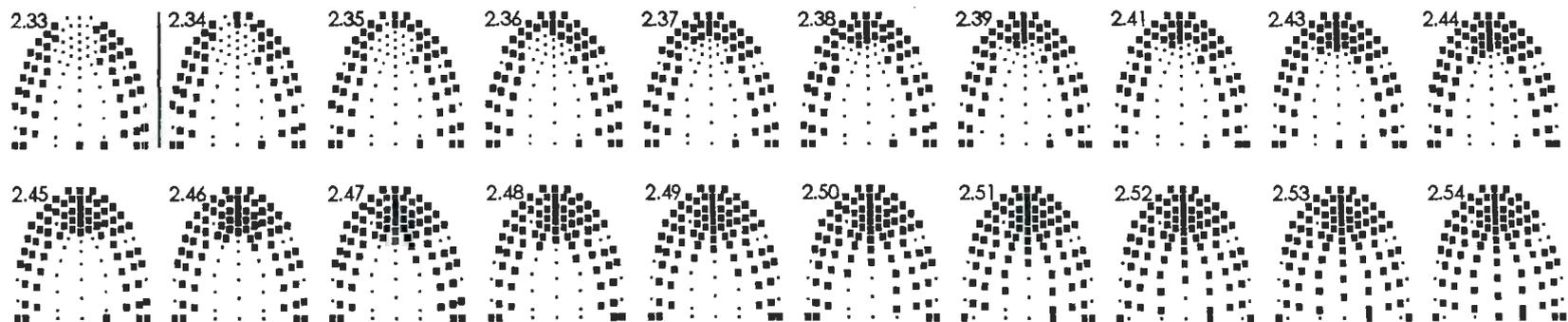
Task effect. No striking effects of swallowing tasks on overall contact patterns were observed. Occasionally, however, there appeared to be slight patterning differences among the tasks. In particular, for Stages II and III, the 30-cc gelatin had an average of 18% less contact (range across subjects = 2-40%) than the other swallowing tasks. In addition, for Stage I, dry swallows had a slightly greater contact (2-17%, \bar{M} = 9%), usually in the back bin, than the other bolus conditions.

Figure 3.12. Raw EPG data from two representative discrete swallows, illustrating Stage-II (propulsion) contact patterns. Pattern 1 (upper two rows) shows simultaneous front-to-back and lateral-to-midline increase in contact. Pattern 2 (lower two rows) shows prominent lateral seal at Stage-II onset and primarily front-to-back progression in contact increase. Each series begins with the last frame of Stage I (prepropulsion). The vertical line demarcates the onset of Stage II.

Pattern 1:



Pattern 2:

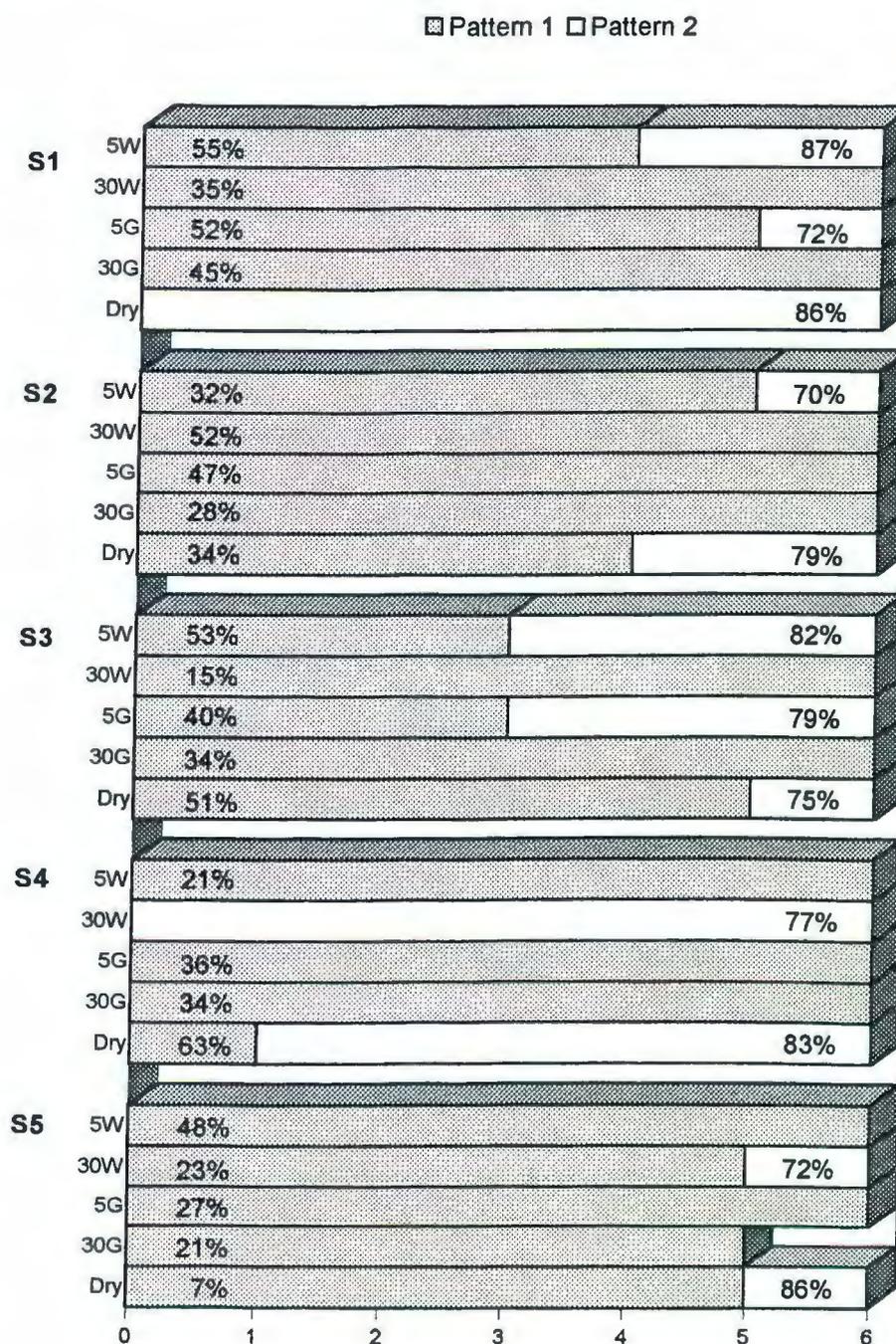


Examination of contact patterns 1 and 2 (described above for the prepropulsion and the propulsion stages) as a function of swallowing task revealed that Pattern 1 occurred across all swallowing tasks, and Pattern 2 occurred in all except the 30-cc gelatin boluses. The dry swallow had a relatively greater frequency of Pattern 2 (15/32 cases) in contrast to the other tasks (6/32 for 5-cc water, 7/32 for 30-cc water, 4/32 for 5-cc gelatin), particularly for S1 and S4 (see Figure 3.13).

Analysis on the order in which maximal contact was achieved in the front (F), lateral (L), and back (B) bins during Stage II showed a variety of sequences. However, the predominant pattern, observed across all tasks in 102 of 149 individual swallows, followed a front-lateral-back progression of “peaking”. In 17 of 149 swallows, the front and the lateral bins reached maximal contact at the same time, followed by the back bin. This was considered a variant of and therefore grouped with the front-lateral-back pattern. Since the remaining patterns (e.g., L-F-B, F-B-L, B-F-L, L-B-F, B-L-F) were few in frequency (most with only 2 or 3 cases), they were grouped as “others.” Subsequent Chi-Square test of the two groups showed a significant subject effect (discussed below) but no significant effect of swallowing tasks.

Subject variability. The post-warp, frame-by-frame descriptive statistics (i.e., M, SD, and CV) were examined by bin, stage, and task for intrasubject variability in overall percent-contact patterns. Data from S1 and S4 were on the whole somewhat less variable than those from the other subjects, although all subjects showed greater replication variability in Stage I than they did in the other stages. The CV data revealed that

Figure 3.13. Frequency distribution of contact patterns 1 and 2 for different discrete swallowing tasks and subjects based on raw percent-contact data in lateral bin at Stage-II onset. Pattern 1 = <65%, Pattern 2 = >65%; 5W = 5-cc water, 30W = 30-cc water, 5G = 5-cc gelatin, 30G = 30-cc gelatin. Inserted percentages are the means for the respective patterns, swallowing tasks, and subjects.



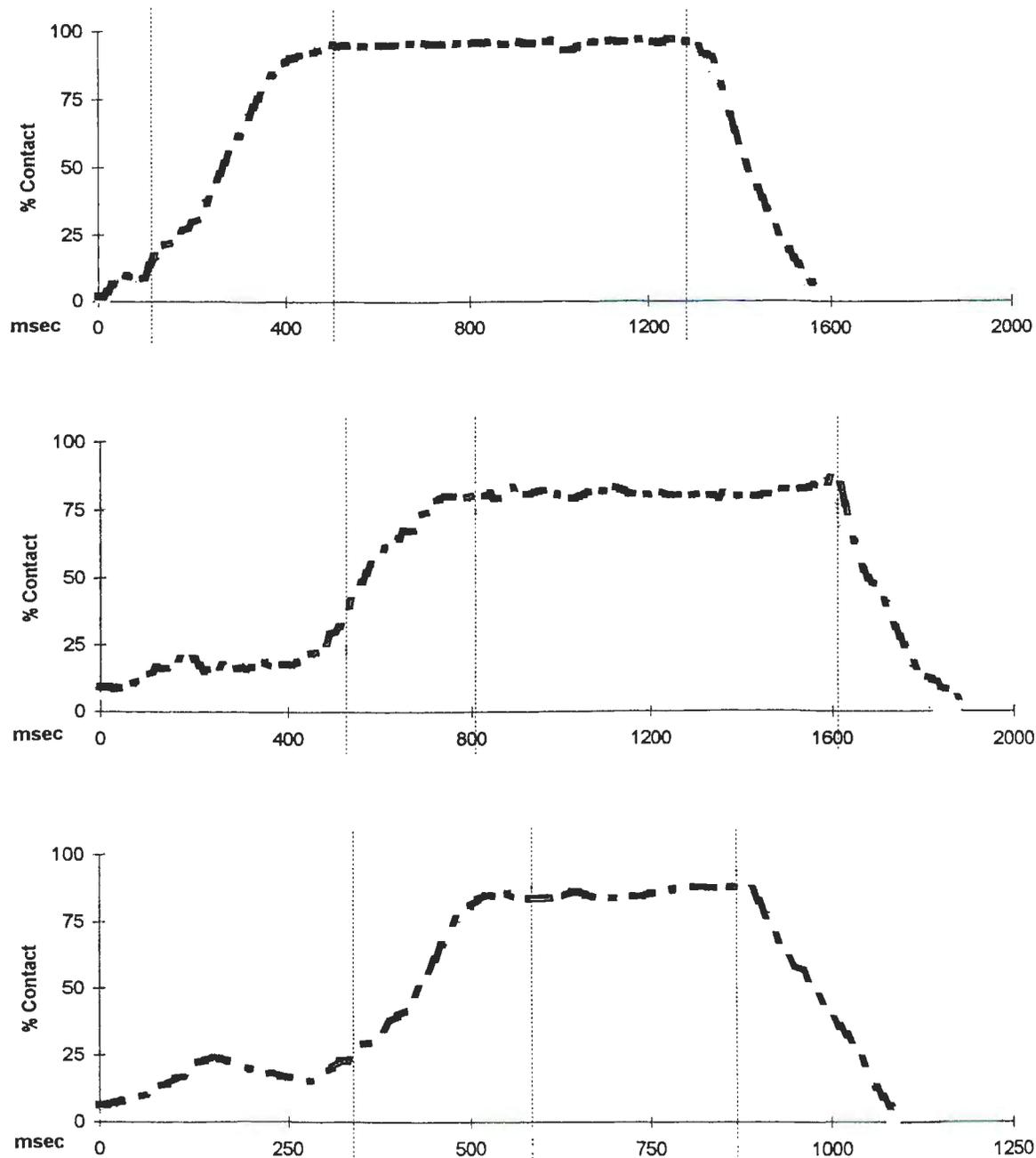
replication variability was high ($\text{CV} > 2$) in 19% of all cases, moderate ($1 < \text{CV} < 2$) in another 19% of cases, and low (mean $\text{CV} = .20$) in the remaining 62% of cases. In all subjects, trial-to-trial variations for Stages II and III were mostly small.

Intersubject variations in overall percent-contact patterns appeared trivial.

Occasionally, some subjects showed less front and/or lateral contact in selected stages, or used extra preparatory tongue movement during Stage I. Substantial subject differences were seen in the use of Patterns 1 versus 2. S1 and S4 used Pattern 2 more often than the other subjects (see Figure 3.13). Subject variations were also apparent in the ordering of percent-contact maxima during Stage II. S3 and S4 (both male) were the primary sources of the “other” sequence patterns (13/30 swallows in S3, 10/30 in S4), while the remaining subjects showed predominantly the front-lateral-back sequence. Of all the single-swallow analyses and observations, this was the only occasion where some differences attributable to subject gender appeared to exist. However, due to the small sample size, gender effect was not specifically evaluated, and no conclusions could or should be drawn.

Left-right symmetry. Remarkable left-right symmetry (see Figure 3.14, upper panel) was observed in the majority of the data. On the occasions where asymmetry was seen, the left and the right sides differed minimally in the amount of percent-contact and not at all in overall contact pattern (see Figure 3.14, middle panel). Most of the asymmetry tended to occur near the beginning of Stage I (prepropulsion) and/or near the end of Stage IV (withdrawal) (see Figure 3.14, lower panel).

Figure 3.14. Changes in average percent-contact over time in left (gray solid line) and right (dashed line) bins from representative discrete swallows of selected subjects. Upper panel shows the remarkable symmetry seen in most cases. Middle panel demonstrates left-right differences in amount but not pattern of percent-contact. Lower panel shows typical locations of assymetry: near Stage-I start and near Stage-IV end. Vertical lines demarcate the four stages.



Ultrasound Findings

The sagittal ultrasound data on discrete swallowing for all subjects were examined. However, due to considerable variations in image quality, only the data from S5 were used in illustrations and for displacement measurements.

Swallow-Related Lingual Behaviors on Ultrasound

The ultrasound visualization of the swallowing task for this study contained four stages, i.e., prepropulsion, propulsion, full contact, and withdrawal, just as distinctly identifiable as those seen on EPG. However, the ultrasound and the EPG stages differed in scope and behavioral details because of the innate capabilities as well as drawbacks of each instrumentation.

Movement-tracking for the four functional tongue segments (anterior, mid, dorsal, and posterior) on ultrasound revealed that a swallow or task response typically began with anterior and superior movement of all tongue segments from the resting position, loading the bolus onto the tongue surface (prepropulsion). Next, the tip of the anterior segment was anchored against the tip of the hard palate, followed by serial elevation of the mid, dorsal and posterior segments to maximal displacement. With these movements, the bolus was progressively propelled backward into the pharynx (propulsion). The entire tongue remained maximally elevated against the palate for a period of time (full contact). Finally, the tongue began to pull away from the palate and return to the resting position (withdrawal). The withdrawing action, as part of the post-swallow mouth-opening gesture, often began with the anterior segment and progressed through the mid or dorsal

segment in a “peel-away” fashion, followed by further lowering of the entire tongue as a whole. However, it was also not uncommon to see a slight descent of the posterior tongue just before the anterior segment lowered. The basic pattern of lingual actions described above was observed across subjects and swallowing tasks.

Ultrasound versus EPG: Descriptive Comparison

Because the sagittal ultrasound images depicted movements of only a 2-mm thick, midline section of the tongue, precise correlations of EPG contact details and ultrasound lingual behaviors were not possible. For example, any EPG activities in the lateral and the medial bins were not visualized on ultrasound. However, with the inclusion of synchronized trigger signals (click and glottalized /ɑ/) on both EPG and ultrasound data, gross comparisons could be made of EPG contact activities and ultrasound tongue movements.

Movements of the anterior, mid, and dorsal (partial) tongue segments during propulsion and withdrawal paralleled the contact activities observed on EPG during Stages II and IV. However, since EPG registers only tongue-hard palate contact, lingual actions before and after contact as well as during steady-state maximal contact, though very much a part of the swallowing maneuver, are not shown. Specifically, four sets of ultrasound lingual behaviors were not reflected on EPG in the present study. These included: (a) some of the initial prepropulsive movements (occurring before any tongue-palate contact), (b) the propulsive motion of the posterior segment as well as part of the dorsal segment, (c) the occasional early withdrawal of the posterior segment, and (d) the

final descent of the entire tongue to the resting position (occurring after EPG withdrawal). As a result, the EPG prepropulsion and withdrawal stages were usually shorter than the equivalent ultrasound periods, and the ultrasound full contact period was usually shorter than the EPG full contact stage. In other words, while full contact was maintained on EPG, propulsive lingual movements were continued in the posterior tongue segment on ultrasound.

The EPG data provided considerably more detailed information than ultrasound on the interaction of the tongue and the palate, adding a new and unique dimension to the understanding of lingual motor function during swallowing. Details such as the front-to-back and simultaneous lateral-to-midline contact increase during propulsion, and the front-to-back and simultaneous midline-to-lateral withdrawal were not visible on ultrasound.

Task Effect on Ultrasound

The finding of some significant bolus effects on EPG provided an incentive to examine tongue shapes as a function of swallowing tasks on ultrasound. Figures 3.15 (Parts a and b) illustrate, in series, temporally comparable, “significant” frames from five representative swallows--one for each bolus type--of the same subject. As discussed below, several bolus-induced differences in tongue shape can be seen in the images, though by the time the dorsal segment reached maximal displacement, tongue shapes became essentially the same.

Pre-swallow (Figure 3.15a, Row 1). While in a rest state, the tongue was compressed to varying extent, depending on the bolus volume. For the small water and

Figure 3.15a. Changes in tongue shape over time as a function of discrete swallowing task. All frames were selected based on specific criteria from representative swallows of the same subject. Frames in Rows 1, 2, and 3, in order, illustrate tongue shapes at rest (tip to back from left to right), when entire bolus was first loaded on tongue surface, and at maximal displacement of anterior tongue segment. Arrows in each image mark points on tongue surface. 5W=5-cc water, 5G=5-cc gelatin, 30W=30-cc water, 30G=30-cc gelatin.

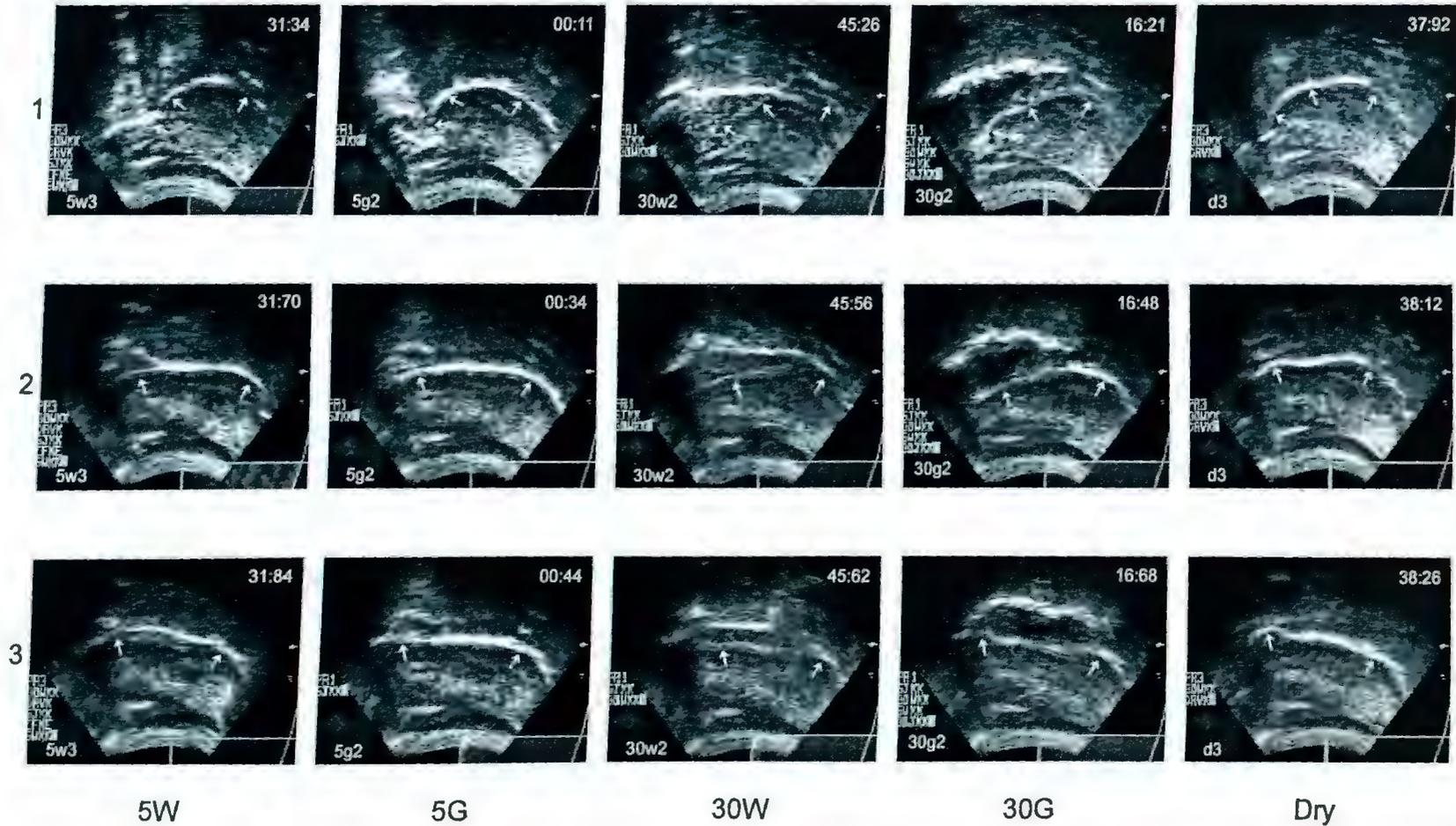
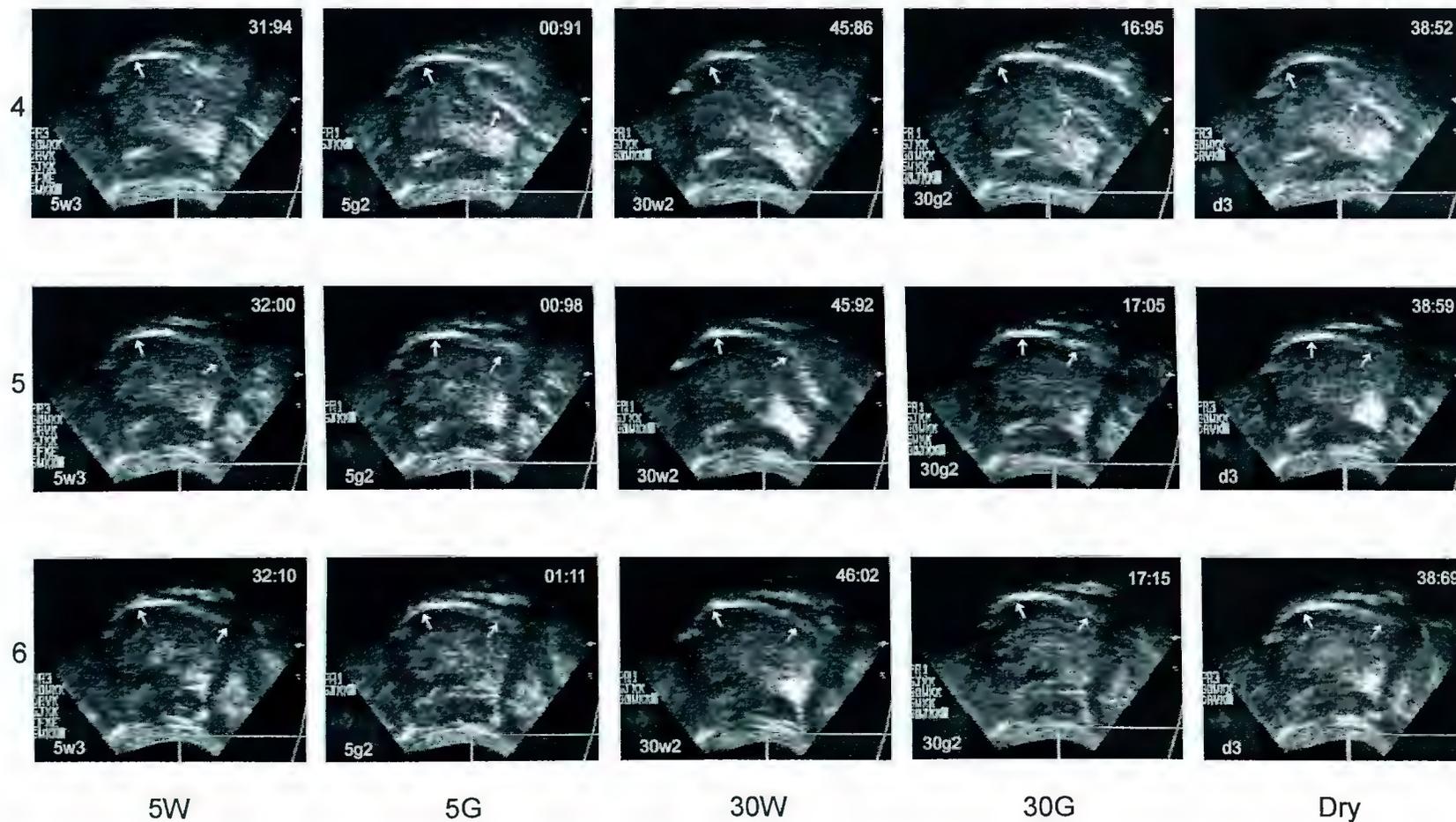


Figure 3.15b. Changes in tongue shape over time as a function of discrete swallowing task. All frames were selected based on specific criteria from representative swallows of the same subject. Frames in Rows 4, 5, and 6 illustrate tongue shapes (tip to back from left to right) at maximal displacement of mid, dorsal, and posterior tongue segments, respectively. Arrows in each image mark points on tongue surface. 5W = 5-cc water, 5G = 5-cc gelatin, 30W = 30-cc water, 30G = 30-cc gelatin.



gelatin boluses, the tongue was arched and slightly retracted. Large-volume boluses were associated with a lower and more compressed tongue. In dry swallows where bolus size was minimal, the tongue showed no compression. Differences due to bolus consistency were more apparent in the case of large boluses. Gelatin tended to remain as a cohesive mass on the tongue with more collected anteriorly than dorsally; water, naturally less cohesive, tended to be contained in front of as well as on the anterior tongue. As a result and for apparent safety reasons, the anterior tongue was somewhat more retracted and the dorsal and posterior segments slightly more hunched for water than for gelatin (see Figure 3.15a, Row 1, 30W vs. 30G).

First appearance of entire bolus on tongue surface (Figure 3.15a, Row 2). At the moment when the entire bolus was loaded onto the lingual surface, the tongue assumed a more level, horizontal posture for dry and 5-cc boluses than for large boluses. The large volumes continued to induce a depression in the anterior and mid tongue segments.

Maximal displacement of anterior segment (Figure 3.15a, Row 3). With the anterior segment anchored to the front of the hard palate and with propulsion commencing, the tongue was seen to assume a slight backward slope regardless of bolus type. Again, the large boluses tended to depress the tongue slightly more. No striking consistency-based differences were observed at this point.

Maximal displacement of mid segment (Figure 3.15b, Row 4). Backward tongue slope was greatest at this moment. The dorsal and the posterior segments were slightly higher for 5-cc water and dry swallows than for the other bolus types.

Maximal displacement of dorsal and posterior segments (Figure 3.15b, Rows 5 and 6). The bolus had essentially left the oral cavity at this point. Therefore, little variation in tongue shape was observed as a function of swallowing task.

In short, volume-based differences in tongue shape were observed during the pre-swallow state, prepropulsion, and most of propulsion, while consistency-based differences were more apparent during pre-swallow. It should be emphasized that regardless of the task at hand, progressive anchoring of functional segments from front to back appeared to be an important and consistent strategy utilized by the tongue to achieve successful transport of the bolus through the oral cavity.

Lingual Velocity Profiles: Single-Subject Data

Recall that the EPG data showed significant differences in contact timing for Stage II (propulsion) as a function of bolus consistency (water faster than gelatin) and size (30 cc faster than 5 cc). Comparable differences in lingual movement velocity were expected. Frame-by-frame, radial displacement data were extracted for the four tongue segments during prepropulsion and propulsion. Velocities were then calculated, and a velocity profile--a waveform of changes in instantaneous velocity over time--was plotted for each swallow. It should be pointed out that the accuracy of frame-by-frame displacement tracking depended greatly on the sharpness of the tongue surfaces imaged. In the present study, due to lingual tissue variations in the individual subjects and resultant variations in image quality, adequate measurement accuracy could only be maintained with

the images from Subject 5 (S5). Therefore, only the velocity data of this subject are reported.

Figure 3.16 illustrates the velocity profiles of the four tongue segments from representative discrete swallows of S5. Intervals equivalent to EPG Stages I - III are marked. The velocity profiles captured the time progression of bolus transport from front to back, demonstrating the stereotypical, spatiotemporal concatenation of the four functional segments. Also visible in the profiles were the upward and downward velocity shifts which corresponded to the ascent and descent of each tongue segment during bolus transport. The succession in which each segment achieved its positive peak velocity, unvarying within and between tasks, resembled that of a “whip” effect, as if the segments were links in a chain. The dorsal and the posterior segments had relatively greater negative velocity peaks than the other segments (EPG Stage II), indicating tongue lowering. The magnitude of the negative peaks, however, showed no consistent task-specific trends. During EPG Stage III, positive peak velocity for the posterior segment was achieved. This was true for the dorsal segment as well, in all except the 30-cc gelatin swallows (see Figure 3.16, 30G).

Average positive peak velocities from the different swallowing tasks for S5 are presented in Table 3.2. Also included are the average intervals from onset to positive peak velocity (OTP). Within-task comparisons showed the dorsal tongue segment to have greater peak velocity than all other segments for all swallow types. Between-task comparisons revealed that 30-cc water swallows had greater mean peak velocities than all other swallows for all tongue segments. The most striking contrasts observed were

Figure 3.16. Velocity profiles for four tongue segments from representative discrete swallows of S5. Values (in mm/sec) are instantaneous velocities from first move of tongue to point of maximal posterior displacement. Missing initial data points for anterior segment were due to lack of tongue-grid intersections. Vertical lines demarcate corresponding EPG Stages I-III. Ant = Anterior; Dors = Dorsal; Post = Posterior; 5W = 5-cc water; 30W = 30-cc water; 5G = 5-cc gelatin; 30G = 30-cc

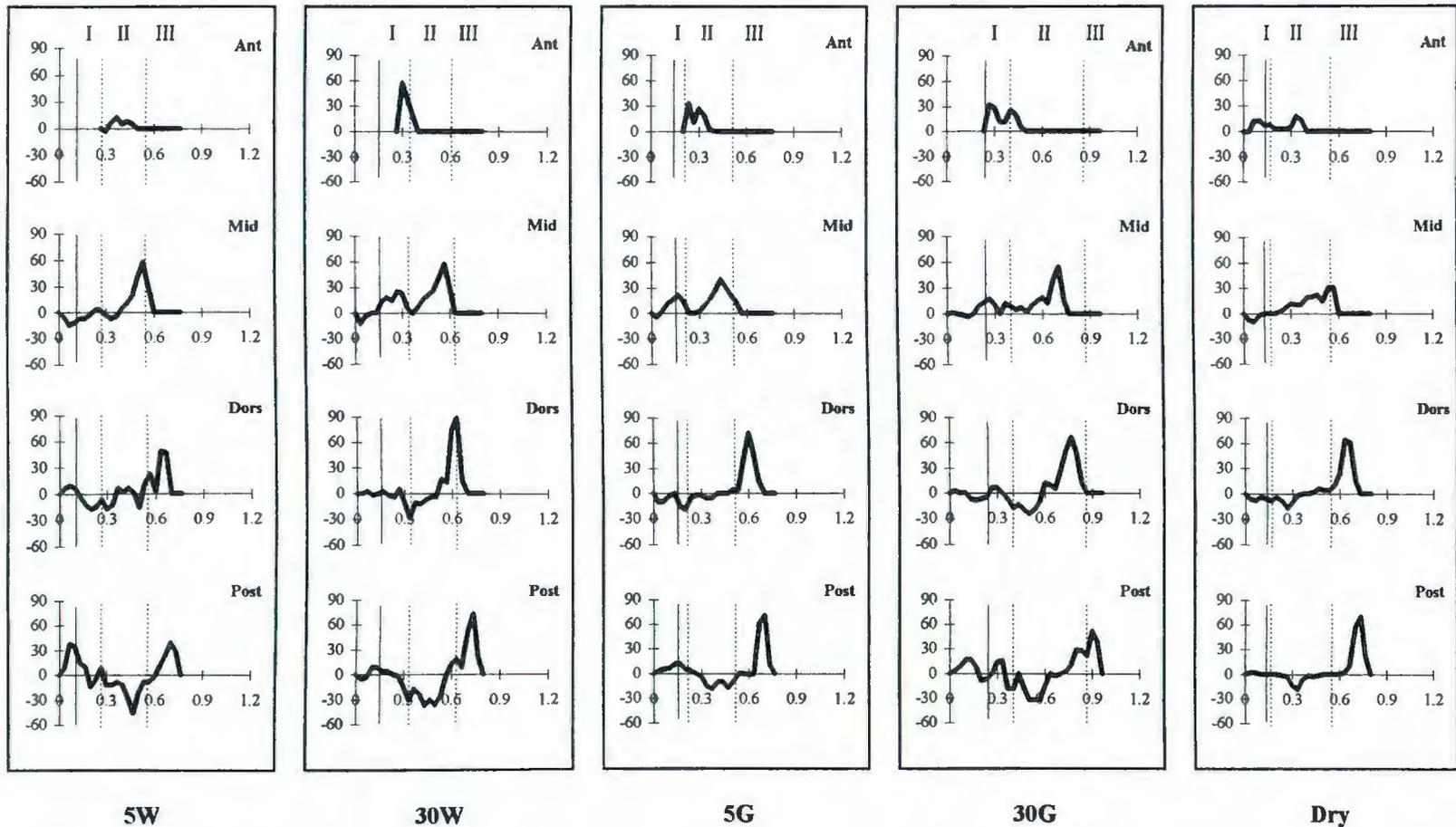


Table 3.2. Mean positive peak velocities (in mm/sec) and onset-to-peak (OTP) intervals (in sec) for the four tongue segments from different discrete swallows of Subject 5. 5W = 5-cc water, 30W = 30-cc water, 5G = 5-cc gelatin, 30G = 30-cc gelatin. Diff = difference in mean OTP values between tongue segments.

		Positive Peak Velocity				OTP Interval			
		Anterior	Mid	Dorsal	Posterior	Anterior	Mid	Dorsal	Posterior
5W	<u>M</u>	21.49	48.72	53.49	30.86	0.42	0.54	0.63	0.73
	<u>SD</u>	8.00	14.76	4.14	8.39	0.05	0.02	0.03	0.03
	<u>Diff</u>						0.12	0.09	0.10
30W	<u>M</u>	53.57	55.44	73.04	67.97	0.32	0.55	0.63	0.73
	<u>SD</u>	5.17	2.32	22.25	7.00	0.02	0.02	0.00	0.00
	<u>Diff</u>						0.23	0.08	0.10
5G	<u>M</u>	33.78	30.30	70.74	61.47	0.27	0.52	0.76	0.86
	<u>SD</u>	2.04	11.49	5.54	19.36	0.09	0.13	0.13	0.14
	<u>Diff</u>						0.26	0.23	0.10
30G	<u>M</u>	27.77	53.30	65.61	53.23	0.35	0.80	0.87	0.98
	<u>SD</u>	5.77	1.56	0.97	2.53	0.12	0.14	0.14	0.12
	<u>Diff</u>						0.45	0.07	0.12
Dry	<u>M</u>	29.13	31.85	70.15	62.71	0.27	0.49	0.61	0.68
	<u>SD</u>	9.93	1.07	9.14	14.61	0.05	0.05	0.04	0.05
	<u>Diff</u>						0.22	0.12	0.07

between 30-cc and 5-cc water tasks for the anterior and the posterior segments, where the larger volume consistently induced 38-78% (based on raw data) greater peak velocities. The 30-cc gelatin swallows also had 23-67% higher peak velocities than their 5-cc parallels, though only for the mid tongue segment. Dry swallows, on the other hand, had consistently greater posterior peak velocity than small-sized water swallows. Other differences due to bolus consistency were generally inconsequential. The gelatin and dry swallows hardly differed in peak velocity for any tongue segment, though most of the water swallows had greater peak velocities than dry swallows for the mid tongue.

Data on the OTP intervals showed no particular size- or consistency-based trends. However, the duration between moments of anterior- and mid-tongue peak velocities was the shortest for 5-cc water and the longest for 30-cc gelatin. In addition, 5-cc gelatin took a longer time than the other tasks to attain dorsal-tongue peak velocity after reaching mid-tongue peak.

Correlation of EPG Timing Measurements with Ultrasound Activity

Guided by the reference images (see Figure 2.4) which depicted the general landmarks of the individual pseudopalates, attempts were made to correlate the EPG timing measurements and associated contact activities with time-aligned ultrasound tongue shapes for general consistency. In 70% of the cases, reasonable parallels between the ultrasound and the EPG activities were observed. That is, activation of electrodes in the front bin on EPG (propulsion onset) matched maximal displacement of the anterior segment on ultrasound; end of propulsion on EPG followed maximal displacement of the mid segment but preceded that of the dorsal segment on ultrasound. In 30% of the cases,

a mismatch by one to two ultrasound frames did occur. Considering the difference in sampling rate between the two instruments (1/30 vs. 1/100 sec per frame for ultrasound and EPG, respectively), the mismatches appeared relatively trivial.

Identification of Unusual Lingual Behaviors

The screening of all swallows on ultrasound revealed only one case of “double swallowing”. This occurred on one 30-cc gelatin trial in S5, where the bolus clearly was emptied in two successive swallows--80% on the first and 20% on the second (estimation based on the imaged bolus “area” at the onset of each swallow). Because there was material remaining in the mouth, the tongue did not lower completely at the end of the first swallow before the next wave of propulsive action began. The EPG correlate for this particular bolus showed the typical prepropulsion and propulsion activities but deactivation of electrodes sporadically on the entire palate near the end of propulsion, followed by complete reenactment of the propulsive process, then full contact, and withdrawal. That is, on EPG, the first swallow did not have a “full contact” stage or a typical “withdrawal” stage, and the second swallow did not have a prepropulsion stage.

Although most swallows exhibited regular and systematic lingual behaviors on ultrasound, extra tongue movements were observed during prepropulsion in 9% of all data. These usually occurred as a rise-fall-rerise (in contrast to a simple elevation) of the tongue. The corresponding EPG data typically had a longer prepropulsion stage during which scattered clusters of electrodes were sequentially activated, deactivated, and reactivated. These cases were distributed across all swallowing tasks, but more in S2 than in the other subjects.

Summary

The EPG data for single swallows showed stage-specific effects of bolus volume and consistency in contact timing. Mainly, larger volume and thinner consistency had a significantly shorter duration of propulsion (Stage II), and dry swallows were significantly longer than water swallows in full contact (Stage III). Contact patterns for the individual stages were distinctive but varied minimally as a function of swallowing task and subject. In the majority of the single swallows examined, tongue-palate contact followed a front-to-back and simultaneous lateral-to-midline progression during bolus propulsion, and a front-to-back and simultaneous midline-to-lateral pattern of withdrawal. These details have not been included in conventional descriptions of deglutitive tongue action.

While the ultrasound and the EPG swallow activities could not be precisely matched due to limitations unique to each instrument, the two techniques provided supplementary information that made the observation of swallowing more complete. Ultrasound imaging supplemented the EPG findings with activities before and after tongue-palate contact, while EPG filled in the missing information on lateral and medial linguopalatal interactions. The single-subject velocity data provided apparent indications of task-induced differences, especially with respect to bolus size. Larger-volume swallows did have greater peak velocities than small-volume swallows, at least for some tongue segments. This primary finding agreed with the EPG results and supported the usefulness of EPG analysis of swallowing.

Experiment 2. Sequential Swallowing in Continuous Drinking

EPG Findings

Tongue-Palate Contact Timing

Total duration. Average total durations of the component (i.e., first and subsequent) swallows during normal- and fast-rate continuous drinking for Subjects 1 to 5 are presented in Table 3.3. It should be pointed out that while the number of “first swallows” averaged was consistently 2 (two replications) for each rate, that of the “subsequent swallows” ranged from 1 to 4. There were two cases where only one subsequent swallow was captured on EPG out of the two trials; as a result, standard deviations and coefficients of variation were missing (marked as “N/A” in Table 3.3). In general, the data in Table 3.3 showed small intrasubject replication variability. In 80% of the cases, the coefficients of variation were less than 0.20. Although the fast-rate sequential swallows averaged 14% shorter than those in normal-rate drinking, the differences were not significant, nor was there an order effect. Subjects, however, differed significantly ($p = .0001$), despite an insignificant subject-by-task interaction. The least-squares means for subjects (see Table 3.3) revealed that S1 (female) and S3 (male) on the whole drank considerably faster than the other subjects.

Average total-duration ratios of sequential versus discrete water swallowing tasks for S1 to S5 are presented in Table 3.4. Sequential swallows, in general, averaged 43-56% faster than single water swallows among the subjects. Subject differences were

Table 3.3. Mean total durations (in milliseconds) of tongue-palate contact for sequential swallows during normal- and fast-rate continuous drinking for Subjects 1 to 5 (S1 to S5). Coefficients of variation (CV) were computed using the formula [SD/M]. LSM = least-squares mean. N/A = not applicable due to single measurement.

		Continuous Drinking				LSM
		Normal Rate		Fast Rate		
		First Swallow	Subsequent Swallows	First Swallow	Subsequent Swallows	
S1	<u>M</u>	432.44	569.82	476.35	466.22	483.11
	<u>SD</u>	19.11	74.42	23.89	66.43	
	<u>CV</u>	0.04	0.13	0.05	0.14	
S2	<u>M</u>	739.87	902.03	608.11	655.40	733.53
	<u>SD</u>	14.33	138.55	9.56	111.64	
	<u>CV</u>	0.02	0.15	0.02	0.17	
S3	<u>M</u>	550.68	439.19	324.33	351.35	416.39
	<u>SD</u>	81.22	200.66	105.11	N/A	
	<u>CV</u>	0.15	0.46	0.32	N/A	
S4	<u>M</u>	975.68	725.33	950.00	725.34	844.09
	<u>SD</u>	217.87	N/A	199.70	9.08	
	<u>CV</u>	0.22	N/A	0.21	0.01	
S5	<u>M</u>	838.18	798.09	721.28	730.97	775.11
	<u>SD</u>	114.18	67.51	21.50	17.48	
	<u>CV</u>	0.14	0.08	0.03	0.02	
LSM		707.37	687.20	616.01	591.20	

Table 3.4. Average total-duration ratios of Sequential:Discrete water swallows for Subjects 1 to 5 (S1 to S5). CN = continuous normal-rate drinking; CF = continuous fast-rate drinking; subscript _F = first swallow; subscript _S = subsequent swallows; 5W = 5-cc water; 30W = 30-cc water; \bar{x} = mean of means.

	Ratio								\bar{x}
	<u>CN_F:5W</u>	<u>CN_S:5W</u>	<u>CN_F:30W</u>	<u>CN_S:30W</u>	<u>CF_F:5W</u>	<u>CF_S:5W</u>	<u>CF_F:30W</u>	<u>CF_S:30W</u>	
S1	0.47	0.62	0.53	0.70	0.52	0.51	0.58	0.57	0.56
S2	0.45	0.55	0.60	0.73	0.37	0.40	0.49	0.53	0.51
S3	0.39	0.31	0.46	0.36	0.23	0.25	0.27	0.29	0.32
S4	0.66	0.49	0.67	0.50	0.65	0.49	0.66	0.50	0.58
S5	0.61	0.58	0.61	0.58	0.53	0.54	0.52	0.53	0.56
\bar{x}	0.52	0.51	0.57	0.57	0.46	0.44	0.50	0.48	

apparent in that S3's ratios ($\bar{x} = .32$) were considerably smaller than those of all other subjects ($\bar{x} = .51-.58$; see Table 3.4).

Because no significant differences could be attributed to drinking rate or swallow order within the sequential swallowing tasks, the data on their total durations were pooled to compare with the total durations of 5-cc and 30-cc single water swallowing tasks. The ANOVA showed significant effects of task ($p < 0.0001$), subject ($p < 0.0105$), and task-by-subject interaction ($p < 0.0021$). Post hoc comparisons indicated that sequential swallows were significantly shorter than single water swallows of either size in total tongue-palate contact duration. (The statistical tables for these tests are presented in Appendix B, section B-5.)

Additional timing data. The same staging criteria set for single swallows were used to examine sequential swallowing. It was discovered that they could not be strictly applied to the majority of the data due to an overlap of propulsion and withdrawal activities in both contact timing and pattern (discussed below). As a result, the durations of propulsion and withdrawal were not measured; timing measurements were made only of the prepropulsion stage in all cases (i.e., 44 component swallows from the continuous-drinking series of all subjects) and of the full contact stage in 10 swallows where it was present.

The duration of prepropulsion activity was less than 60 msec in 71% of the sequential swallows pooled from all subjects ($M = 61.10$, range = 26.18-144.43). No striking differences were observed due to drinking rate or swallow order. On the average,

prepropulsion was 72% (range = 49-90%) shorter in sequential swallows than it was in single water swallows.

When present, full-contact activity averaged 112.13 msec in duration (range = 33.78-301.69). This was on the average 84% (range = 81-87) shorter than that in the single water swallows. Nearly all 10 cases in which full contact was present came from the data of S2 (female) and S4 (male), representing about 55% of their individual total number of sequential swallows. No apparent relationship was detected between the incidence of full contact and drinking rate or swallow order.

Tongue-Palate Contact Pattern

General characteristics. The percent-contact profiles from representative continuous drinking series of Subjects 1 to 5 are illustrated in Figures 3.17 to 3.21, respectively. Figure 3.22 presents a representative raw EPG time series. In general, sequential swallowing shared some of the basic contact characteristics of discrete swallowing. That is, in each component swallow during continuous drinking, there were distinctive, progressive activation of electrodes for propulsive purposes, as well as progressive deactivation of electrodes during withdrawal. However, sequential swallows differed strikingly from single swallows due to an overlap of propulsion and withdrawal activities. Specifically, as seen in 77% of the data, progressive deactivation of electrodes (i.e., onset of withdrawal) began to occur in the front or central bin while back electrodes were still being activated as part of propulsion (see Figure 3.22). As a result, the majority of the sequential task responses did not have a period of stable, maximal contact.

Figure 3.17. Changes in percent-contact over time in front-central-back and lateral-medial-midline bins from representative continuous drinking series of S1 (female, age 47). CN = continuous, normal-rate; CF = continuous, fast-rate.

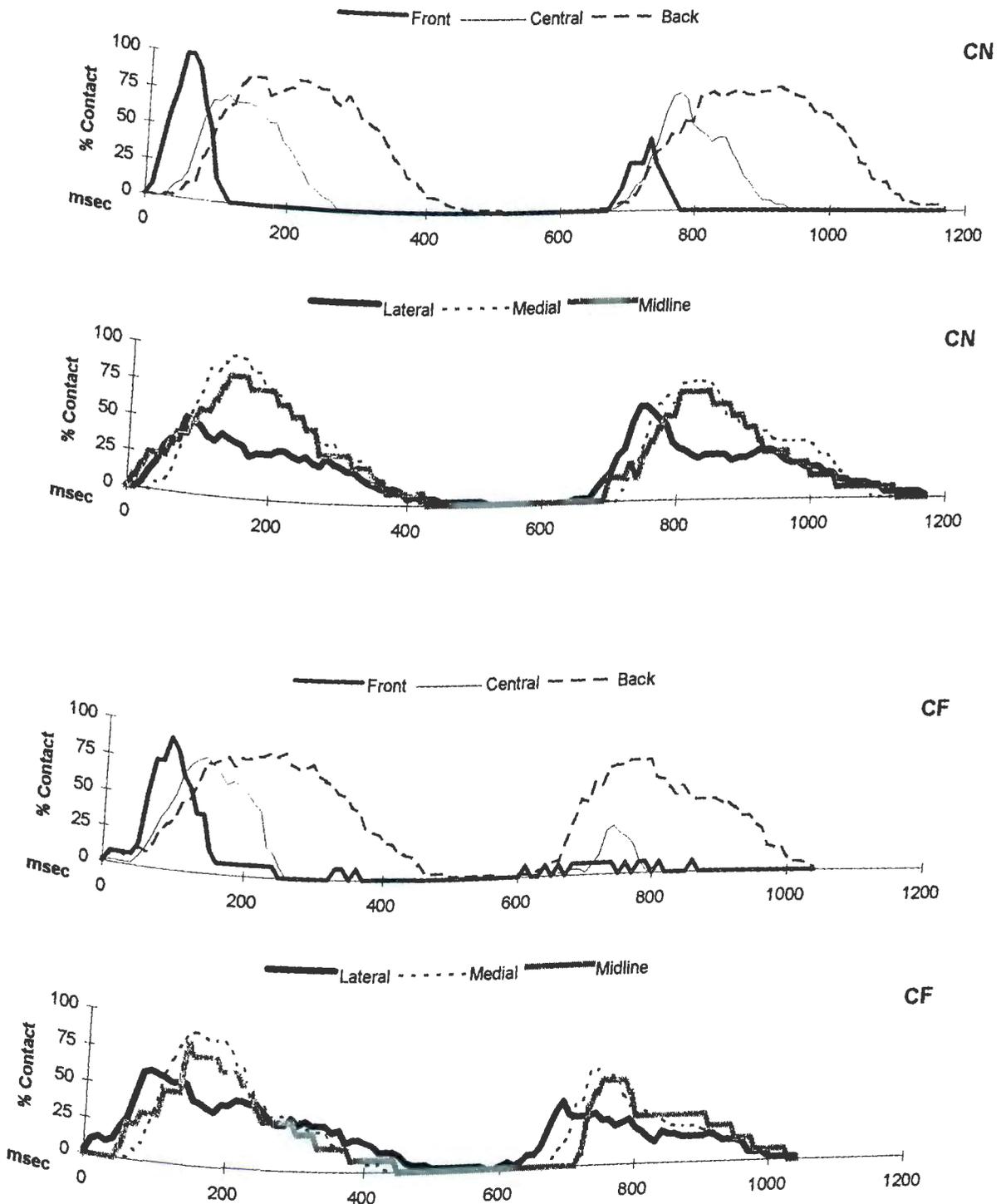


Figure 3.18. Changes in percent-contact over time in front-central-back and lateral-medial-midline bins from representative continuous drinking series of S2 (female, age 46). CN = continuous, normal-rate; CF = continuous, fast-rate.

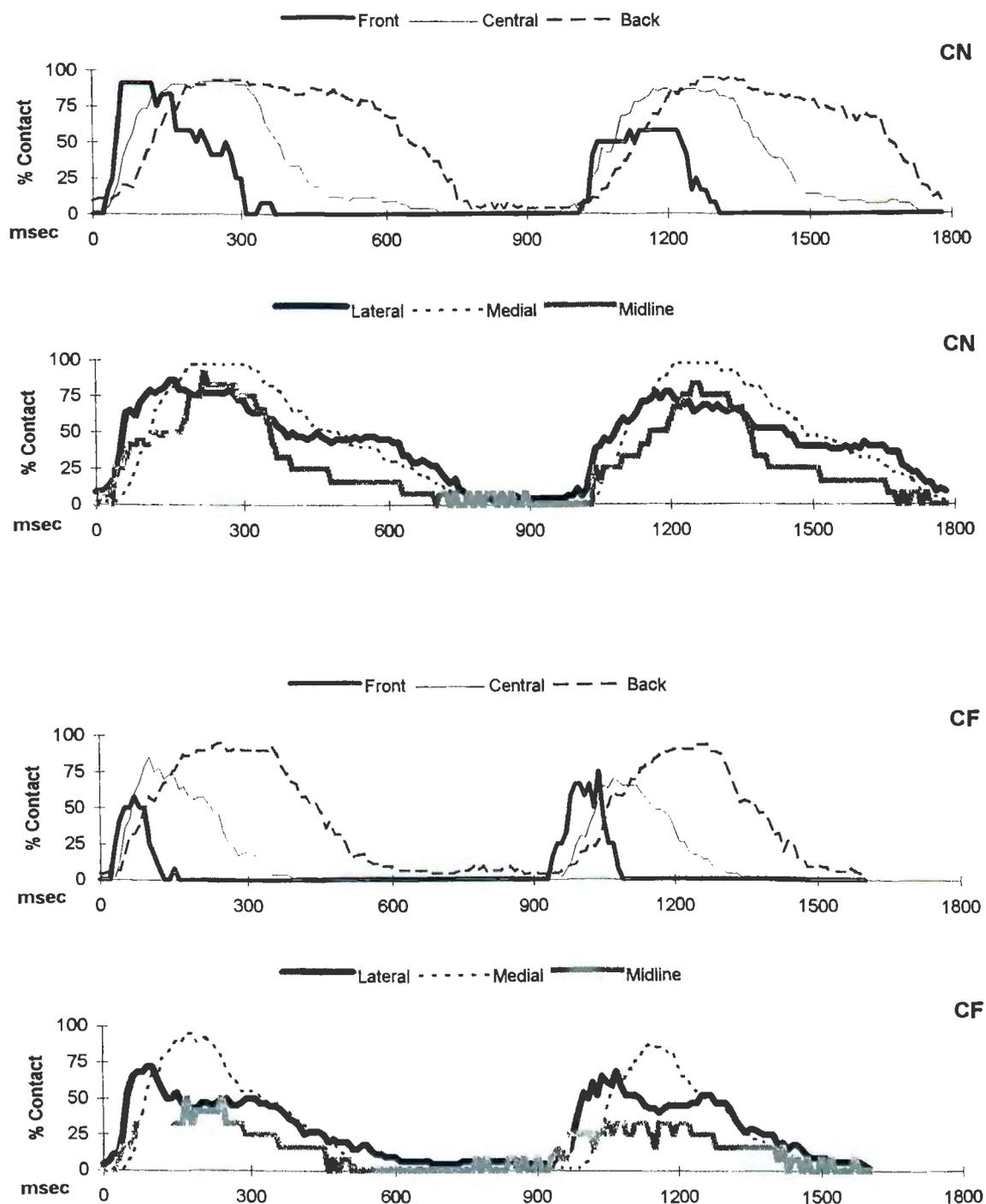


Figure 3.19. Changes in percent-contact over time in front-central-back and lateral-medial-midline bins from representative continuous drinking series of S3 (male, age 23). CN = continuous, normal-rate; CF = continuous, fast-rate.

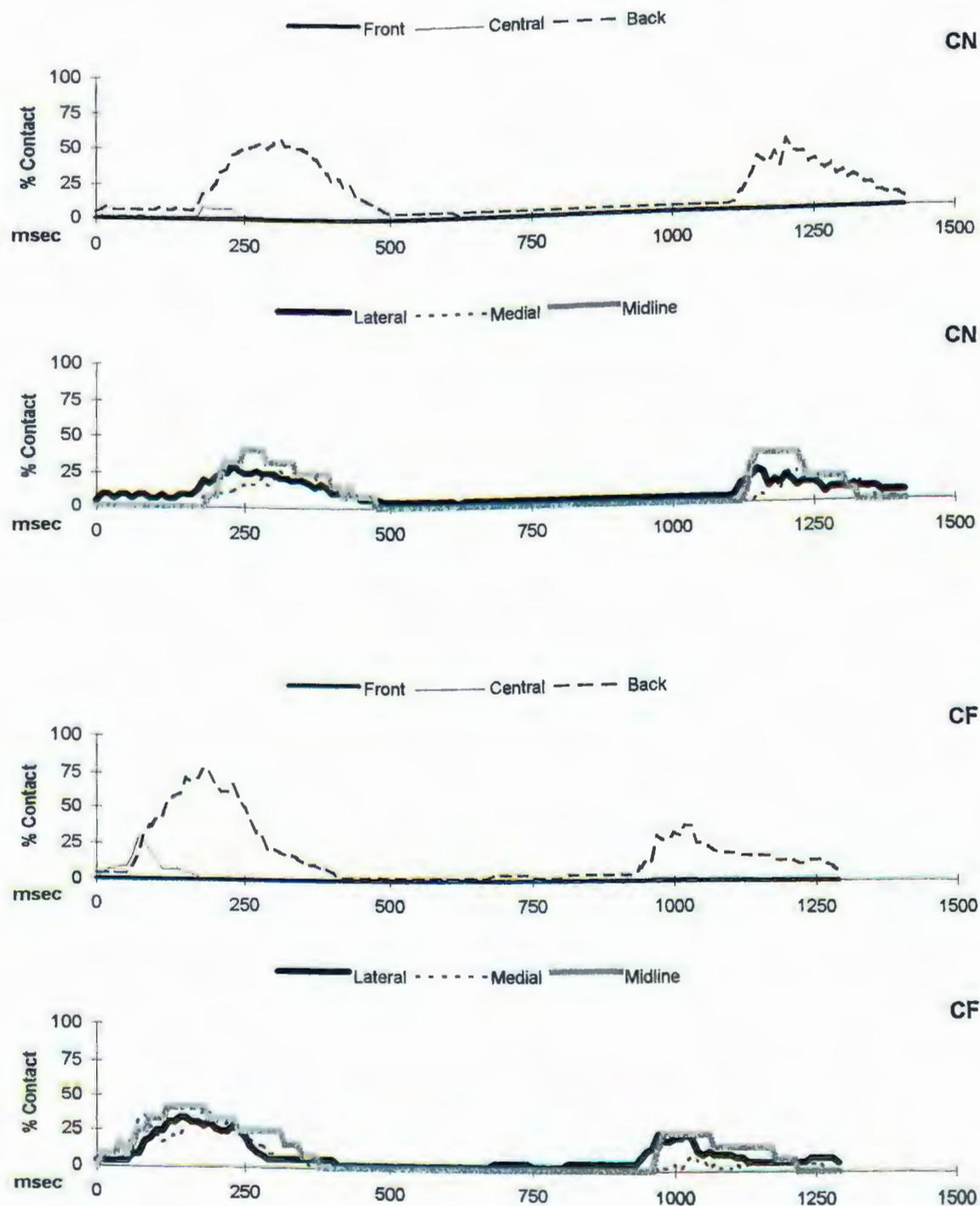


Figure 3.20. Changes in percent-contact over time in front-central-back and lateral-medial-midline bins from representative continuous drinking series of S4 (male, age 37). CN = continuous, normal-rate; CF = continuous, fast-rate.

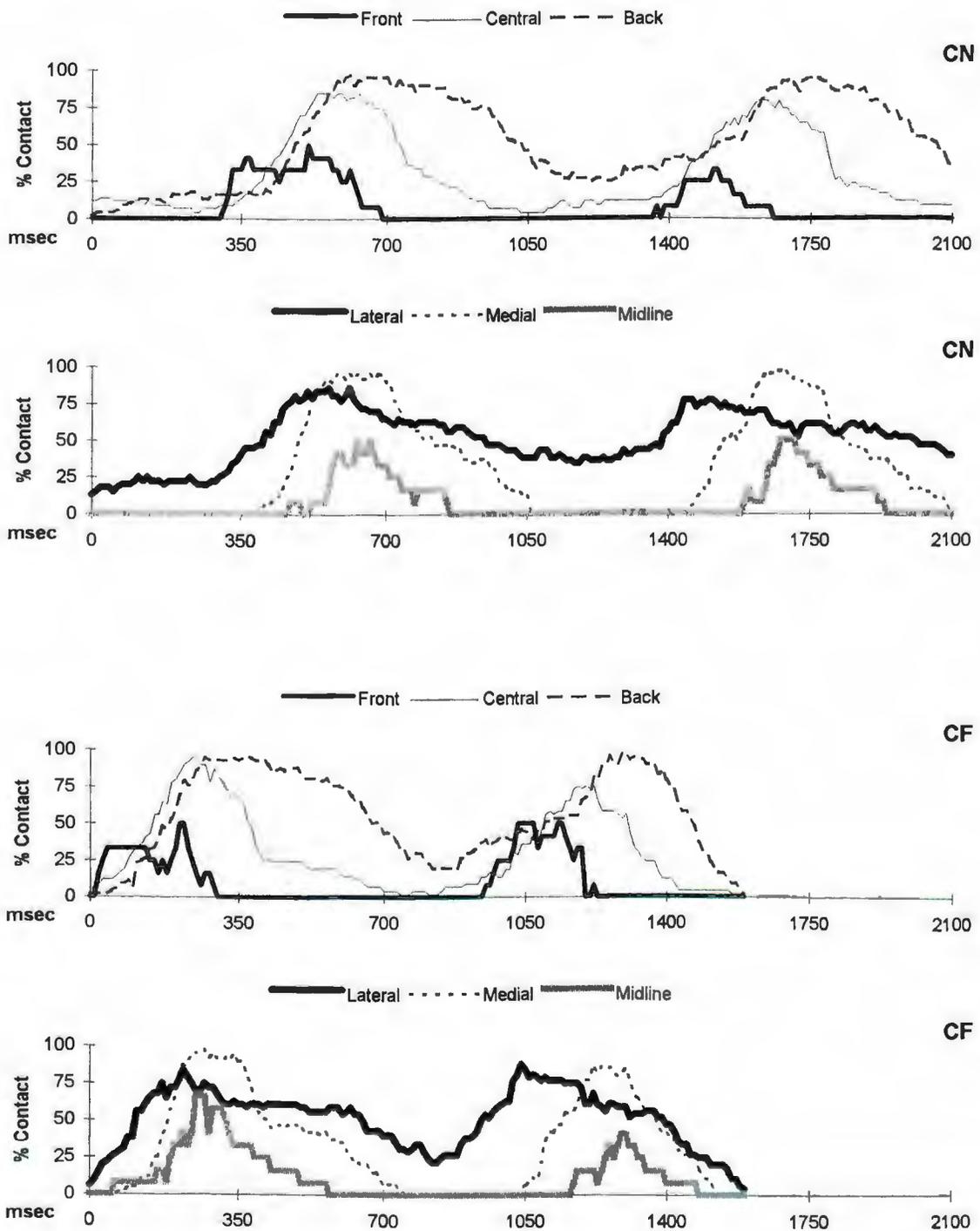


Figure 3.21. Changes in percent-contact over time in front-central-back and lateral-medial-midline bins from representative continuous drinking series of S5 (female, age 23). CN = continuous, normal-rate; CF = continuous, fast-rate.

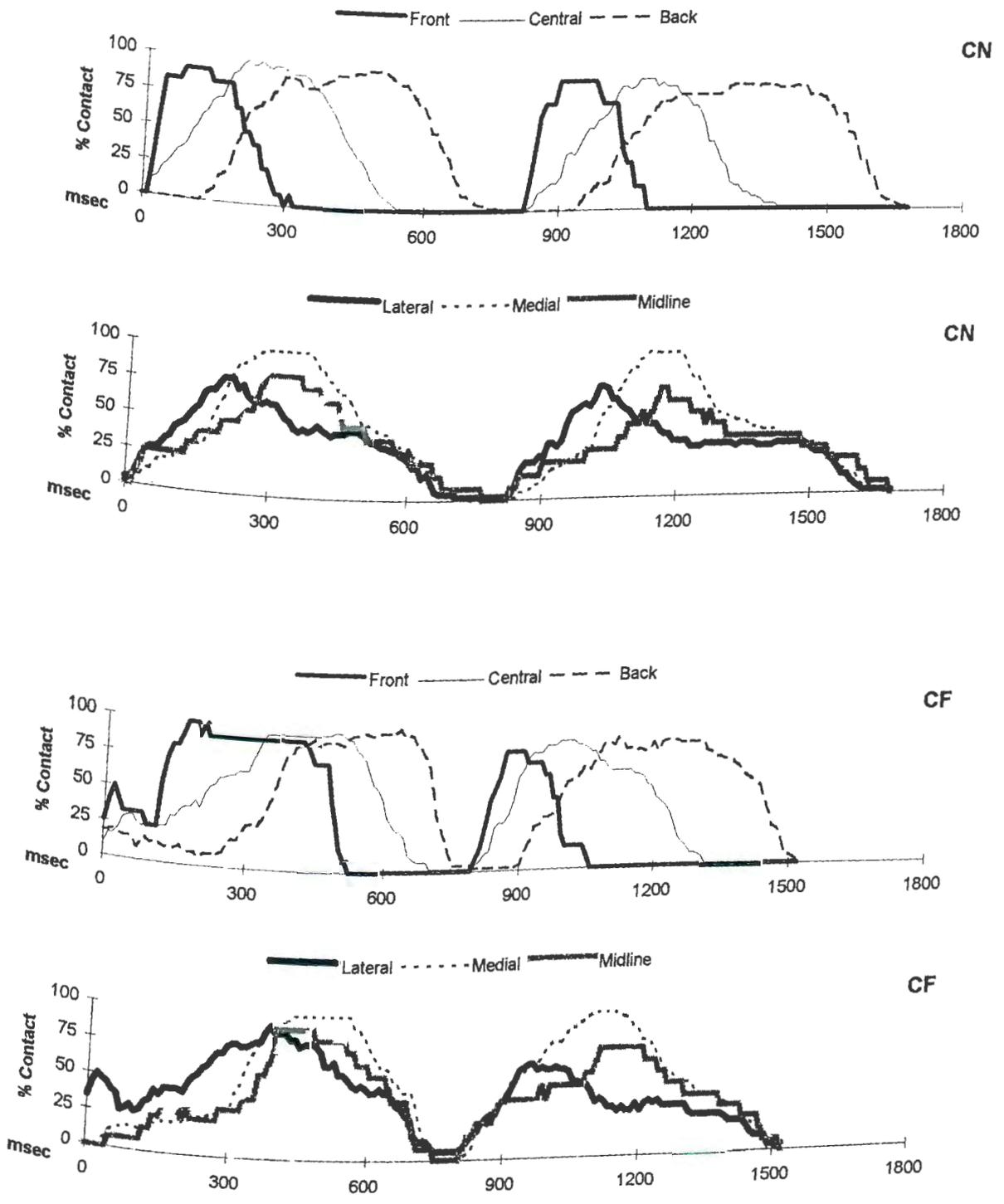
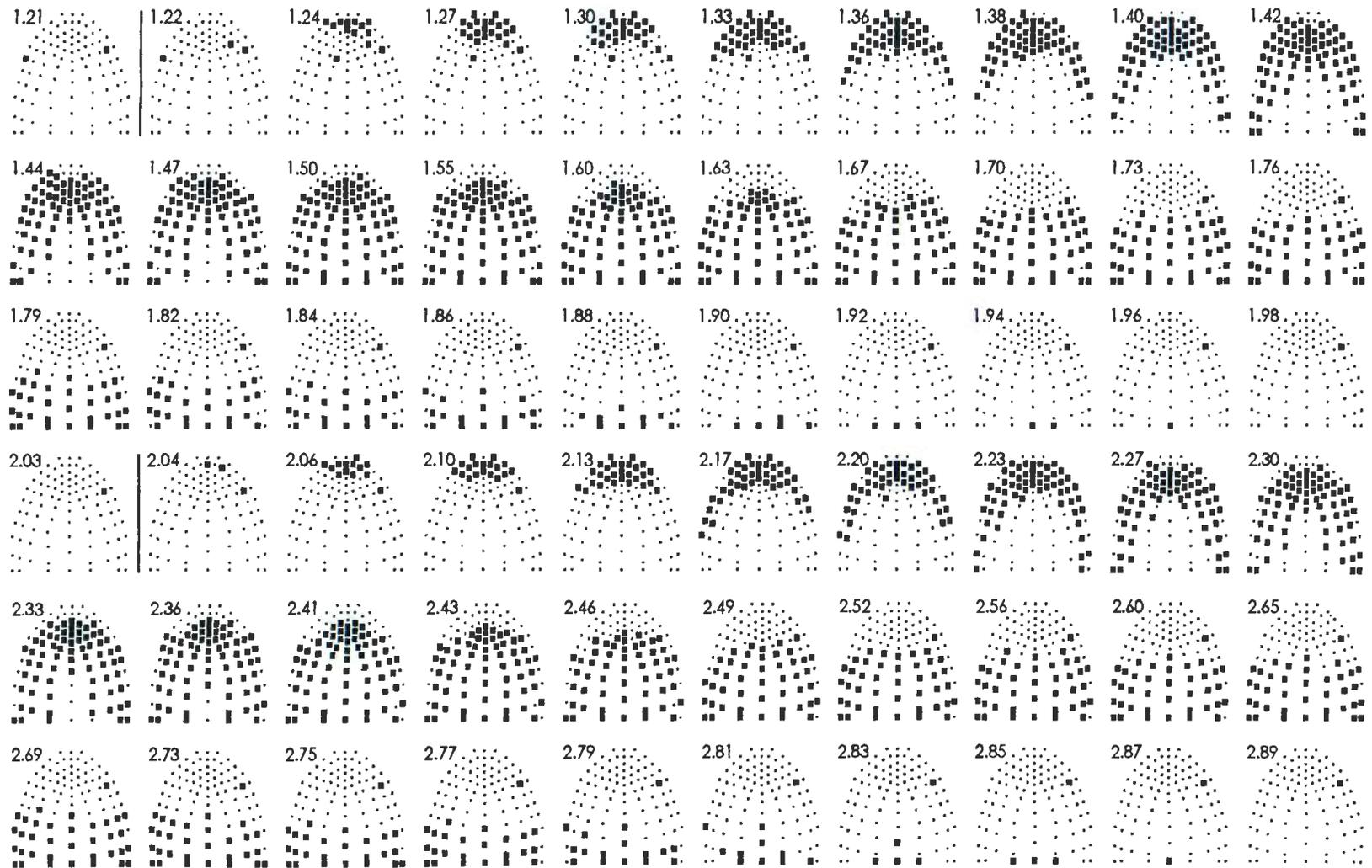


Figure 3.22. Raw EPG data for two sequential swallows in a representative continuous drinking series. An overlap of propulsion and withdrawal activities is evident. Vertical line demarcates onset of each swallow.

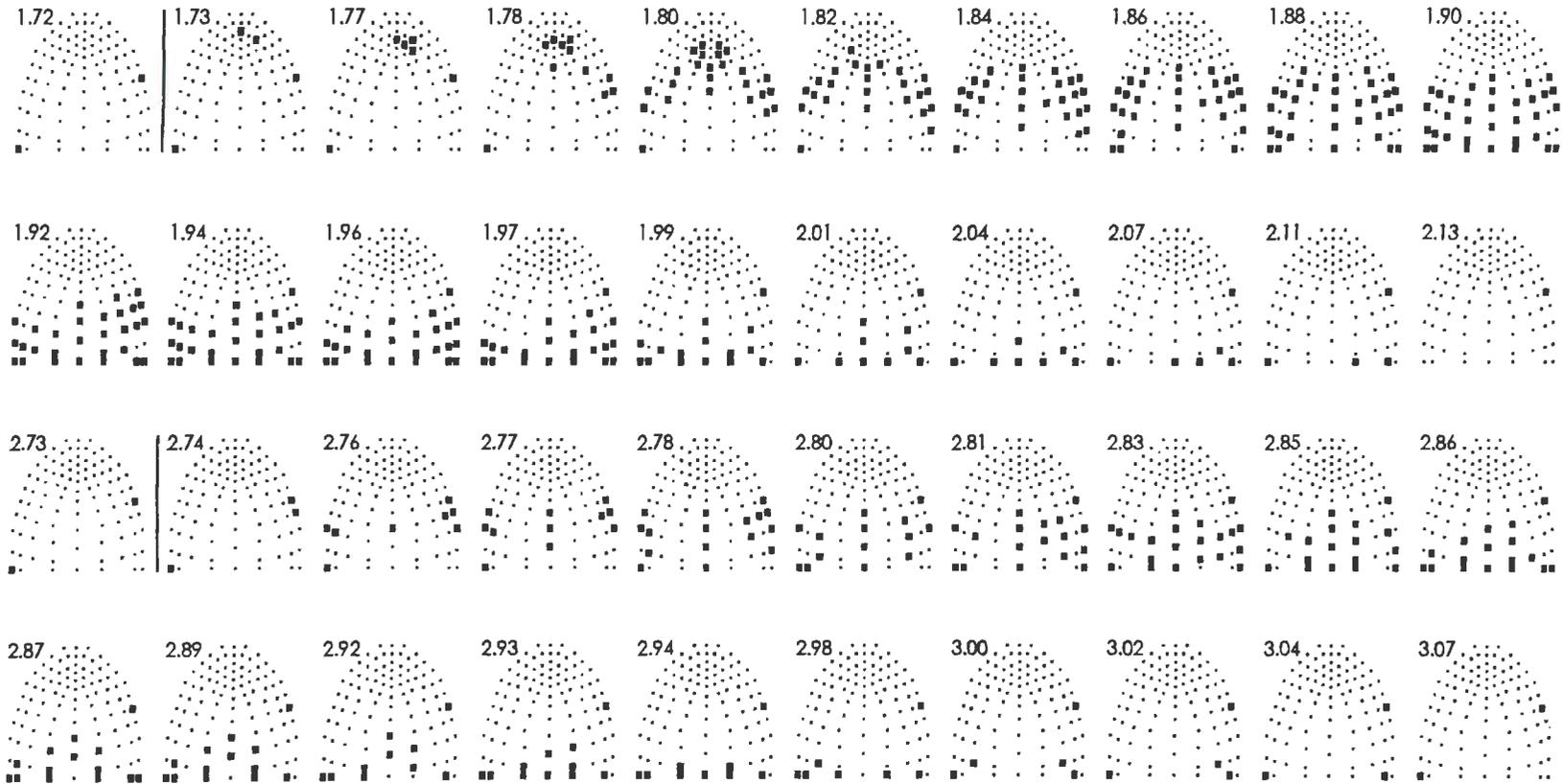


A second characteristic of sequential swallowing was that the withdrawal pattern followed a front-to-back progression without a distinct, simultaneous midline-to-lateral component (see Figure 3.22). This was observed in 70% of the cases.

A third characteristic, though somewhat less compelling, was that 89% of all sequential swallows showed contact Pattern 1 during prepropulsion (i.e., small, scattered changes in contact over a brief period, mostly in the lateral bin, resulting in lateral contacts of < 25%). The incidence surpassed that of the same pattern for single swallows by almost 10%.

No striking differences in contact pattern were observed due to drinking rate or swallow order. Intrasubject variability in overall contact pattern was small in nearly all cases. Intersubject variations, however, were apparent and primarily due to S3 who used predominantly back-bin contacts to accomplish propulsion during continuous drinking (see Figures 3.19 and 3.23). A post-experiment interview revealed that this subject described his manner of drinking as “chugging”. Interestingly, even in the self-proclaimed chugging, the propulsion-withdrawal overlap was present at times. Additional subject differences were seen in prepropulsion and withdrawal patterns. Four of the five cases demonstrating prepropulsion Pattern 2 occurred in the data of S4. Interestingly, S1, S2, and S3 who used Pattern 2 in some of their single swallows used strictly Pattern 1 during continuous drinking. Cases where the withdrawal pattern was similar to that for the single swallows (i.e., in a simultaneous front-to-back and midline-to-lateral progression) occurred mainly in the data of S2 and S4.

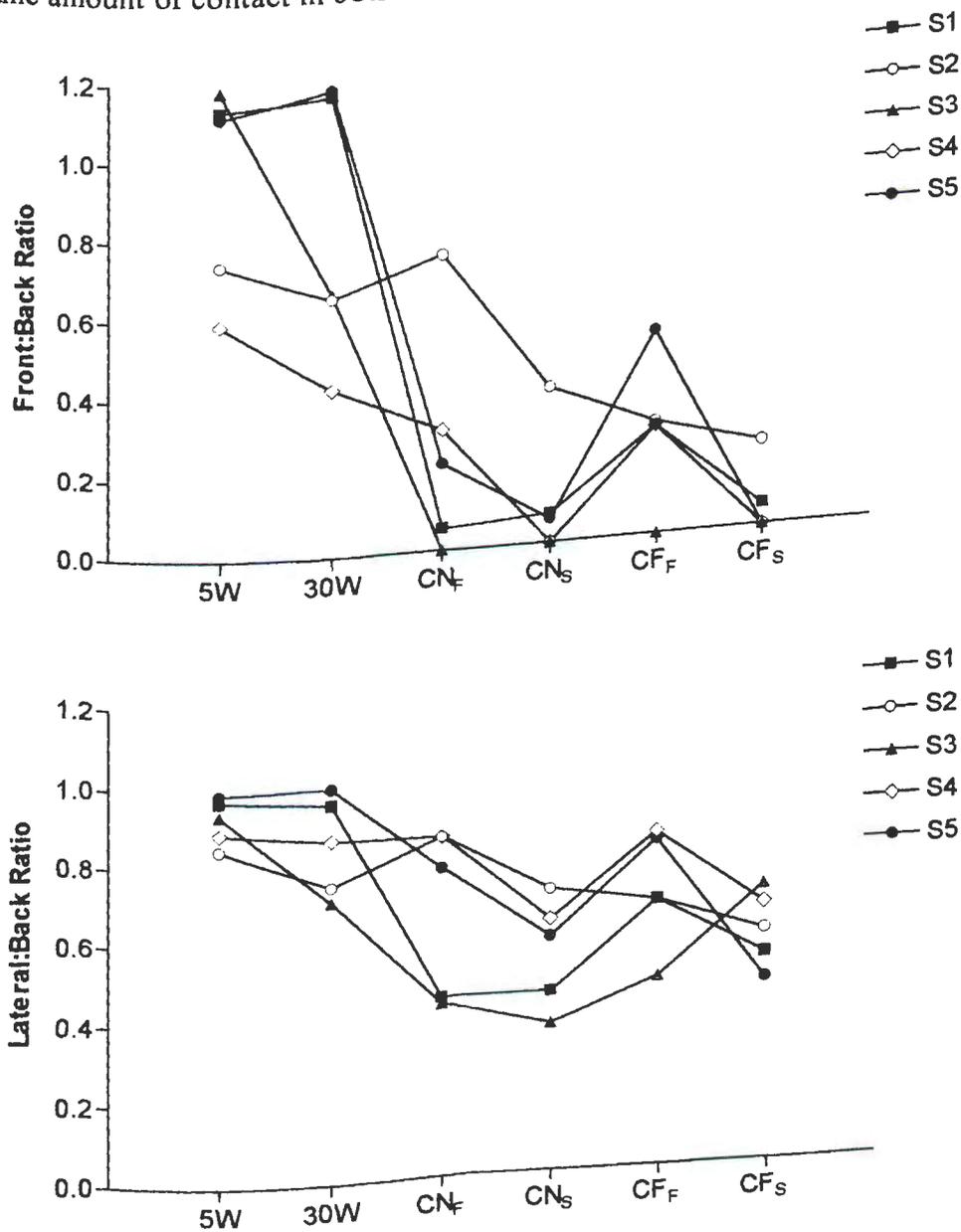
Figure 3.23. Raw EPG data for two sequential swallows in the continuous drinking (self-proclaimed "chugging") series of S3. Contact activities occur predominantly in the back bin. Vertical line demarcates onset of each swallow.



Sequential versus discrete: statistical analyses. Sequential swallows were compared with single water swallows for the order in which maximal contact was achieved in the front (F), lateral (L), and back (B) bins during propulsion. Results showed that single water swallows had a variety of sequences, whereas sequential swallows had only a few. The predominant pattern, observed in 46/60 single water swallows and 35/44 sequential swallows, followed a front-lateral-back (F-L-B) progression of “peaking”. The other patterns were few in frequency and thus grouped as “others.” Subsequent Chi-Square analysis of the “F-L-B” and “others” groups showed a significant subject effect but no significant effect due to task nature (sequential vs. discrete), drinking rate (normal vs. fast), or swallow order (first vs. subsequent). As in the discrete swallowing experiment, the sources of the subject effect for this analysis were S3 and S4 (both male). For sequential swallowing, while all female subjects showed only the F-L-B sequence, the male subjects showed predominantly the “other” sequence patterns (6/7 swallows in S3, 4/7 in S4).

Front:back and lateral:back ratios in percent-contact at the time of maximal midline contact were calculated for all sequential and discrete water swallows. Results of the ANOVA for each comparison showed a significant task effect and a significant task-by-subject interaction. Subject differences were not significant in either case. (See Appendix B, sections B-6 and B-7 for ANOVA tables.) These results are illustrated in Figure 3.24, a plot of the least-squares means for the subjects as a function of swallowing task. Post hoc contrasts revealed that single water swallows of either size had

Figure 3.24. Least-squares means for Front:Back (upper panel) and Lateral:Back (lower panel) percent-contact ratios at time of maximal midline contact for Subjects 1 to 5 (S1 to S5) as a function of sequential swallowing task. 5W = 5-cc water; 30W = 30-cc water; CN = continuous normal-rate drinking; CF = continuous fast-rate drinking; subscript _F = first swallow; subscript _S = subsequent swallows. Lower numbers mean more contact in the back; a ratio of 1.0 means the same amount of contact in both bins.



significantly higher ratios than the component swallows of continuous drinking. However, there were no significant differences among the sequential swallows due to drinking rate or swallow order.

Ultrasound Findings

The ultrasound data on sequential swallowing during continuous drinking were examined for all subjects. However, due to considerable variations in image quality, only the data from S5 were used in illustrations and for displacement measurements.

Swallow Volume Estimation

Bolus size for the component swallows of continuous drinking was estimated for each subject, using the sagittal ultrasound data. As shown in Table 3.5, S1 used an equal number of swallows for both normal- and fast-rate drinking, while all other subjects showed slightly fewer swallows (hence slightly greater volume per swallow) while drinking fast. On the average, the two male subjects--S3 and S4--consumed more water per swallow than did the female subjects, especially for the fast-rate series.

Lingual Movement Characteristics

Tongue movements for sequential swallowing during continuous drinking were fundamentally the same as those seen during single swallows (see Figure 3.25; cf. single swallows in Figure 3.15). That is, the sequence in which the anterior, mid, dorsal, and posterior segments elevated to and withdrew from their respective maximal displacement remained unchanged. However, in agreement with the EPG findings, shorter overall

Table 3.5. Estimated bolus size (in cc) of sequential swallows during continuous drinking for Subjects 1 to 5 (S1 to S5). The total amount of water consumed for each trial was 200 cc.

Subject	Rate	No. of Swallows	Average Amount per Swallow
S1	Normal	7	29
	Fast	7	29
S2	Normal	12	17
	Fast	8	25
S3	Normal	5	40
	Fast	4	50
S4	Normal	7	29
	Fast	5	40
S5	Normal	16	13
	Fast	13	15

Figure 3.25. Changes in tongue shape in first and second swallows during normal- (CN, panels on left) and fast-rate (CF, panels on right) continuous drinking. Frames in Rows 1 to 6 panels on left, in order, illustrate, in order, lingual surface contours at swallow onset, when entire bolus was first loaded on tongue surface, and at maximal displacement of anterior, mid, dorsal, and posterior tongue segments. Arrows in each image delineate tongue surface.



swallow durations and an overlap of propulsion and withdrawal activities characterized the ultrasound images of most sequential swallows. The overlap usually became visible near the time of maximal displacement of the posterior segment, at which point a slight descent of the anterior segment could be seen (see Figure 3.25, Row 6). This was followed by further descent of the anterior and mid segments, which coincided with signs of water re-entry, while the dorsal and posterior segments remained “anchored” (see Figure 3.25, Row 1, CN-2nd and CF-2nd swallows). When apparent descent was seen in the dorsal and posterior segments, the anterior segment usually had just begun re-elevating (see Figure 3.25, Row 2, CN-2nd and CF-2nd swallows) to initiate the propulsive action for the subsequent swallow. Thus, it appeared that the dorsal-posterior lowering gesture overlapped the anterior re-elevation gesture. As a result of the movement overlaps, most sequential swallows during continuous drinking, especially those that were not the first in a series, did not display the same extent of prepropulsion and full contact tongue behaviors as did the single swallows.

Because of large intersubject differences in per-swallow volume, the starting tongue height for sequential swallows varied considerably from subject to subject. While no marked within-subject differences in tongue shape due to drinking rate appeared to exist, some variations were observed due to swallow order. Specifically, the anterior segment was usually less depressed and the dorsal and posterior segments less humped for the first swallow than for the subsequent swallows (see Figure 3.25, Row 1).

Lingual Velocity Profiles: Single-Subject Data

Frame-by-frame displacement data were extracted from the four tongue segments for the continuous drinking series of S5, using the radial grid system. Instantaneous velocities were then calculated for four sequential swallows in each series. The plotted velocity profiles (time-series waveforms) are illustrated in Figures 3.26 and 3.27. As in the case of single swallows, these velocity profiles clearly captured the anterior-to-posterior progression of bolus transport and the spatiotemporal concatenation of the four functional tongue segments. A comparison of normal- versus fast-rate series and of first versus subsequent swallows showed no marked differences in overall waveform characteristics.

Average positive peak velocities for the sequential swallows of S5 are presented in Table 3.6. Also included are the average OTP intervals. As in the single-swallow study, within-task comparisons showed the dorsal tongue segment to have greater peak velocity than all other segments for most sequential swallows. Between-task comparisons revealed that “subsequent swallows” in either normal-rate or fast-rate drinking had lower mean peak velocities than the “first swallow” for the mid tongue segment but greater mean peak velocities for the dorsal and posterior tongue segments. Differences due to drinking rate, however, appeared minimal. In contrast to 30-cc single water swallows, sequential swallows regardless of rate and order had considerably lower peak velocities for the anterior segment, and “first swallows” regardless of rate had considerably lower peak velocities for the posterior segment. In contrast to 5-cc single water swallows, “subsequent swallows” regardless of rate had greater peak velocities for the dorsal and

Figure 3.26. Velocity profiles for four tongue segments from the continuous, normal-rate drinking series of S5. Values (in mm/sec) are instantaneous velocities from first move to end of fourth swallow. Missing data points for anterior tongue were due to either lack of or difficulty in discerning tongue-grid intersections. Vertical lines separate the four swallows in the series.

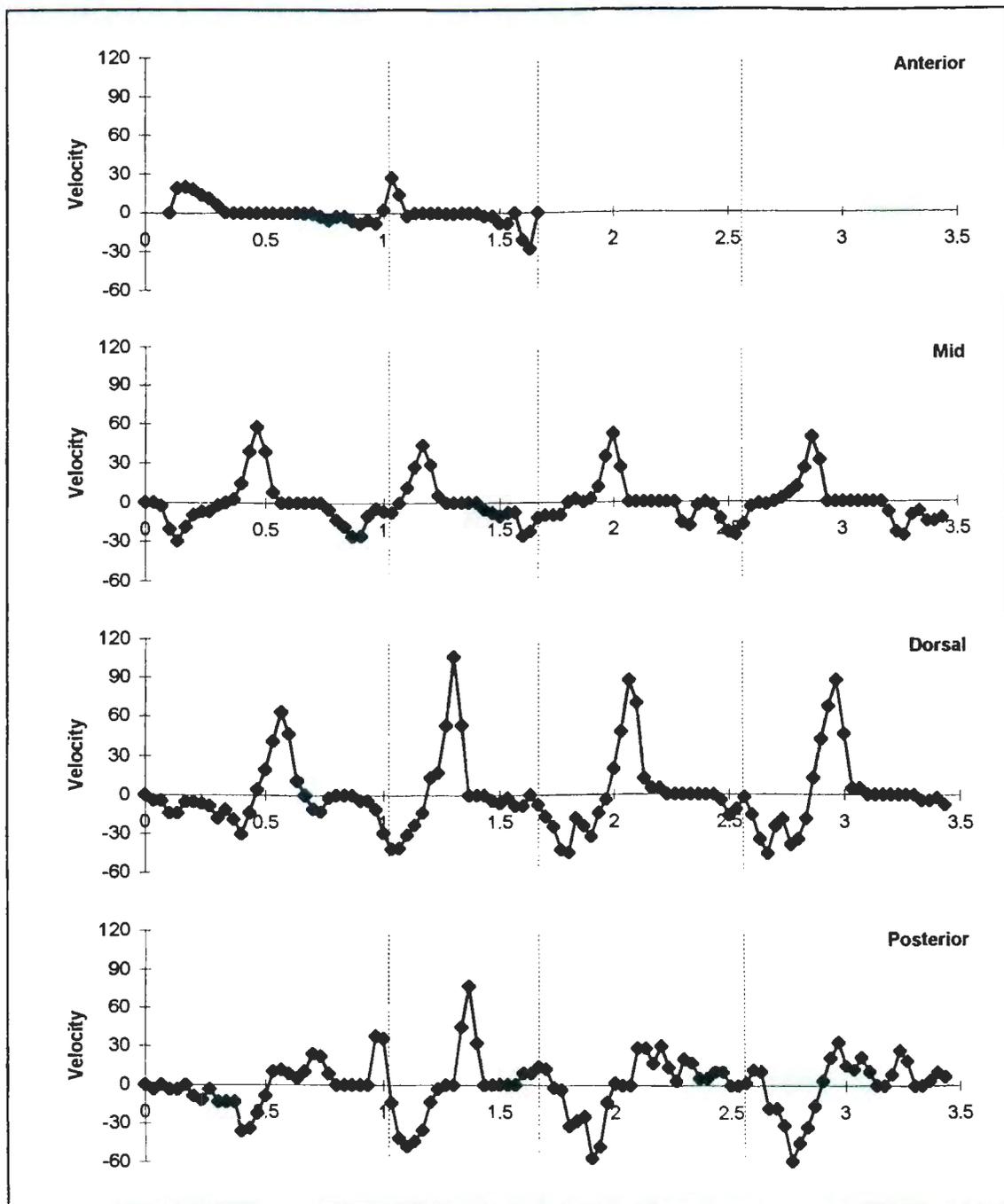


Figure 3.27. Velocity profiles for four tongue segments from the continuous, fast-rate drinking series of S5. Values (in mm/sec) are instantaneous velocities from first move to end of fourth swallow. Missing data points for anterior tongue were due to either lack of or difficulty in discerning tongue-grid intersections. Vertical lines separate the four swallows in the series.

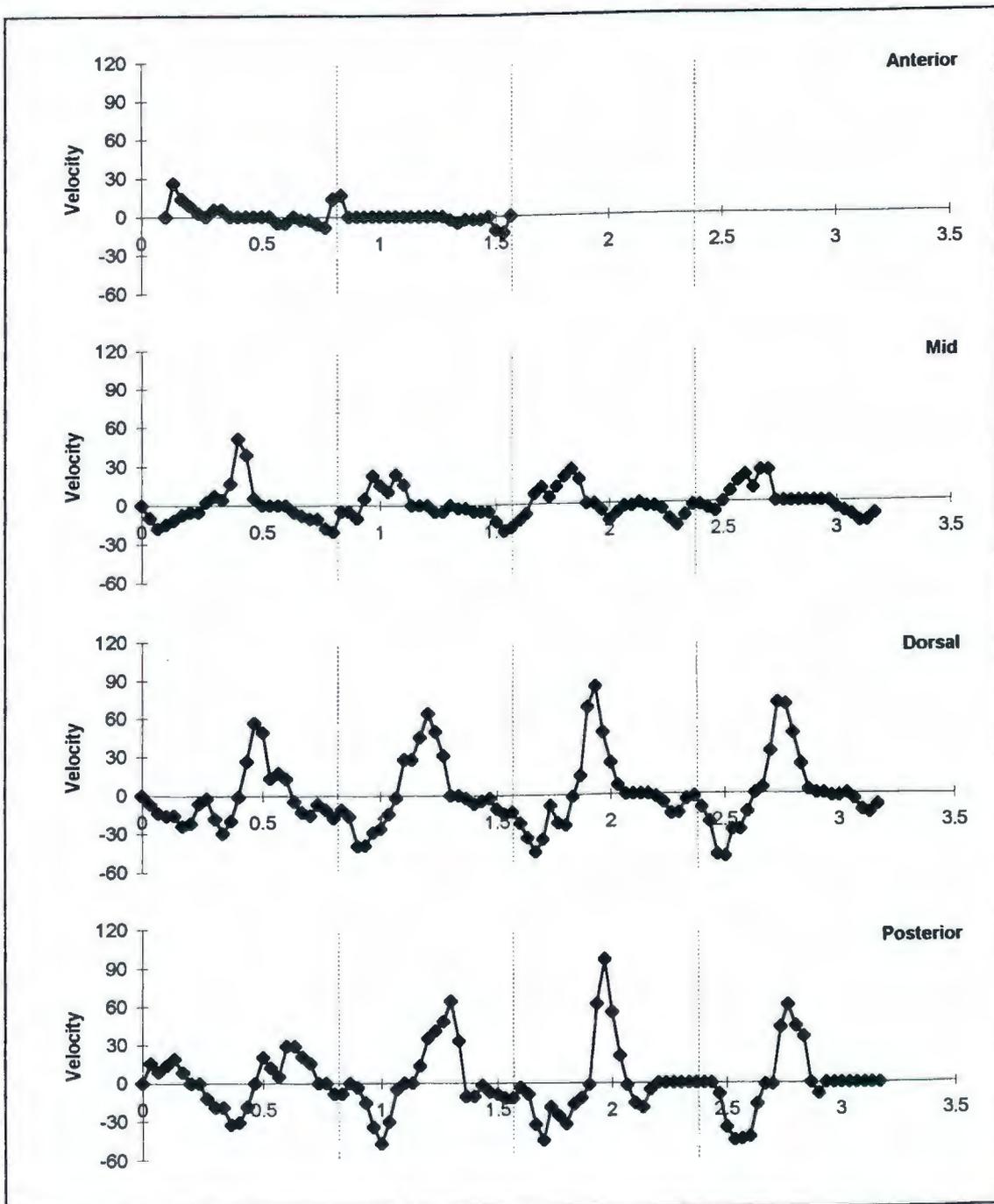


Table 3.6. Mean positive peak velocities (in mm/sec) and onset-to-peak (OTP) intervals (in sec) for the four tongue segments from the continuous drinking series of Subject 5. CN = continuous normal-rate; CF = continuous fast-rate; subscript _F = first swallow; subscript _S = 3 subsequent swallows. CONT_{ALL} = all swallows of continuous drinking. Diff = difference in mean OTP values between tongue segments. CN_F and CF_F lack standard deviation data due to single n.

		Positive Peak Velocity				OTP Interval			
		Anterior	Mid	Dorsal	Posterior	Anterior	Mid	Dorsal	Posterior
CN _F	<u>M</u>	20.12	57.91	63.47	37.95	0.17	0.47	0.57	0.97
	<u>Diff</u>					0.30	0.10	0.40	
CN _S	<u>M</u>	27.20	47.82	97.19	54.14	0.00	0.22	0.32	0.42
	<u>SD</u>	0.00	4.01	11.11	26.32		0.09	0.06	0.09
	<u>Diff</u>					0.23	0.10	0.07	
CF _F	<u>M</u>	25.98	51.44	56.77	29.03	0.13	0.40	0.47	0.63
	<u>Diff</u>					0.27	0.07	0.17	
CF _S	<u>M</u>	16.76	24.59	72.77	74.12	0.00	0.24	0.34	0.40
	<u>SD</u>	0.00	1.41	10.28	19.91		0.02	0.02	0.06
	<u>Diff</u>					0.24	0.10	0.06	
CONT _{ALL}	<u>M</u>	22.52	41.00	77.54	53.94	0.08	0.29	0.38	0.50
	<u>SD</u>	4.93	14.13	16.74	25.08	0.09	0.10	0.09	0.21
	<u>Diff</u>					0.25	0.10	0.12	

posterior segments (see Tables 3.2 and 3.6). It should be reiterated that this subject's average bolus size was estimated to be 13 cc during normal-rate drinking and 15 cc during fast-rate drinking (see Table 3.5).

Data on the OTP intervals revealed no outstanding dissimilarities among the "difference scores" (differences in mean OTP values between tongue segments) as a function of drinking rate or swallow order. Sequential swallows on the whole were also similar in difference scores to the single water swallows (see Tables 3.2 and 3.6).

Summary

The EPG data showed that in contrast to discrete water swallows, the sequential swallows during continuous drinking had a significantly shorter total task duration, a shorter prepropulsion interval, an overlap of propulsion and withdrawal activities, a higher incidence of prepropulsion Pattern 1, a predominantly front-to-back withdrawal pattern, and significantly lower Front:Back as well as lateral:back percent-contact ratios at the time of maximal midline contact.

The ultrasound data on sequential swallowing during continuous drinking were useful in confirming two prominent contact features observed on EPG, namely, the shortened overall swallow duration and the propulsion-withdrawal overlap. The single-subject velocity data showed some differences in peak velocity for selected tongue segments due to swallow order but not drinking rate. There was also evidence, based on the comparison between sequential and discrete water swallows, that larger boluses had greater peak velocities than smaller boluses, at least for some tongue segments.

CHAPTER IV. DISCUSSION

The present study represents a first attempt to examine in detail linguopalatal contact characteristics with support from associated tongue shape changes during discrete and sequential swallowing via simultaneous eletropalatography and ultrasound. This chapter discusses findings in relation to the experimental questions raised. In addition, a model is proposed for a 3-D representation of lingual action for swallowing.

Discrete Swallowing

Tongue-Palate Contact Patterns

The first question asked by the present study was whether bolus properties--size and consistency--would affect EPG contact patterns and timing during single swallows. With respect to tongue-palate contact pattern, no striking, bolus-induced differences were identified. Instead, systematic, stereotypical contact behaviors persisted across swallowing tasks and subjects. These contact behaviors showed distinct, time-varying regional specificity. That is, EPG activities occurred systematically in different palatal areas at specific times during a swallow. To delineate the contact characteristics in detail, the present study devised three new data analysis schemes: compartmentalization of the palate into six bins that encompassed the lengthwise as well as the crosswise spatial domains, segmentation of the time course of the swallowing task into four functional

stages, and the use of time-warping to average by bin and stage across repetitions. The division of the palate into bins and the swallowing task into stages does not imply interruptions in contact continuity. Rather, these were useful strategies that optimized examination of the spatial and temporal details of linguopalatal interactions unique to swallowing. The use of averaged data also added robustness to the interpretation of findings.

The observations of systematic, prescribed tongue-palate contact patterns suggested stereotypical lingual movement strategies for discrete swallowing. In her X-ray microbeam study (1991) that examined midsagittal movements of the tongue, Martin concluded that "during swallowing, the tongue functions as many small units that are selectively activated in a highly organized, invariant manner" (p. 283). The finding of this investigation supported such a conclusion, providing indirect evidence for concatenated, functionally dependent lingual units. However, in contrast to the conventional observations of swallowing based on 2-D imaging data, the present EPG findings revealed that the linked lingual units possess multidimensionality. Specifically, the swallowing movement patterns observed on EPG exhibited two degrees of freedom for tongue-palate contact: a front/back continuum and a lateral/midline continuum. In other words, two sets of concatenated tongue units were revealed, one in the lengthwise domain and one in the crosswise domain. Moreover, during propulsion, the activation of each set of lingual units followed two distinct patterns of temporal coordination. In one pattern (80% of data), the lengthwise and crosswise units were activated simultaneously in a front-to-back and lateral-to-midline progression. In another pattern (20% of data), the lateral and outer-

medial units of the crosswise domain were activated prior to the front-to-back activation of the lengthwise units, suggesting the formation of a prominent lateral seal prior to propulsion which was subsequently completed by primarily the medial portion of the tongue. It was clear that the EPG contact patterns provided important information on deglutitive lingual strategies, and indirectly on tongue constraints in stereotypical behaviors. Swallowing investigations using midsagittal radiographic or ultrasonographic imaging techniques cannot capture the multidimensional components of deglutitive tongue behaviors. Even in biplane videofluorography or combined sagittal and coronal ultrasound, only a thin slice of the tongue may be visualized at a time, limiting the perspective of observable lingual action. EPG, therefore, represents a very useful tool that reveals conventionally unavailable information.

The four EPG stages reflected four specific oral lingual motor goals carried out within the experimental design for the discrete swallowing task of this study. It should be reiterated that while the motor events for Stages II and III were integral parts of discrete swallowing, activities during Stages I and IV were influenced by requirements of the experimental protocol and consequently had artificial components. Furthermore, while Stage I was not totally unrelated to swallowing, Stage IV might well be, considering the specific instructions given to the subjects (open mouth immediately after the swallow). Nevertheless, two interesting observations were borne of Stages I and IV. First, with respect to Stage I, it was apparent that normal individuals had the option of loading/positioning the bolus in preparation for oral transport with or without a prominent lateral seal. Second, with respect to Stage IV, while the retraction of contact followed the

same front-to-back progression as in Stage II, the medial-to-lateral offset progression was the reverse of the lateral-to-medial onset sequence seen in Stage II. This withdrawal pattern appeared to reflect the action of the genioglossus muscle. Since this extensive muscle inserts midsagittally across the length of the tongue, sequential contraction of its anterior, middle, and posterior fibers would produce the front-to-back withdrawal progression and at the same time cause an earlier release of contact from the midline than from the lateral bins.

The EPG stages cannot be directly compared to the conventional swallowing phases extracted from videofluoroscopy (Dodds et al., 1990) or ultrasonography (Wein et al., 1991). However, some links between the stages and phases can be made. The EPG Stages I and II, when combined, reflected the major portion of the videofluoroscopic or ultrasonographic oral phase where the main activity was the loading and transport of the bolus through the oral cavity. Because EPG registered only tongue-hard palate contact, the propulsive elevation of the posterior tongue segment (still part of the radiographic and ultrasonographic oral phase) was not shown. It is reasonable to conclude that such action occurred during the initial portion of EPG Stage III. It is likely that the EPG Stage III also included the radiographic pharyngeal phase where orally the tongue remained in a fully elevated, anchored position while its posterior segment and root (again, not visible on EPG) expanded into the oropharynx for pharyngeal bolus transport. Furthermore, it is reasonable to infer that the “pharyngeal swallowing response” occurred during EPG Stage III. Finally, it is likely that the release of posterior linguopharyngeal contact to reopen the respiratory passage, again not visible on EPG, occurred near the end of Stage III while

oral full contact was still intact. Typically, radiographic staging of deglutitive activities in the upper alimentary tract does not consider the activity of the tongue immediately after a swallow, as the emphasis is often on the ensuing esophageal responses. However, Wein et al. (1991) described a recovery phase based on ultrasound imaging, in which the tongue returned to the resting position. The EPG Stage IV seems comparable to at least part of this ultrasonographic recovery phase (up to the point where the tongue has completely retracted from the hard palate). As stated previously, the EPG stages are not identical to the conventional swallowing phases, because EPG provides information only on the interactions between the tongue and the hard palate. Any lingual movement that might occur before or after tongue-palate contact, while visible on radiography and ultrasonography, is not seen on EPG.

Effect of Bolus Size and Consistency on Contact Timing

With respect to tongue-palate contact timing, the EPG evidence showed that thinner and larger boluses were propelled significantly faster through Stage II. The slower propulsion rate for gelatin than for water supported previous findings that viscosity affected deglutitive oral motor behaviors by lengthening the transit time (see Dantas et al., 1990, Lazarus et al., 1993, and Robbins et al., 1992). The faster propulsion rate for 30-cc boluses supported the findings of Kahrilas et al. (1993), suggesting that more forceful tongue movements were used to complete the all-at-once oral transport of a large quantity. Since the 5-cc gelatin bolus used in the present study was both smaller and thicker, one could understand why it had the longest propulsion duration in all subjects

tested. In general, the finding of significant effects of bolus properties on contact timing indicated that EPG was a technique sensitive enough to unveil evidence for peripheral sensory and biomechanical modulation of the temporal aspect of swallowing movements.

Another timing effect occurred for dry swallows. In Stage III, dry swallows were significantly longer than water swallows. A possible explanation is that the saliva bolus, being small, caused small oral pressure gradients and perhaps a small pharyngeal gravitational effect. Consequently, a longer time would be needed to generate sufficient impetus for pharyngeal transport of the bolus, lengthening Stage III.

Continuous Drinking

Sequential versus Single Swallows

The second question asked by the present study was whether continuous drinking would be performed by simply concatenating single swallows. The evidence revealed a shared characteristic as well as differences between the discrete and sequential swallowing gestures. The basic movement characteristic shared by both swallowing tasks was the sequential upward displacement of the four tongue segments from front to back and lateral to midline, as the means of backward bolus propulsion. Reflecting a fundamental relationship between the tongue and the hard palate, these movement components served as the basis for all swallowing tasks, regardless of their properties and demands.

In two areas, however, the demands of the sequential swallowing task induced lingual reactions quite different from those seen for the discrete swallows: increased speed of tongue movement, and overlap of gestural components. Specifically, in contact timing,

sequential swallows were significantly shorter in total duration than single water swallows, indicating a much faster pace of lingual motions. In contact pattern, the majority of the sequential swallows were characterized by an overlap of activity between front contact retraction and back contact activation with the omission of full contact. On ultrasound, there was evidence for the co-occurrence of both tongue tip lowering and tongue body elevation, and the reverse, tongue tip elevation and tongue body lowering at different times during continuous drinking. This pattern of lingual action and linguopalatal interaction was clearly different from that observed for single swallows where a period of tongue inactivity consistently followed propulsion and preceded withdrawal. Thus, the answer to the second question was that continuous drinking was not carried out by simply repeating full and absolute cycles of single swallows (i.e., by successively completing each component swallow with preservation of all four stages, as that seen during the discrete swallowing task).

Motor Control Strategies

The present study proposes that the fundamental motor strategies used for discrete swallowing remained unchanged for sequential swallowing. To elaborate on this point, it is necessary to first recount the motor elements involved in each behavior.

Sequential swallowing occurred as part of continuous drinking which contained reciprocal water-intake (“drink”) and water-clearing (“swallow”) cycles. As part of the drink-swallow cycles, there were reduplicated opening and closing of the oral tract by action of the tongue. The opening event, seen on EPG as contact withdrawal and on

ultrasound as lingual retraction, reflected the “drink” portion of the cycle, while the closing event, seen on both EPG and ultrasound as propulsion, reflected the “swallow” portion. Each of these events consisted of a sequence of gestures that involved progressive, front-to-back activation of the four tongue segments: front-to-back lowering in one case, and front-to-back elevation in the other.

It has been well established that swallowing is a complex motor process involving both voluntary and reflexive physiological components. In this process, responses from the oral cavity, pharynx, larynx, and esophagus are integrated to achieve successful preparation and transport of food and protection of the airway. It has also been well established that the pharyngeal response is governed by the brainstem central pattern generator, while the interaction of tongue, jaw and facial movements for food preparation and oral transport is under cortical control (Miller, 1982, 1993). The lowering of the tongue to receive the bolus is an obvious food-intake behavior. It is uncertain if this behavior should be considered as part of food preparation or as a pre-preparation event. It is certain, however, that the behavior is voluntary, and that cortical intervention is in effect. The elevation of the tongue to propel the bolus is a food transport behavior. This behavior, having oral and oropharyngeal components, is both voluntary and reflexive--voluntary up to the point when the bolus head passes the anterior faucial pillar, and reflexive thereafter (cf. Logemann, 1983). Because swallowing is a continuum of integrated motor events, it is difficult to separate one event from the other or to set specific event boundaries, especially those occurring in the oral cavity. However, the

complexity of interaction between different oral motor sequences during continuous drinking does suggest that more than one motor strategy is at work.

The protocol for the discrete swallowing experiment of this study required each subject to hold the bolus in the mouth for a short period before being prompted by trigger signals to commence task-related oral maneuvers. This requirement, a means of experimental control, is certainly not unique to the present investigation. An activity that was not considered as part of the task but took place with each discrete swallow in every subject was the presentation of the bolus in a syringe by the experimenter. As seen consistently on ultrasound, occurring with each bolus presentation was a natural lowering of the tongue to receive the material (see Appendix C for illustration of this behavior). This lowering gesture without exception followed a front-to-back progression but stopped short of the posterior tongue segment, reflecting the mechanism at work for prevention of premature spillage and aspiration. The suggestion, thus, is that had the artificial “hold” period been removed, or had the subject been asked to self-present the bolus and to swallow immediately afterwards (as in the sequential swallowing experiment), the motor events seen would probably have consisted of an opening gesture for bolus intake followed by a closing gesture for bolus propulsion.

Conceptually, therefore, the opening and closing motor sequences are inherent parts of both continuous drinking and discrete swallowing, but reciprocation of the behaviors is characteristic of one and not the other. To efficiently and safely carry out the task requirement for reciprocation of motor events, the timing coordination of these events was modified. Since the task demanded “sequential swallowing without any

between-swallow pause," increased rate of lingual movement was a necessity and not an option. As an effect of the rate increase, component gestures of the two motor sequences overlapped in time and with harmony, resulting in rhythmical, stereotypic reduplication of bolus intake, transport and swallow. The harmonious merging of the two sequences gave the impression that one continuous flow of lingual actions took place for each drink-swallow cycle and from cycle to cycle.

Given the above interpretations, one would then conclude that discrete water drinking without artificial bolus-holding would be composed of a single drink-swallow cycle in which lingual "opening" and "closing" events occurred successively. In addition, one would propose that continuous water drinking would be performed by concatenating a string of discrete drinks with temporal overlaps of the opening and closing sequences as a function of rate increase. Recall that for speech, Browman and Goldstein (1990) used different articulatory tiers to represent linguistic gestures, and proposed two separate ones for the tongue--tip and body (see review in Chapter I). Under a similar premise, since the overlaps during continuous drinking were most apparent between the tongue tip and the tongue body, oral lingual gestures for reciprocal drink-swallow cycles might be organized into at least these two tiers. The model of Browman and Goldstein (1990) proposes that while the individual speech gestures are discrete and invariant across contexts, the "overlapping activation of several invariant gestures" during continuous speech "results in context-varying articulatory trajectories" (p. 342). Evidence from the present study showed that the coordinated co-occurrences of two complex yet innately invariant motor

sequences during continuous drinking also resulted in task-varying lingual movement trajectories.

Lingual gestural rate increases and overlaps brought about the omission or drastic shortening of the full contact stage during continuous drinking, indicating that the motor correlate of a rapid rate was the “dropping or fusing of movement elements” (cf. Stetson, 1951). In single swallows, the consistency of full contact across all subjects suggested that a period of stable anchoring of the oral tongue against the palate served a distinct function. That function may well have been to maintain oral stabilization so as to attain maximal posterior lingual expansion and lingual driving force for pharyngeal bolus transport. If this interpretation is accurate, the absence or meager presence of full contact in sequential swallowing raises several difficult questions. Is full contact not an innate, necessary stage of swallowing, and is oral tongue anchoring replaced by other temporal modifications, movement components, and/or biomechanical factors in the aerodigestive tract as a function of increased rate? To what extent does “momentum” contribute to bolus movement during sequential swallowing, and how is that related to the concurrent motor events in the pharynx, larynx, and cervical esophagus? Does linguopharyngeal contact pressure differ, for example, in onset/offset timing and magnitude between discrete and sequential swallowing? All of these questions remain unanswered. Future investigations using combined videofluorography and manometry are likely to offer insights. The present study does, however, support the hypothesis that full contact is not a dispensable stage in normal discrete swallowing, although it is drastically reduced in continuous drinking due to rapid movement rate. An analogy may be found in the

compression of vowels with rate increase during speech. It is well known that when speaking rate is increased, vowels become shortened to a larger extent than consonants. Similarly, in sequential swallowing and perhaps even in a fast discrete swallow, Stage III has considerably greater latitude for compression than, for example, Stage II.

Interestingly, despite the considerable increase in lingual movement pace, there were no overt indications of the speed-accuracy trade-off that is common for aimed movements (cf. Meyer et al., 1982 and Newell, 1980). More specifically, no reduction in swallowing safety or efficiency (i.e., no choking or spillage of liquid) was observed as a function of rate increase. There are at least three explanations that are not mutually exclusive:

The first explanation lies in the velocity range of deglutitive tongue motion. As Meyer et al. (1982) put it, "Faster movements can usually occur only at the expense of being spatially less accurate on the average, and movements having greater spatial accuracy can usually occur only at the expense of being slower on the average" (p. 449). The tongue's action during sequential swallowing never achieved very high velocities even on the fast continuous drinking task. Presumably this was necessary in order to maintain a high level of movement accuracy, and the reason for high accuracy is the need to protect the airway. Although the overlap of gestures allowed greater velocity for sequential than for single swallows, there was an apparent limit to the extent of allowable maximal velocity for deglutitive tongue movement due to the range of motion involved and the issue of airway safety. This does not imply, however, that a threshold for the speed-

accuracy trade-off does not exist in this case, nor does it imply that lingual action during swallowing has no finer rate-adjustment potential.

A second explanation lies in the mechanical properties of the tongue muscles.

Although the present research did not directly examine lingual muscle mechanics, elements such as force, elasticity, and viscosity, as well as other biomechanical factors (e.g., inertia, force inherent in the bolus) undoubtedly were at play and contributed to the task responses observed. The factor of muscle contraction force is especially relevant here. It has been shown via electrical stimulation to motor nerves that all muscles have an upper limit of force increase in response to increasing rate of stimulation, that muscle twitch force curves fuse at high stimulation rates, and that marked reduction in the frequency-response curve occurs as a result (above 3-4 Hz in speech muscles) (McClellan, 1988). Functionally, in fact, at very high movement rates (e.g., at maximal diadochokinetic rates) "there is invariably a reduction in the structural displacement" as a "result of the mechanical properties of muscle" (McClellan, 1988, p. 32). Thus, from the perspective of lingual muscle mechanics, to preserve adequate displacement of the tongue for effective sequential swallowing, lingual movement rate cannot exceed a certain level. Exactly what that "certain level" is remains unknown. Also undetermined are: the appropriate amount of force needed, the activation levels and relative timing of different tongue muscles, and how their intercoordination affects each other's force output as well as the overall patterns of lingual displacement. Future studies are needed to directly address these important biomechanical issues. It is understood, however, that this type of investigative task is challenging because of the complex decussations of lingual muscles and the constant

interaction of all lingual muscles in any movement involving the tongue (Smith & Kier, 1989). Isolating specific muscles within the tongue for electromyographic or biomechanical recording is conceivably difficult.

A third explanation lies in the probable changes that are occurring elsewhere in the aerodigestive tract during continuous drinking. With rapid movements of the tongue and the successive arrival of water boluses in the pharynx, there are likely to be associated adjustments in the movement timing and patterning of laryngeal/pharyngeal structures and in their temporal and spatial coordinations with the tongue. The velopharyngeal sphincter, the hyoid bone, the epiglottis, the larynx as a whole, and the upper esophageal sphincter (UES) are examples of these structures. To execute a complete single swallow, each of them engages in “on-and-off” movements. The larynx, for example, elevates as a whole against the base of the tongue during the swallow (“on”) and lowers to its normal position afterwards (“off”). The upper esophageal sphincter, as another example, relaxes to allow bolus passage during the “on” period and recontracts during the “off” period. To preserve airway safety when liquid arrives rapidly and continuously, these laryngeal/pharyngeal structures must simplify their internal as well as external coordinations. Because the “on” activities are crucial, one way of accomplishing such simplification is perhaps to adjust the range of movement for the “off” period. For example, the larynx may lower but not to the extent it does in a single swallow before it re-elevates for the subsequent swallow, and the upper esophageal sphincter may not recontract fully or by much until the end of the last swallow. On ultrasound, the hyoid shadow exhibited reduced range of reciprocal forward-backward displacement from swallow to swallow and did not completely return to its

resting position until the end of drinking. Since movement efficiency is an important consideration of dynamic motor systems, the “partial off” seems a reasonable strategy for attaining safe and cost-effective (as in energy and time) movement execution. This theory undoubtedly requires verification. Future continuous-swallowing investigations that combine EPG with videofluoroscopy or with nasendoscopy should unveil supporting or negating evidence.

Methodological Consideration

As a first attempt in examining tongue-palate contact for sequential swallowing during continuous drinking, this study did not apply stringent controls over the rate variable and focused more on the spontaneous management strategies used by the individual subjects. The finding of no significant rate difference between “normal” and “fast” drinking appeared to reflect this lack of tight control, at least to some extent. When left to their discretion, some subjects (e.g., S1) used practically the same rate for normal and fast drinking while perceiving themselves as using differential speed (based on the subjects’ statements during post-experiment interviews). A second explanation for the similarities across the two rates is that because choking is unpleasant, subjects might have a strong disinclination to very fast drinking. Chugging which some but not all individuals can perform might be one of the few successful ways to overcome this. Nevertheless, for optimal experimental control, future investigations in this area may consider a protocol that induces sequential swallowing via mechanical oral infusion of liquid at graded rates (e.g., 40, 60, 80, and 100 cc/min; cf. Issa & Porostocky, 1994). The use of an infusion

pump to systematically control the rate and amount of liquid presentation will increase experimental objectivity and permit more accurate calculation of per-swallow consumption and more precise data analysis.

Ultrasound as a Supplementary Technique for EPG

As stated earlier, the major weakness of EPG is that it provides information on only tongue-hard palate contact. As a compensation for such weakness, the present study used ultrasound imaging to gain an avenue for data verification and supplementation. Although direct, feature-by-feature matching of the EPG and ultrasound findings was impossible due to instrumental differences, gross comparisons could be made in timing as well as between tongue shape changes and contact activities. The most important benefit from combining EPG and ultrasound was that the two techniques provided entirely different perspectives, and together they made the observations of deglutitive tongue behaviors more complete. Specifically, EPG supplied lateral and medial contact information that was absent on ultrasound, and ultrasound showed posterior tongue action as well as pre-contact and post-contact lingual movements that were not seen on EPG. In addition, the two sets of data when combined offered insights that would not have been found in one alone:

First, viewing the contact patterns in light of the visualized tongue actions and vice versa, one gained a deeper appreciation for how the tongue took advantage of the immobile palate during swallowing. Systematic, front-to-back anchoring against the hard palate was the apparent and only way through which propulsion could be accomplished.

As Stone (1995) put it, “The immobility of the hard palate can be a real advantage to the tongue because the tongue does not have to deal with palatal variability in the motor planning for their contact” (p. 143). The rather straight-forward linguopalatal interaction could also be an advantage to the overall motor planning for swallowing, considering the multiplicity of other neuromuscular coordinations (e.g., linguopharyngeal, linguolaryngeal, laryngopharyngeal, etc.) that must occur with precision to maximally ensure the safety of the airway.

Second, tongue shape changes during swallowing, which presumably were the results of linguopalatal contact, were noticeably limited in variety. Although some signs of bolus-induced tongue shape differences were observed, they tended to be more prominent during pre-swallow bolus holding or loading. Thus, unlike speech where fine differences in tongue shape are relied on for differential phoneme production, the principal task of oral manipulation during swallowing is effective propulsion of the bolus. Shape alterations during swallowing, in other words, are secondary results and not part of the primary goal.

Third, although the tongue possesses multiple potential degrees of freedom in movement as well as many spatial options of contact with the palate, only a few are required to fulfill the requirements for swallowing. Sequential elevation and bunching in conformity with the shape of the palate, lateral arching, lowering, and horizontal/vertical expansion and compression appear to be the basic lingual gestures needed. Twisting, curling, and other complex local deformations which conceivably are needed in speech and in mastication are not necessary for swallowing. This suggests that the recruitment of

lingual muscles, intrinsic as well as extrinsic, is relatively less complex in swallowing than in the other two activities.

Ultrasound imaging provided an additional opportunity to examine regional lingual movement kinematics through the tracking of instantaneous velocities. The velocity profile permitted not only the observation of local velocity changes over time but also the comparison of peak-velocity differences as a function of swallowing task. The shape of the velocity profiles, especially the locations of peak velocities along the time continuum, provided at least three pieces of information. First, it revealed the invariance of the sequence of maximal displacement of the four tongue segments across swallowing tasks. This supported the theory that serial anchoring of each segment against the palate from front to back is the basic motor scheme for bolus propulsion. Second, prominent negative peaks of the dorsal and posterior segments were consistently shown. Their occurrences corresponded in time to the EPG Stage II (see Figure 3.16), reflecting "segmental" lowering of the tongue to allow bolus passage. How the magnitude of these negative peaks varies as a function of bolus properties warrants further investigation and may offer additional insight into lingual strategies for bolus accommodation during swallowing. Third, for each tongue segment, detailed information is available on the velocity patterns which may be quantitatively analyzed for more extensive examination of task-related, kinematic properties of deglutitive lingual action. When more data become available on normal patterns, the velocity profile potentially can provide a basis for comparing and describing abnormal lingual movements during swallowing.

Toward a Model of Deglutitive Tongue Action

Discrete Swallowing

In Stone's proposal (1990, 1991) for a three-dimensional model of lingual movement during speech, the tongue was divided into functional segments--five sagittal (anterior, middle, dorsal, posterior, root) and five coronal (medial, lateral 1, lateral 2). In this "functional segment" model, the lengthwise segments operated semi-independently to produce local displacement as well as front-to-back rotational effects for articulatory purposes. The crosswise segments carried out concerted or opposing movements to effect central grooving and left-right asymmetries. Palatal contact or bracing was optional, because certain speech sounds are produced without it. However, the tongue does rely heavily on contact with the palate to effect shape and positional changes for the majority of speech gestures.

The EPG and sagittal ultrasound data of the present investigation suggest considerable applicability of this model for describing tongue movements during discrete swallowing. Three conceptual modifications, however, are necessary:

First, tongue-palate contact is fundamental to swallow-related lingual action under normal conditions. Therefore, there are no "unbraced" gestures. The principal goal of such contact, as stated earlier, is to achieve positional changes for bolus propulsion and not necessarily to effect alterations in tongue shape.

Second, the lengthwise lingual segments operate as concatenated, functionally dependent units during discrete swallowing. In the front-to-back propulsive sweep the maximal displacement of each successive unit, though appearing to occur locally, is

chained to that of the previous unit (cf. Martin, 1991). In addition, the positional stability of one unit is a prerequisite for the attainment of maximal displacement of the ensuing unit, regardless of the swallowing task at hand. This prerequisite anchoring is due to the fact that the tongue has no skeletal support within itself. It uses sequential, sectional bracing against the hard palate from front to back to generate and transmit bolus propulsive force, and redistribute its own volume from front to back, thereby accomplishing the task of food transport. Serial anchoring of the sagittal units, therefore, is not only the source of the bolus-transport force needed but also the origin of the stereotypic wave-like contours.

Third, each lengthwise tongue segment is composed of five cross-sectional segments which also operate as concatenated, functionally dependent units to contribute to the task of swallowing. During propulsion, the crosswise units are responsible for symmetrical elevation of the tongue from the sides toward the midline (as if narrowing a central channel) to assist in transporting the bolus backward.

In sum, the functional segment model, in order to be applied to swallowing, must be modified to include anchored rather than unanchored gestures. In addition, the model must define the tongue units as functionally dependent and concatenated in both the lengthwise and the crosswise domains.

An interesting question that has not been resolved by any current swallowing data is how the volume-preserving constraint interacts with the anchoring constraint. The anchoring constraint is a given in swallowing, because the tongue must take advantage of the palate to propel the bolus. The volume-preserving constraint, originally pointed out by

Kier and Smith (1985), says that tongue volume can be shifted from place to place but not increased or decreased. Recent three-dimensional reconstructions of tongue shapes during speech confirmed the presence of local displacement-compression tradeoffs on the tongue surface (Stone & Lundberg, 1996). For example, during production of the vowel /i/, upward displacement of the anterior tongue unit was found associated with inward compression of the posterior unit. The authors hypothesized that this tradeoff was the basic mechanism for tongue positioning in the production of vowels. Two-dimensional radiographic or ultrasonographic depiction of tongue movements during swallowing cannot provide evidence for such a tradeoff. Granted that the tongue operates differently during swallowing than during speech, still the differential operations are carried out by the same volume-preserving muscular hydrostat. At the height of a swallow when the posterior tongue expands to contact the pharyngeal walls, the rest of the tongue remains in firm contact with the palate. Where is the complementary, local displacement-compression tradeoff? How, then, does the tongue preserve its volume? One possible explanation is that the tongue is thinned, allowing for backward extension without shortening or compressing the front. However, based on clinical observation of modified barium swallows, it appears that the posterior tongue reaches its maximal backward position in close temporal proximity with the hyoid reaching its maximal upward/forward position. Therefore, the upward hyoid movement, ostensibly compressing the tongue and jaw muscles, is associated, at least indirectly, with the backward expansion of the tongue. In other words, the hyoid bone compresses not only the jaw opening muscles (mylohyoid,

geniohyoid, digastric) but also the posterior tongue, allowing it to push outward into the pharynx.

Continuous Drinking

The model presented above for discrete swallowing is also applicable to continuous drinking. For both water intake and clearing during each drink-swallow cycle, the tongue uses invariant, progressive front-to-back activation of its oral segments to open and close the oral tract and accomplish the motor goals specified. In the sequence of closing gestures, these segments continue to function as concatenated, dependent units in both the lengthwise and the crosswise domains. In addition, anchored rather than unanchored gestures remain rudimentary to the process. In the sequence of opening gestures, the linkage and dependency among the tongue segments are again apparent, as at no time can the tongue lower itself to replenish water in an order other than front-to-back. One may add that this stereotypic front-to-back opening is tightly coupled with and a reflection of jaw action, granted that the jaw is constrained in its degree of motion during cup-drinking.

When gestures of the same structure overlap in time, the indication is usually that parts of that structure are functionally independent. The temporal overlaps between the tongue tip and the tongue body during continuous drinking could, therefore, be interpreted that segments of the tongue performed independent gestures across motor sequences while simultaneously maintaining within-sequence gestural dependency. While this interpretation is supported by multiple analogies in speech (see Browman & Goldstein,

1990), the high degree of inter-sequence behavioral correlation during continuous drinking cannot be overlooked. Specifically, the invariant "tip down, body up" and "tip up, body down" patterns of lingual overlaps reflected distinct functional significance: one to prevent premature bolus spillage, the other to make room for propulsion. Because these overlaps or oppositional movements were readily predictable, the indication would be that the two motor sequences, perfectly integrated, were still not totally free from the influence of each other. What is apparent, though, is the remarkable flexibility of the tongue as a soft-tissue organ. Since multiple muscles are in or connected to the tongue, it can theoretically move in multiple, different ways. Slightly more contraction of a set of lingual muscles versus another can result in subtle variations of behaviors.

Evidence of the present study supports the notion that swallowing and speech are different behaviors of the vocal tract (cf. Martin, 1991). Although both are motorically complex, swallowing is highly stereotypic with reflexive as well as voluntary components, and speech is highly variable and completely voluntary. Thus, when applying speech models--physiologic or linguistic--to deglutitive behaviors, revisions are necessary in order to properly represent the characteristics of the motor components being addressed.

Clinical Implications

Dysphagia may be associated with a variety of neurologic disorders and structural abnormalities (see Logemann, 1983). In adults and children with upper motoneuron, lower motoneuron, basal ganglia, and cerebellar dysfunctions, as well as patients who have undergone surgical intervention for head and neck cancer, deficits in tongue movement

and coordination are common and may even be one of the primary causes for dysphagia symptoms (Hirano, et al., 1992; LaBlance, Kraus, & Steckol, 1991; Lazarus & Logemann, 1987; Logemann, 1983; Veis & Logemann, 1985). A general reduction in the range of lingual motion and control or a specific impairment such as repetitive tongue rolling/pumping (as seen in Parkinson's disease) can lead to delayed oral transit, ineffective bolus propulsion, oral and pharyngeal residue, and even premature spillage of the bolus which threatens airway safety (Cook, 1991; Dodds, Logemann, & Stewart, 1990; Logemann, 1983).

As shown in the present study, stable anchoring of the tongue against the palate is crucial for overall swallowing efficiency, because it provides the necessary leverage for generating the appropriate oral propulsive force and for achieving maximal base of tongue expansion and adequate pharyngeal propulsive force. Thus, results of this investigation support not only the conventional linguomotor exercises (e.g., protrusion, retraction, lateralization, twist, curl, etc.) but also the practice of deliberately prolonged (for 4-5 seconds at a time), hard, squeezing lingual action from front to back in association with dry swallows to facilitate forceful tongue-palate contact and tongue base retraction. The recommendation for using this maneuver with dry swallows is a safety precaution. Patients who have adequate laryngeal control or cough reflex may not need to be as conservative and may advance from dry to wet swallows using the "lingual hard-squeeze" maneuver after a period of systematic training. Moreover, in head and neck cancer patients who present abnormal oral and laryngeal signs but benefit from the use of supraglottic or Mendelsohn maneuvers (i.e., breath-holding following by swallowing and

then a deliberate cough, or maximal laryngeal elevation using the suprahyoid muscles in the midst of a swallow; see Lazarus, Logemann, & Gibbons, 1993), lingual hard-squeeze can be easily incorporated into these exercises for maximal results.

The modified barium swallow (Logemann, 1983) is probably one of the most widely applied protocols for swallowing evaluation. This approach emphasizes the use of small bolus size (2 cc of barium liquid and paste, and 1/4 of a cookie) as a conservative precaution against damaging consequences in case of aspiration. While such rationale is appreciated and holds true in many patients, clinicians should not ignore the possibility that some patients swallow larger boluses more efficiently than they do smaller ones. The radiographic study of Robbins, Sufit, Rosenbek, Levine, and Hyland (1987) showed that three of the 64 patients they examined aspirated on only 2-cc but not 30-cc barium swallows. These authors speculated that this finding could reflect different muscle recruitment patterns for the oral phase of swallowing and the possibly altered threshold for the pharyngeal swallowing response. Based on the results of the present study and of Kahrilas et al. (1993), one may add that biomechanically, the benefit of the larger bolus could have also been drawn from faster propulsion rate and greater movement vigor. The important message is that not all patients will find smaller boluses easier to manage than the larger ones. In patients without evidence of aspiration from the modified barium swallow, additional radiographic testing using larger boluses may reveal more clues on the nature of the breakdown in swallowing efficiency and on clinical management strategies. Conceivably, some neurologic patients (e.g., some of those with cerebrovascular accident or closed head injury) presenting mild, generalized difficulty in motor coordination may

show better swallowing performance with larger-and-thicker materials, taking advantage of the timing and force factors from bolus size and the increased cohesiveness from bolus consistency.

Continuous drinking, compared with discrete swallowing, is a task that imposes even greater demands for motor coordination, because it involves alternating action sequencing, gestural overlaps, increased overall movement rate, and a prolonged, heightened state of activity in all deglutitive motor participants. These increased demands may be further exemplified by the fact that many motor behaviors developmentally follow a progression from a discrete to a sequential version with learning and maturity. Indeed, children learn to utter single words before coarticulated speech, and to print single characters before cursive writing. Developmentally, swallowing is known to first emerge in the embryo, and its neural organization is well established by the time of birth (Bosma, 1973; Humphrey, 1970). However, the motor coordination for cup-drinking and sequential swallowing on one breath requires time to develop and mature.

Severe, generalized motor dysfunction (such as that occurring in the later stage of Parkinson's disease) can cause a patient to lose the coordination necessary for performing sequential swallowing. Nonetheless, just as there are patients who manage larger-volume swallows better than smaller ones, some dysphagic patients in whom adequate laryngeal function is preserved are likely to find continuous drinking easier to achieve than discrete swallowing because of movement momentum or other undetermined factors. Clinical investigations are needed to evaluate such likelihood in patients presenting different diseases and dysphagia symptoms.

EPG appears to have potential applications in clinical research and management. One of the distinct advantages for clinical usage of EPG is that the technique is nonhazardous and relatively noninvasive. As such, it may be used repeatedly and for prolonged periods, thus permitting extensive observations of linguopalatal interaction and training. As indicated above, abnormal tongue activities of different sorts occur during swallowing in several clinical populations. Deviations in tongue-palate contact timing and patterns from the normal data are expected in, for example, postsurgical oral cancer patients, patients with hypokinesia or hyperkinesia, and some patients after stroke or closed head trauma. However, the details of the abnormal contact behaviors have not been characterized for different disorders. EPG presents a readily available means for in-depth quantitative and qualitative characterizations of abnormal linguopalatal interactions, and for identification of the specific components of deviant deglutitive tongue action. Such detail, typically not accessible via conventional radiography and ultrasonography, may provide clues for therapy planning.

The clinical management procedures for postoperative oral cancer patients with dysphagia sometimes include the fitting of a maxillary prosthesis. The purpose is to reshape or augment the palate so that the patient achieves better swallowing efficiency through more appropriate tongue-palate contact. The effectiveness of such a device has been documented (Davis, Lazarus, Logemann, & Hurst, 1987; Logemann, Kahrilas, Hurst, Davis, & Krugler, 1989; Robbins, Bowman, & Jacob, 1987; Wheeler, Logemann, & Rosen, 1980). In some of the patients the benefits of the prosthesis are immediate. In others, however, a period of training is required for adaptation and improvement to take

place. For these patients, EPG can be conveniently incorporated as a biofeedback tool to facilitate the adaptation-improvement process. EPG's applicability in swallowing therapy is not limited to the oral cancer patient population. Any patients who present reduced lingual control for deglutition may benefit from the visualization of their tongue-palate contact and work on increasing lingual control or finding appropriate compensatory maneuvers with direct feedback.

Conclusions

EPG provided detailed information on linguopalatal contact during swallowing and revealed how the tongue used the hard palate to impel the bolus. It also provided inferred information on deglutitive tongue movements which were then confirmed using ultrasound. Compartmentalization of the palate into six primary bins (front, central, back, lateral, medial, midline) extracted deglutitive linguopalatal contact characteristics that were regionally specific, three-dimensional, and typically not revealed through conventional radiography and ultrasonography. Specifically, tongue-palate contact for swallowing, though invariant across bolus types and subjects, was seen to have two degrees of freedom: front/back movement and lateral/midline movement. These EPG continua reflected a lingual motor system composed of concatenated, functionally dependent units in the lengthwise as well as crosswise domains, that produced stereotypical tongue movements.

The discrete swallowing task of the present study was defined as having four tongue-palate contact stages-- prepropulsion, propulsion, full contact, and withdrawal--

based on specific, time-varying contact characteristics. The division of the EPG time series into these stages was functionally meaningful, as it captured the distinct and unique features of each stage, the variations in patterns within a stage, and the relationship between patterns across stages. The timing aspect of discrete swallowing can be modulated by the sensory features inherent in a bolus, despite the stereotypy in its overall motor pattern. In particular, propulsion rate was significantly faster for thinner and larger boluses, and full contact was significantly longest for dry swallows. These temporal effects indicated that the swallowing central pattern generator was at least partially regulated by peripheral input.

The present study represents an initial attempt to better understand lingual behaviors for sequential swallowing. In continuous drinking where there were reduplicated drink-swallow sequences, the tongue was seen to use faster movement rate and overlapping gestures to maintain safe and efficient swallowing. Gestural overlaps were most apparent in the anterior and the posterior tongue, and reflected a change in the timing coordination of the motor sequences for “drink” and “swallow” implemented to meet changed task requirements. Further research on the responses of other motor elements and on oral, laryngeal, and pharyngeal coordinations during continuous drinking is warranted and likely to improve our knowledge of swallowing motor control in general.

Ultrasound provided supplementary data on lingual contour and velocity changes over time. The single-subject velocity profiles supported the EPG findings and presented additional evidence for bolus- and task-induced differences in peak velocities. The

velocity profile is a useful tool for the analysis of lingual kinematic properties during swallowing.

There is potential value in using EPG to investigate disordered swallowing, particularly the timing and patterning of abnormal tongue movements. In addition to possible future applications in swallowing research, EPG might be used for diagnostic purposes as a supplement to the more traditional imaging and pressure measurements, and for treatment purposes as a biofeedback tool.

In sum, evidence of the present study supported a theory that swallowing motor control included a peripheral mechanism capable of modulating centrally generated responses, and that the general deglutitive motor program consisted of both invariant and variant parameters. Specifically, movement pattern or action sequence reflected a fixed element within the structure of the motor program. Movement timing, on the other hand, was variant and could be modified according to the properties of the material ingested and the demands of the task at hand.

APPENDIX A. ULTRASOUND TRANSDUCER PLACEMENT DATA

Specific placement of the ultrasound transducer for individual subjects during sagittal and coronal imaging is presented below. Angle refers to degree posterior to the vertical. Position refers to distance posterior to the mental symphysis. The transducer used was a 3.5-MHz convex-curved-linear-array type with 96 active elements.

<u>Subject</u>	<u>Jaw Length (mm)</u>	<u>Sagittal Placement</u>			<u>Coronal Placement</u>		
		<u>Angle (°)</u>	<u>Position (mm)</u>	<u>% of Jaw Length</u>	<u>Angle (°)</u>	<u>Position (mm)</u>	<u>% of Jaw Length</u>
S1	83.74	8	33.50	40.00%	14	27.63	32.99%
S2	93.74	8	31.40	33.50%	11	31.03	33.10%
S3	82.11	8	25.20	30.69%	11	27.37	33.33%
S4	87.54	6	29.50	33.70%	14	29.18	33.33%
S5	87.42	8	33.18	37.95%	14	29.14	33.33%

APPENDIX B. STATISTICAL TABLES

B-1. Random effects analysis of variance on EPG total durations for the discrete swallowing tasks, using the general linear models procedure.

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Source: TASK

Error: $0.9993 \cdot \text{MS}(\text{TASK} \cdot \text{SUBJECT}) + 0.0007 \cdot \text{MS}(\text{Error})$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	731560.43883	16.00	234021.98581	3.1260	0.0444

Source: SUBJECT

Error: $0.9993 \cdot \text{MS}(\text{TASK} \cdot \text{SUBJECT}) + 0.0007 \cdot \text{MS}(\text{Error})$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	2073593.8019	16.00	234021.98581	8.8607	0.0006

Source: TASK*SUBJECT

Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
16	234145.22582	124	48669.021832	4.8110	0.0001

B-2. Repeated measures analysis of variance on mean durations of EPG stages for different discrete swallowing tasks, using the general linear models procedure. Multivariate tests were performed on the variables TASK and STAGE, but not on TASK*STAGE interaction due to insufficient error degrees of freedom. Instead, the interaction was assessed using univariate tests.

Manova Test Criteria and Exact F Statistics for
the Hypothesis of no TASK Effect

H = Type III SS&CP Matrix for TASK E = Error SS&CP Matrix
S=1 M=1 N=-0.5

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.00079757	313.202	4	1	0.0424
Pillai's Trace	0.99920243	313.202	4	1	0.0424
Hotelling-Lawley Trace	1252.80832	313.202	4	1	0.0424
Roy's Greatest Root	1252.80832	313.202	4	1	0.0424

Manova Test Criteria and Exact F Statistics for
the Hypothesis of no STAGE Effect

H = Type III SS&CP Matrix for PHASE E = Error SS&CP Matrix
S=1 M=0.5 N=0

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.14327308	3.98645	3	2	0.2070
Pillai's Trace	0.85672692	3.98645	3	2	0.2070
Hotelling-Lawley Trace	5.97967801	3.98645	3	2	0.2070
Roy's Greatest Root	5.97967801	3.98645	3	2	0.2070

Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Type III SS	Mean Square	F Value	Pr > F	G - G	H - F
TASK*STAGE	19	2317839.664	121991.561	5.57	0.0001	0.0195	0.0004
Error	76	1663900.096	21893.422				

Greenhouse-Geisser Epsilon = 0.1315

Huynh-Feldt Epsilon = 0.3682

B-3. Post hoc repeated measures multivariate analysis of variance of pairwise contrasts for EPG Stage-II duration between selected discrete swallowing tasks. Only cases where $p < 0.05$ are included below, although α for these comparisons was set at 0.01. 5W = 5cc water; 30W = 30cc water; 5G = 5cc gelatin; 30G = 30cc gelatin.

Manova Test Criteria and Exact F Statistics for
the Hypothesis of no Overall INTERCEPT Effect
on the variables defined by the M Matrix Transformation
H = Type III SS&CP Matrix for INTERCEPT E = Error SS&CP Matrix
S=1 M=-0.5 N=1

Contrast variable: 30W - 30G

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.03998767	96.0308	1	4	0.0006
Pillai's Trace	0.96001233	96.0308	1	4	0.0006
Hotelling-Lawley Trace	24.0077058	96.0308	1	4	0.0006
Roy's Greatest Root	24.0077058	96.0308	1	4	0.0006

Contrast variable: 5W - 5G

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.13149271	26.4199	1	4	0.0068
Pillai's Trace	0.86850729	26.4199	1	4	0.0068
Hotelling-Lawley Trace	6.60498432	26.4199	1	4	0.0068
Roy's Greatest Root	6.60498432	26.4199	1	4	0.0068

Contrast variable: 30G - 5G

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.21751734	14.3893	1	4	0.0192
Pillai's Trace	0.78248266	14.3893	1	4	0.0192
Hotelling-Lawley Trace	3.59733454	14.3893	1	4	0.0192
Roy's Greatest Root	3.59733454	14.3893	1	4	0.0192

Contrast variable: 30W - 5W

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.32967607	8.13312	1	4	0.0463
Pillai's Trace	0.67032393	8.13312	1	4	0.0463
Hotelling-Lawley Trace	2.03328048	8.13312	1	4	0.0463
Roy's Greatest Root	2.03328048	8.13312	1	4	0.0463

B-3. (continued)

Contrast variable: 5G - Dry

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.03570459	108.03	1	4	0.0005
Pillai's Trace	0.96429541	108.03	1	4	0.0005
Hotelling-Lawley Trace	27.0076063	108.03	1	4	0.0005
Roy's Greatest Root	27.0076063	108.03	1	4	0.0005

Contrast variable: (mean of 30W and 30G) - (mean of 5W and 5G)

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.22283645	13.9504	1	4	0.0202
Pillai's Trace	0.77716355	13.9504	1	4	0.0202
Hotelling-Lawley Trace	3.48759618	13.9504	1	4	0.0202
Roy's Greatest Root	3.48759618	13.9504	1	4	0.0202

Contrast variable: (mean of 30W and 5W) - (mean of 30G and 5G)

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.03871082	99.3303	1	4	0.0006
Pillai's Trace	0.96128918	99.3303	1	4	0.0006
Hotelling-Lawley Trace	24.8325734	99.3303	1	4	0.0006
Roy's Greatest Root	24.8325734	99.3303	1	4	0.0006

B-4. Post hoc repeated measures multivariate analysis of variance of pairwise contrasts for EPG Stage-III duration between selected discrete swallowing tasks. Only cases where $p < 0.05$ are included below, although α for these comparisons was set at 0.01. 5W = 5cc water; 30W = 30cc water; 5G = 5cc gelatin; 30G = 30cc gelatin.

Manova Test Criteria and Exact F Statistics for
the Hypothesis of no Overall INTERCEPT Effect
on the variables defined by the M Matrix Transformation
H = Type III SS&CP Matrix for INTERCEPT E = Error SS&CP Matrix
S=1 M=-0.5 N=1

Contrast variable: 30W - Dry

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.20092697	15.9077	1	4	0.0163
Pillai's Trace	0.79907303	15.9077	1	4	0.0163
Hotelling-Lawley Trace	3.97693255	15.9077	1	4	0.0163
Roy's Greatest Root	3.97693255	15.9077	1	4	0.0163

Contrast variable: 5W - Dry

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.21248622	14.8248	1	4	0.0183
Pillai's Trace	0.78751378	14.8248	1	4	0.0183
Hotelling-Lawley Trace	3.70618759	14.8248	1	4	0.0183
Roy's Greatest Root	3.70618759	14.8248	1	4	0.0183

Contrast variable: 30W - 5W

Statistic	Value	F	Num DF	Den DF	Pr > F
Wilks' Lambda	0.2711003	10.7547	1	4	0.0305
Pillai's Trace	0.7288997	10.7547	1	4	0.0305
Hotelling-Lawley Trace	2.68867164	10.7547	1	4	0.0305
Roy's Greatest Root	2.68867164	10.7547	1	4	0.0305

B-5. Analyses of variance of (a) main effect and (b) pairwise contrasts on mean EPG total durations for sequential (pooled), 5-cc water (5W), and 30-cc water (30W) swallows, using the general linear models procedure.

(a) Main Effect

Tests of Hypotheses for Mixed Model Analysis of Variance

Source: TASK

Error: $0.9952 * MS(TASK * SUBJECT) + 0.0048 * MS(Error)$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	5202717.8634	8.02	131054.48319	39.6989	0.0001

Source: SUBJECT

Error: $0.9851 * MS(TASK * SUBJECT) + 0.0149 * MS(Error)$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	889601.00469	8.07	130121.19376	6.8367	0.0105

Source: TASK*SUBJECT

Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
8	131497.90186	89	39252.950238	3.3500	0.0021

(b) Pairwise Contrasts

Analysis of Variance of Contrast Variables

Contrast Variable: (Pooled Sequential) - (5W)

Source	DF	Type III SS	F Value	Pr > F
MEAN	1	2515716.871380	44.84	0.0026
Error	4	224401.958920		

Contrast Variable: (Pooled Sequential) - (30W)

Source	DF	Type III SS	F Value	Pr > F
MEAN	1	1590243.128820	58.24	0.0016
Error	4	109218.359880		

B-6. Analyses of variance of (a) main effect and (b) pairwise contrasts on Front:Back percent-contact ratios at time of maximal midline for sequential (pooled), 5-cc water (5W), and 30-cc water (30W) swallows, using the general linear models procedure.

(a) Main Effect

Tests of Hypotheses for Mixed Model Analysis of Variance

Source: TASK

Error: $0.9952 * MS(TASK * SUBJECT) + 0.0048 * MS(Error)$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	6.6546278153	8.01	0.413608646	16.0892	0.0016

Source: SUBJECT

Error: $0.9851 * MS(TASK * SUBJECT) + 0.0149 * MS(Error)$

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	0.5999607626	8.02	0.4097039707	1.4644	0.2987

Source: TASK*SUBJECT

Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
8	0.415463811	89	0.0295314676	14.0685	0.0001

(b) Pairwise Contrasts

Analysis of Variance of Contrast Variables

Contrast Variable: (Pooled Sequential) - 5W

Source	DF	Type III SS	F Value	Pr > F
MEAN	1	3.16808000	22.40	0.0091
Error	4	0.56572000		

Contrast Variable: (Pooled Sequential) - 30W

Source	DF	Type III SS	F Value	Pr > F
MEAN	1	2.15168000	14.12	0.0198
Error	4	0.60972000		

B-7. Analyses of variance of (a) main effect and (b) pairwise contrasts on Lateral:Back percent-contact ratios at time of maximal midline for sequential (pooled), 5-cc water (5W), and 30-cc water (30W) swallows, using the general linear models procedure.

(a) Main Effect

Tests of Hypotheses for Mixed Model Analysis of Variance

Source: TASK						
Error: $0.9952 * MS(TASK * SUBJECT) + 0.0048 * MS(Error)$						
DF	Type III MS	Denominator	Denominator	F Value	Pr > F	
		DF	MS			
2	1.0427676398	8.01	0.0745735983	13.9831	0.0024	
Source: SUBJECT						
Error: $0.9851 * MS(TASK * SUBJECT) + 0.0149 * MS(Error)$						
DF	Type III MS	Denominator	Denominator	F Value	Pr > F	
		DF	MS			
4	0.0865437127	8.03	0.0739163832	1.1708	0.3918	
Source: TASK*SUBJECT						
Error: MS(Error)						
DF	Type III MS	Denominator	Denominator	F Value	Pr > F	
		DF	MS			
8	0.0748858503	89	0.0099276721	7.5431	0.0001	

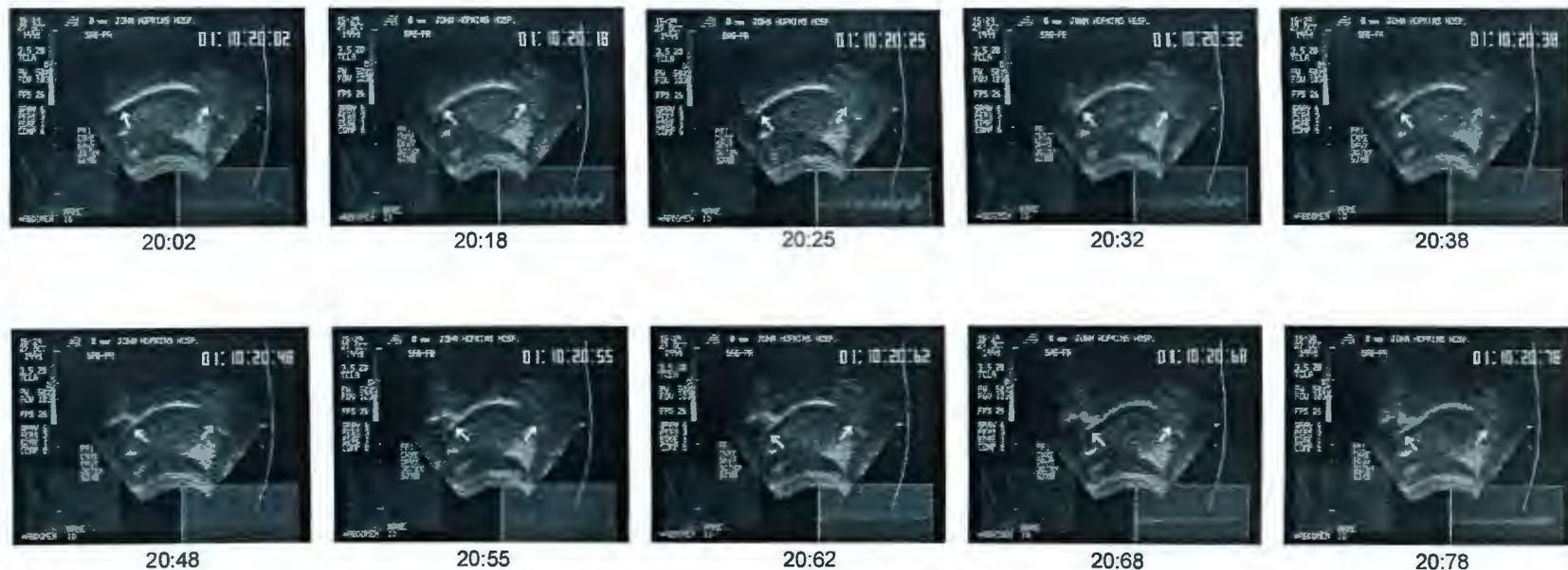
(b) Pairwise Contrasts

Analysis of Variance of Contrast Variables

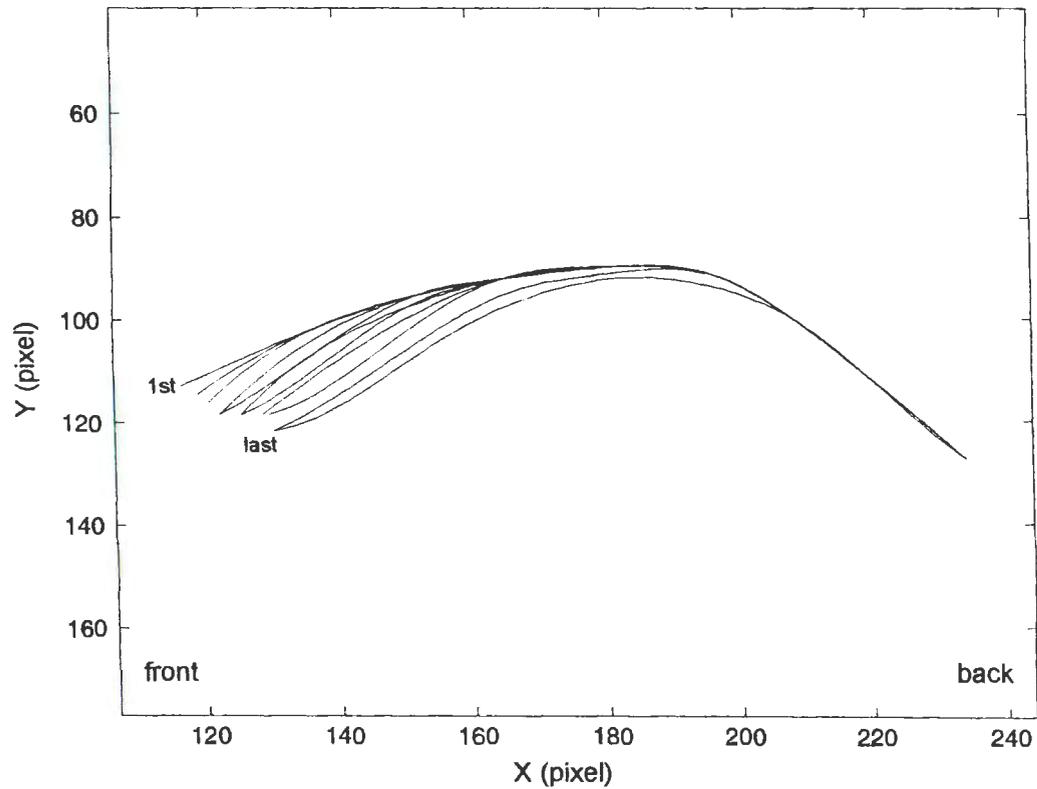
Contrast Variable: (Pooled Sequential) - 5W				
Source	DF	Type III SS	F Value	Pr > F
MEAN	1	0.51842000	20.39	0.0107
Error	4	0.10168000		
Contrast Variable: (Pooled Sequential) - 30W				
Source	DF	Type III SS	F Value	Pr > F
MEAN	1	0.31250000	11.75	0.0266
Error	4	0.10640000		

APPENDIX C. TONGUE LOWERING DURING BOLUS INTAKE IN DISCRETE SWALLOWING

C-1. Digitized ultrasound images illustrating progressive lowering of the tongue to receive the bolus during a representative single swallow. As shown, displacement of the anterior, mid, and dorsal tongue segments (left to right) is graded in extent, while that of the posterior segment is minimal throughout bolus presentation. Arrows in each image mark points on the tongue surface. The time under each frame reflects second and 1/100th of a second.



C-2. Composite display of lingual surface curves extracted from the digitized ultrasound images shown in Appendix C-1, illustrating progressive lowering of the tongue to receive the bolus during a representative single swallow. Curve marked "1st" corresponds to frame 20:02; curve marked "last" corresponds to frame 20:78. Each curve is plotted based on the x- (on X axis) and y-values (on Y axis) of the coordinates for 101 surface points. Unit of measurement = pixel (with 320x240 pixels per frame and 18 pixels per cm). Edge extraction and curve plotting were accomplished using a Matlab-based image processing package (Sze, 1996).



REFERENCES

- Abbs, J. H. (1973). The influence of the gamma motor system on jaw movement during speech: A theoretical framework and some preliminary observations. Journal of Speech and Hearing Research, 16, 175-200.
- Abbs, J. H., & Connor, N. P. (1991). Motorsensory mechanisms of speech motor timing and coordination. Journal of Phonetics, 19, 333-342.
- Abbs, J. H., & Gracco, V. L. (1983). Sensorimotor actions in the control of multimovement speech gestures. Trends in Neurology, 6, 391-395.
- Abbs, J. H., & Gracco, V. L. (1984). Control of complex motor gestures: Orofacial muscle responses to load perturbations of the lip during speech. Journal of Neurophysiology, 51, 705-723.
- Abbs, J. H., Gracco, V. L., & Cole, K. J. (1984). Control of multimovement coordination: Sensorimotor mechanisms in speech motor programming. Journal of Motor Behavior, 16, 195-232.
- Abd-el-Malek, S. (1939). Observations on the morphology of the human tongue. Journal of Anatomy, 73, 201-210.
- Abd-el-Malek, S. (1955). The part played by the tongue in mastication and deglutition. Journal of Anatomy, 89, 250-255.
- Adnerhill, I., Ekberg, O., & Groher, M. E. (1989). Determining normal bolus size for thin liquids. Dysphagia, 4, 1-3.
- Alfonso, P. J., & Baer, T. (1982). Dynamics of vowel articulation. Language and Speech, 25, 151-173.
- Allen, L. R. (1958). Improved phonetics in denture construction. Journal of Prosthetic Dentistry, 8, 753-763.

- Altschuler, S. M., Bao, X., Bieger, D., Hopkins, D. A., & Miselis, R. R. (1989). Viscerotopic representation of the upper alimentary tract in the rat: Sensory ganglia and nuclei of the solitary and spinal trigeminal tracts. Journal of Comparative Neurology, 283, 248-268.
- Amri, M., & Car, A. (1988). Projections from the medullary swallowing center to the hypoglossal motor nucleus: A neuroanatomical and electrophysiological study in sheep. Brain Research, 441, 119-126.
- Amri, M., Car, A., & Roman, C. (1990). Axonal branching of medullary swallowing neurons projecting on the trigeminal and hypoglossal motor nuclei: Demonstrated by electrophysiological and fluorescent double labeling techniques. Experimental Brain Research, 81, 384-390.
- Amri, M., Lamkadem, M., & Car, A. (1989). Activity of extrinsic tongue muscles during swallowing in sheep. Brain Research, 503, 141-143.
- Amri, M., Lamkadem, M., & Car, A. (1991). Effects of lingual nerve and chewing cortex stimulation upon activity of the swallowing neurons located in the region of the hypoglossal motor nucleus. Brain Research, 548, 149-155.
- Anderson, D. J., & Matthews, B. (Eds.). (1976). Mastication. Bristol: John Wright.
- Åström, K. E. (1953). On the central course of afferent fibers in the trigeminal, facial, glossopharyngeal and vagal nerves and their nuclei in the mouse. Acta Physiologica Scandinavica, 29, Supplement 106, 209-320.
- Baum, B. J. (1987). Saliva secretion and composition. Frontiers of Oral Physiology, 6, 126-134.
- Beckstead, R. M., & Norgren, R. (1979). An autoradiographic examination of the central distribution of the trigeminal, facial, glossopharyngeal, and vagal nerves in the monkey. Journal of Comparative Neurology, 184, 455-472.
- Bieger, D., & Hockman, C. H. (1976). Suprabulbar modulation of reflex swallowing. Experimental Neurology, 52, 311-324.
- Bole, C. T., II. (1965). Electromyographic kinesiology of the genioglossus muscles in man. Unpublished master's thesis, Ohio State University, Dayton, OH.
- Borden, G. J., & Gay, T. (1979). Temporal aspects of articulatory movements for /s/-stop clusters. Phonetica, 36, 21-31.

- Borden, G. J., & Harris, K. S. (1984). Speech science primer (2nd ed.). Baltimore: Williams & Wilkins.
- Bosma, J. F. (1957). Deglutition: Pharyngeal stage. Physiological Reviews, 37, 275-300.
- Bosma, J. F. (1973). Prologue to symposium. In J. F. Bosma (Ed.), Fourth symposium on oral sensation and perception: Development in the fetus and infant (pp. 1-8). Bethesda, MD: National Institute of Health.
- Bosma, J. F., Hepburn, L. G., Josell, S. D., & Baker, K. (1990). Ultrasound demonstration of tongue motions during suckle feeding. Developmental Medicine and Child Neurology, 32, 223-229.
- Bowman, J. P. (1968). Muscle spindles in the intrinsic and extrinsic muscles of the rhesus monkey's (*Macaca mulatta*) tongue. Anatomical Record, 161, 483-487.
- Bowman, J. P., & Combs, C. M. (1968). Discharge patterns of lingual spindle afferent fibers in the hypoglossal nerve of the rhesus monkey. Experimental Neurology, 21, 105-119.
- Bowman, J. P., & Combs, C. M. (1969). The cerebrocortical projections of hypoglossal afferents in the monkey as revealed by the evoked potential method. Experimental Neurology, 23, 291-301.
- Browman, C. P., & Goldstein, L. (1990). Tiers in articulatory phonology, with some implications for casual speech. In J. Kingston & M. E. Beckman (Eds.), Papers in laboratory phonology I: Between the grammar and the physics of speech (pp. 341-376). Cambridge: Cambridge University Press.
- Butcher, A. (1989). Measuring coarticulation and variability in tongue contact patterns. Clinical Linguistics & Phonetics, 3, 39-47.
- Byrd, D., Flemming, E., Mueller, C. A., & Tan, C. C. (1995). Using regions and indices in EPG data reduction. Journal of Speech and Hearing Research, 38, 821-827.
- Capra, N. F. (1995). Mechanisms of oral sensation. Dysphagia, 10, 235-247.
- Car, A., & Amri, M. (1987). Activity of neurons located in the region of the hypoglossal motor nucleus during swallowing in sheep. Experimental Brain Research, 69, 175-182.

- Castell, J. A., Dalton, C. B., & Castell, D. O. (1990a). Effects of body position and bolus consistency on the manometric parameters and coordination of the upper esophageal sphincter and pharynx. Dysphagia, 5, 179-186.
- Castell, J. A., Dalton, C. B., & Castell, D. O. (1990b). Pharyngeal and upper esophageal sphincter manometry in humans. American Journal of Physiology, 258, G173-G178.
- Catford, J. C. (1977). Fundamental problems in phonetics. Bloomington, IN: Indiana University Press.
- Cerenko, D., McConnel, F. M. S., & Jackson, R. T. (1989). Quantitative assessment of pharyngeal bolus driving force. Otolaryngology and Head and Neck Surgery, 100, 57-63.
- Chi-Fishman, G., Capra, N. F., & McCall, G. N. (1994). Thermomechanical facilitation of swallowing evoked by electrical nerve stimulation in cats. Dysphagia, 9, 149-155.
- Cleall, J. F. (1965). Deglutition: A study of form and function. American Journal of Orthodontics, 51, 566-594.
- Contreras, R. J., Beckstead, R. M., & Norgren, R. (1982). The central projections of the trigeminal, facial, glossopharyngeal and vagus nerves: An autoradiographic study in the rat. Journal of the Autonomic Nervous System, 6, 303-322.
- Cook, I. J. S. (1991). Normal and disordered swallowing: New insights. Baillière's Clinical Gastroenterology, 5, 245-267.
- Cook, I. J., Dodds, W. J., Dantas, R. O., Kern, M. K., Massey, B. T., Shaker, R., & Hogan, W. J. (1989). Timing of videofluoroscopic, manometric events, and bolus transit during the oral and pharyngeal phases of swallowing. Dysphagia, 4, 8-15.
- Cook, I. J., Dodds, W. J., Dantas, R. O., Massey, B., Kern, M. K., Lang, I. M., Brasseur, J. G., & Hogan, W. J. (1989). Opening mechanisms of the human upper esophageal sphincter. American Journal of Physiology, 257, G748-G759.
- Cooper, S. (1953). Muscle spindles in the intrinsic muscles of the human tongue. Journal of Physiology, 122, 193-202.
- Cordaro, M. A. (1991). A personal computer-based display of three-dimensional tongue surface dynamics. Unpublished master's thesis. Johns Hopkins University, Baltimore, MD.

- Cottle, M. K. (1964). Degeneration studies of primary afferents of IXth and Xth cranial nerves in the cat. Journal of Comparative Neurology, 122, 321-345.
- Cunningham, D. P., & Basmajian, J. V. (1969). Electromyography of genioglossus and geniohyoid muscles during deglutition. Anatomical Record, 165, 401-410.
- Dantas, R. O. & Dodds, W. J. (1990). Effect of bolus volume and consistency on swallow-induced submental and infrahyoid electromyographic activity. Brazilian Journal of Medical and Biological Research, 23, 37-44.
- Dantas, R. O., Dodds, W. J., Massey, B. T., & Kern, M. K. (1989). The effect of high- vs low-density barium preparations on the quantitative features of swallowing. American Journal of Roentgenology, 153, 1191-1195.
- Dantas, R. O., Dodds, W. J., Massey, B. T., Shaker, R., & Cook, I. J. (1990). Manometric characteristics of glossopalatal sphincter. Digestive Diseases and Sciences, 35, 161-166.
- Dantas, R. O., Kern, M. K., Massey, B. T., Dodds, W. J., Kahrilas, P. J., Brasseur, J. G., Cook, I. J., & Lang, I. M. (1990). Effect of swallowed bolus variables on oral and pharyngeal phases of swallowing. American Journal of Physiology, 258, G675-G681.
- Davis, J. W., Lazarus, C., Logemann, J., & Hurst, P. S. (1987). Effect of a maxillary glossectomy prosthesis on articulation and swallowing. Journal of Prosthetic Dentistry, 57, 715-719.
- Dodds, W. J. (1988, March). Physiology of swallowing. In W. J. Ravich, M. W. Donner, B. Jones, & J. A. Logemann (Chairs), Second symposium on dysphagia. Symposium sponsored by the Johns Hopkins Swallowing Center, Baltimore, MD.
- Dodds, W. J., Logemann, J. A., & Stewart, E. T. (1990). Radiologic assessment of abnormal oral and pharyngeal phases of swallowing. American Journal of Roentgenology, 154, 965-974.
- Dodds, W. J., Man, K. M., Cook, I. J., Kahrilas, P. J., Stewart, E. T., & Kern, M. K. (1988). Influence of bolus volume on swallow-induced hyoid movement in normal subjects. American Journal of Roentgenology, 150, 1307-1309.
- Dodds, W. J., Stewart, E. T., & Logemann, J. A. (1990). Physiology and radiology of the normal oral and pharyngeal phases of swallowing. American Journal of Roentgenology, 154, 953-963.

- Dodds, W. J., Taylor, A. J., Stewart, E. T., Kern, M. K., Logemann, J. A., & Cook, I. J. (1989). Tipper and dipper types of oral swallows. American Journal of Roentgenology, 153, 1197-1199.
- Donner, M. W., Bosma, J. F., & Robertson, D. L. (1985). Anatomy and physiology of the Pharynx. Gastrointestinal Radiology, 10, 196-212.
- Doty, R. W. (1951). Influence of stimulus pattern on reflex deglutition. American Journal of Physiology, 166, 142-158.
- Doty, R. W. (1968). Neural organization of deglutition. In C. F. Code (Ed.), Handbook of physiology: Sec. 6. Alimentary canal: Vol. IV. Motility, Chapter 92 (pp. 1861-1902). Washington, DC: American Physiological Society.
- Doty, R. W., & Bosma, J. F. (1956). An electromyographic analysis of reflex deglutition. Journal of Neurophysiology, 19, 44-60.
- Doty, R. W., Richmond, W. H., & Storey, A. T. (1967). Effect of medullary lesions on coordination of deglutition. Experimental Neurology, 17, 91-106.
- Dubner, R., Sessle, B. J., & Storey, A. T. (1978). The neural basis of oral and facial function. New York: Plenum Press.
- Ekberg, O. (1986). The normal movements of the hyoid bone during swallow. Investigative Radiology, 21, 408-410.
- Ekberg, O., & Borgstrom, P. S. (1989). A graphic representation of pharyngeal wall motion during swallow: Technical note. Dysphagia, 4, 43-47.
- Ekberg, O., Liedberg, B., & Öwall, B. (1986). Barium and meat. A comparison between pharyngeal swallow of fluid and solid boluses. Acta Radiologica. Diagnosis, 27, 701-704.
- Ekberg, O., Olsson, R., & Sundgren-Borgström, P. (1988). Relation of bolus size and pharyngeal swallow. Dysphagia, 3, 69-72.
- Fallside, F., & Woods, W. A. (1985). Computer speech processing. Englewood Cliffs, NJ: Prentice-Hall.
- Fitzgerald, M. J. T., & Sachithanandan, S. R. (1979). The structure and source of lingual proprioceptors in the monkey. Journal of Anatomy, 128, 523-552.

- Fletcher, S. G. (1985). Speech production and oral motor skill in an adult with an unrepaired palatal cleft. Journal of Speech and Hearing Disorders, 50, 254-261.
- Fletcher, S. G., Dagenais, P. A., & Critz-Crosby, P. (1991). Teaching consonants to profoundly hearing-impaired speakers using palatometry. Journal of Speech and Hearing Research, 34, 929-942.
- Folkins, J. W., & Abbs, J. H. (1975). Lip and jaw motor control during speech: Responses to resistive loading of the jaw. Journal of Speech and Hearing Research, 18, 207-220.
- Fontdevila, J., Pallarès, M. D., & Recasens, D. (1994). The contact index method of electropalatographic data reduction. Journal of Phonetics, 22, 141-154.**
- Freund, H.-J., & Büdingen, H. J. (1978). The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. Experimental Brain Research, 31, 1-12.
- Fujimura, O., Tatsumi, I. F., & Kagaya, R. (1972). Computational processing of palatographic patterns. Journal of Phonetics, 1, 47-54.
- Gay, T. (1981). Mechanisms in the control of speech rate. Phonetica, 38, 148-158.
- Gibbon, F., Hardcastle, W., & Nicoladis, K. (1993). Temporal and spatial aspects of lingual coarticulation in /kl/ sequences: A cross-linguistic investigation. Language and Speech, 36, 261-277.
- Gracco, V. L., & Abbs, J. H. (1985). Dynamic control of the perioral system during speech: Kinematic analyses of autogenic and nonautogenic sensorimotor processes. Journal of Neurophysiology, 54, 418-432.
- Gracco, V. L., & Abbs, J. H. (1989). Sensorimotor characteristics of speech motor sequences. Experimental Brain Research, 75, 586-598.
- Gramiak, R., Kelley, M. L. Jr., & Gravinia, R. F. (1967). Nasal pressure changes during swallowing. American Journal of Roentgenology, 99, 562-576.
- Grillner, S., & Wallen, P. (1985). Central pattern generators for locomotion, with special reference to vertebrates. Annual Review of Neuroscience, 8, 233-262.
- Halsell, C. B., Travers, J. B., & Travers, S. P. (1993). Gustatory and tactile stimulation of the posterior tongue activate overlapping but distinctive regions in the nucleus of the solitary tract. Brain Research, 632, 161-173.

- Ham, H. R., Georges, B., Froideville, J. L., & Piepsz, A. (1985). Oesophageal transit of liquid: Effects of single or multiple swallows. Nuclear Medicine Communications, *6*, 263-267.
- Hamlet, S. L. (1989). Dynamic aspects of lingual propulsive activity in swallowing. Dysphagia, *4*, 136-145.
- Hamlet, S. L., Bunnell, H. T., & Struntz, B. G. (1986). Articulatory asymmetries. Journal of the Acoustical Society of America, *79*, 1164-1169.
- Hamlet, S., Choi, J., Zormeier, M., Shamsa, F., Stachler, R., Muz, J., & Jones, L. (1996). Normal adult swallowing of liquid and viscous material: Scintigraphic data on bolus transit and oropharyngeal residues. Dysphagia, *11*, 41-47.
- Hamlet, S., Jones, L., Mathog, R., Bolton, M., & Patterson, R. (1988). Bolus propulsive activity of the tongue in dysphagic cancer patients. Dysphagia, *3*, 18-23.
- Hamlet, S. L., & Stone, M. (1978). Compensatory alveolar consonant production induced by wearing a dental prosthesis. Journal of Phonetics, *6*, 227-248.
- Hamlet, S. L., Stone, M., & Shawker, T. H. (1988). Posterior tongue grooving in deglutition and speech: Preliminary observations. Dysphagia, *3*, 65-68.
- Hanamori, T., & Smith, D. V. (1986). Central projections of the hamster superior laryngeal nerve. Brain Research Bulletin, *16*, 271-279.
- Hancock, P. A., & Newell, K. M. (1985). The movement speed-accuracy relationship in space-time. In H. Heuer, U. Keinbeck, & K.-H. Schmidt (Eds.), Motor behavior: Programming, control, and acquisition (pp. 153-188). New York: Springer-Verlag.
- Hardcastle, W. J., Gibbon, F., & Nicolaidis, K. (1991). EPG data reduction methods and their implications for studies of lingual coarticulation. Journal of Phonetics, *19*, 251-266.
- Hardcastle, W., Jones, W., Knight, C., Trudgeon, A., & Calder, G. (1989). New developments in electropalatography: A state-of-the-art report. Clinical Linguistics & Phonetics, *3*, 1-38.
- Hellstrand, E. (1982a). Reflex control of cat extrinsic and intrinsic tongue muscles exerted by intraoral receptors. Acta Physiologica Scandinavica, *115*, 245-256.

- Hellstrand, E. (1982b). The neuromuscular system of the tongue. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), Speech motor control (pp. 141-157). New York: Pergamon Press.
- Hendrix, T. R. (1980). The motility of the alimentary canal. In V. B. Mountcastle (Ed.), Medical physiology, Vol. 2 (pp. 1320-1347). St. Louis: C. V. Mosby.
- Hedrick, W. R., Hykes, D. L., & Starchman, D. E. (Eds.). (1995). Ultrasound physics and instrumentation (3rd ed.). St. Louis: Mosby.
- Hiatt, J. L., & Gartner, L. P. (1987). Textbook of head and neck anatomy. Baltimore, MD: Williams & Wilkins.
- Hiiemae, K. M., & Crompton, A. W. (1985). Mastication, food transport, and swallowing. In M. Hildebrand, D. M. Bramble, K. F. Liem, & D. B. Wake (Eds.), Functional vertebrate morphology (pp. 262-290). Cambridge, MA: Harvard University Press.
- Hiki, S., & Itoh, H. (1986). Influence of palate shape on lingual articulation. Speech Communication, 5, 141-158.
- Hirano, M., Kuroiwa, Y., Tanaka, S., Matsuoka, H., Sato, K., & Yoshida, T. (1992). Dysphagia following various degrees of surgical resection for oral cancer. Annals of Otology, Rhinology and Laryngology, 101, 138-141.
- Hockman, C. H., Bieger, D., & Weerasuriya, A. (1979). Supranuclear pathways of swallowing. Progress in Neurobiology, 12, 15-32.
- Hollshwandner, C. H., Brenman, H. S., & Friedman, M. H. F. (1975). Role of afferent sensors in the initiation of swallowing in man. Journal of Dental Research, 54, 83-88.
- Hoole, P., Ziegler, W., Hartmann, E., & Hardcastle, W. (1989). Parallel electropalatographic and acoustic measures of fricatives. Clinical Linguistics & Phonetics, 3, 59-69.
- Hrychshyn, A. W., & Basmajian, J. V. (1972). Electromyography of the oral stage of swallowing in man. American Journal of Anatomy, 133, 330-340.
- Hughes, O. M., & Abbs, J. H. (1976). Labial-mandibular coordination in the production of speech: Implications fro the operation of motor equivalence. Phonetica, 33, 199-221.

- Humphrey, T. (1970). Reflex activity in the oral and facial area of the human fetus. In J. F. Bosma (Ed.), Second symposium on oral sensation and perception (pp. 195-233). Springfield, IL: Charles C. Thomas.
- Ingervall, B., Bratt, C. M., Carlsson, G. E., Helkimo, M., & Lantz, B. (1972). Duration of swallowing with and without anesthesia of the temporomandibular joints. Scandinavian Journal of Dental Research, 80, 189-196.
- Ingervall, B., & Lantz, B. (1973). Significance of gravity in the passage of bolus through the human pharynx. Archives of Oral Biology, 2, 351-356.
- Issa, F. G. & Porostocky, S. (1994). Effect of continuous swallowing on respiration. Respiration Physiology, 95, 181-193.
- Jack, F. R. & Gibbon, F. (1995). Electropalatography in the study of tongue movement during eating and swallowing (a novel procedure for measuring texture-related behavior). International Journal of Food Science and Technology, 30, 415-423.
- Jacob, P., Kahrilas, P. J., Logemann, J. A., Shah, V., & Ha, T. (1989). Upper esophageal sphincter opening and modulation during swallowing. Gastroenterology, 97, 1469-1478.
- Jean, A. (1984a). Brainstem organization of the swallowing network. Brain, Behavior and Evolution, 25, 109-116.
- Jean, A. (1984b). Control of the central swallowing program by inputs from the peripheral receptors. A review. Journal of the Autonomic Nervous System, 10, 225-233.
- Jean, A. (1990). Brainstem control of swallowing: Localization and organization of the central pattern generator for swallowing. In A. Taylor (Ed.), Neurophysiology of the jaw and teeth (pp. 294-321). Houndmills, England: Macmillan Press.
- Jean, A., Amri, M., & Calas, A. (1983). Connections between the ventral medullary swallowing area and the trigeminal motor nucleus of the sheep studied by tracing techniques. Journal of the Autonomic Nervous System, 7, 87-96.
- Jean, A., & Car, A. (1979). Inputs to the swallowing medullary neurons from the peripheral afferent fibers and the swallowing cortical area. Brain Research, 178, 567-572.
- Jenny, A. B., & Saper, C. B. (1987). Organization of the facial nucleus and corticofacial projection in the monkey: A reconsideration of the upper motor neuron facial palsy. Neurology, 37, 930-939.

- Jürgens, U. (1976). Projections from the cortical larynx area in the squirrel monkey. Experimental Brain Research, 25, 401-411.
- Kahrilas, P. J., Dodds, W. J., Dent, J., Logemann, J. A., & Shaker, R. (1988). Upper esophageal sphincter function during deglutition. Gastroenterology, 95, 52-62.
- Kahrilas, P. J., Lin, S., Logemann, J. A., Ergun, G. A., & Facchini, F. (1993). Deglutitive tongue action: Volume accommodation and bolus propulsion. Gastroenterology, 104, 152-162.
- Kahrilas, P. J., & Logemann, J. A. (1993). Volume accommodation during swallowing. Dysphagia, 8, 259-265.
- Kahrilas, P. J., Logemann, J. A., Lin, S., & Ergun, G. A. (1992). Pharyngeal clearance during swallowing: A combined manometric and videofluoroscopic study. Gastroenterology, 103, 128-136.
- Kaplan, M. D., & Baum, B. J. (1993). The Functions of Saliva. Dysphagia, 8, 225-229.
- Kawasaki, M., Ogura, J. H., & Takenouchi, S. (1964). Neurophysiological observations of normal deglutition. I. Its relationship to the respiratory cycle. Laryngoscope, 74, 1747-1765.
- Kennedy, D. (1969). The control of output by central neurons. In M. A. B. Brazier (Ed.), The interneuron (pp. 21-36). Berkeley, CA: University of California Press.
- Kennedy, J. G., III, & Kent, R. D. (1985). Anatomy and physiology of deglutition and related functions. Seminars in Speech and Language, 6, 257-273.
- Kennedy, J. G., III, & Kent, R. D. (1988). Physiological substrates of normal deglutition. Dysphagia, 3, 24-37.
- Kent, R. D., Martin, R. E., & Sufit, R. L. (1990). Oral sensation: A review and clinical prospective. In H. Winitz (Ed.), Human communication and its disorders: A review, 1990 (pp. 135-191). Norwood, NJ: Ablex Publishing.
- Kerr, F. W. L. (1962). Facial, vagal and glossopharyngeal nerves in the cat. Archives of Neurology, 6, 264-281.
- Kessler, J. P., & Jean, A. (1985). Identification of the medullary swallowing regions in the rat. Experimental Brain Research, 57, 256-263.

- Kessler, J. P., & Jean, A. (1986). Inhibitory influence of monoamines and brainstem monoaminergic regions on the medullary swallowing reflex. Neuroscience Letters, 65, 41-46.
- Kier, W. M., & Smith, K. K. (1985). Tongues, tentacles and trunks: The biomechanics of movement in muscular-hydrostats. Zoological Journal of the Linnean Society, 83, 307-324.
- Ku, D. N., Ma, P.-P., McConnel, F. M. S., & Cerenko, D. (1990). *A kinematic study of the oropharyngeal swallowing of a liquid*. Annals of Biomedical Engineering, 18, 655-669.
- Kuypers, H. G. J. M. (1958a). Corticobulbar connexions to the pons and lower brain-stem in man: An anatomical study. Brain, 81, 364-388.
- Kuypers, H. G. J. M. (1958b). Some projections from the peri-central cortex to the pons and lower brain stem in monkey and chimpanzee. Journal of Comparative Neurology, 110, 221-255.
- LaBlance, G. R., Kraus, K., & Steckol, K. F. (1991). Rehabilitation of swallowing and communication following glossectomy. Rehabilitation Nursing, 16, 266-270.
- Landgren, S., & Olsson, K. Å. (1982). Oral mechanoreceptors. In S. Grillner, B. Lindblom, J. Lubker, & A. Persson (Eds.), Speech motor control (pp. 129-139). New York: Pergamon Press.
- Lazarus, C., & Logemann, J. A. (1987). Swallowing disorders in closed head trauma patients. Archives of Physical Medicine and Rehabilitation, 68, 79-84.
- Lazarus, C., Logemann, J. A., & Gibbons, P. (1993). Effects of maneuvers on swallowing function in a dysphagic oral cancer patient. Head & Neck, 15, 419-424.
- Lazarus, C. I., Logemann, J. A., Rademaker, A. W., Kahrilas, P. J., Pajak, T., Lazar, R., & Halper, A. (1993). Effects of bolus volume, viscosity, and repeated swallows in nonstroke subjects and stroke patients. Archives of Physical Medicine and Rehabilitation, 74, 1066-1070.
- Lindblom, B. (1983). Economy of speech gestures. In P. F. MacNeilage (Ed.), The production of speech (pp. 217-245). New York: Springer-Verlag.
- Logemann, J. A. (1983). Evaluation and treatment of swallowing disorders. San Diego: College-Hill Press.

- Logemann, J. A. (1988). Swallowing physiology and pathophysiology. Otolaryngologic Clinics of North America, 21, 613-623.
- Logemann, J. A. (1991). Approaches to management of disordered swallowing. Baillière's Clinical Gastroenterology, 5, 269-280.
- Logemann, J. A., Kahrilas, P. J., Cheng, J., Pauloski, B. R., Gibbons, P. J., Rademaker, A. W., & Lin, S. (1992). Closure mechanisms of laryngeal vestibule during swallow. American Journal of Physiology, 262, G338-G344.
- Logemann, J. A., Kahrilas, P. J., Hurst, P., Davis, J., & Krugler, C. (1989). Effects of intraoral prosthetics on swallowing in patients with oral cancer. Dysphagia, 4, 118-120.
- Lowe, A. A. (1978). Excitatory and inhibitory inputs to hypoglossal motoneurons and adjacent reticular formation neurons in cats. Experimental Neurology, 62, 30-47.
- Lowe, A. A. (1981). The neural regulation of tongue movement. Progress in Neurobiology, 15, 295-344.
- Lowe, A. A. (1984). Tongue movements--brainstem mechanisms and clinical postulates. Brain, Behavior and Evolution, 25, 128-137.
- Lowe, A. A., Gurza, S. C., Sessle, B. J. (1977). Regulation of genioglossus and masseter muscle activity in man. Archives of Oral Biology, 22, 579-584.
- Lowe, A. A., & Sessle, B. J. (1973). Tongue activity during respiration, jaw opening, and swallowing in cat. Canadian Journal of Physiology and Pharmacology, 51, 1009-1011.
- Lowe, A. A., & Sessle, B. J. (1974). Genioglossus activity during respiration, jaw opening and swallowing in cat and monkey. Journal of Dental Research, 53 (Special Issue), 201.
- MacNeilage, P. F., & Sholes, G. N. (1964). An electromyographic study of the tongue during vowel production. Journal of Speech and Hearing Research, 7, 209-232.
- Månsson, I., & Sandberg, N. (1974). Effects of surface anesthesia on deglutition. Laryngoscope, 84, 427-437.
- Månsson, I., & Sandberg, N. (1975). Oro-pharyngeal sensitivity and elicitation of swallowing in man. Acta Otolaryngologica, 79, 140-145.

- Marchal, A. (1988). Coproduction: Evidence from EPG data. Speech Communication, 7, 287-295.
- Martin, R. E. (1991). A comparison of lingual movement in swallowing and speech production. Dissertation Abstracts International, 52, 1982-B. (University Microfilms No. 91-22486)
- Martin, R. E., Murray, G. M., & Sessle, B. J. (1991). Firing patterns and properties of neurones in primate tongue motor cortex (MI) in relation to swallowing. Neuroscience Abstract, 17, 309.
- Martin, R. E., & Sessle, B. J. (1993). The role of the cerebral cortex in swallowing. Dysphagia, 8, 195-202.
- McClellan, M. D. (1988). Neuromotor aspects of speech production and dysarthria. In K. Yorkston, D. Beukelman, & K. Bell (Eds.), Clinical management of dysarthric speakers. San Diego: College-Hill.
- McConnel, F. M. S. (1988). Analysis of pressure generation and bolus transit during pharyngeal swallowing. Laryngoscope, 98, 71-78.
- McConnel, F. M. S., Guffin, T. N., Jr., Cerenko, D., & Ko, A. S. (1992). *The effects of bolus flow on vertical pharyngeal pressure measurement in the pharyngoesophageal segment: Clinical significance*. Otolaryngology and Head and Neck Surgery, 106, 169-174.
- McNamara, J. A., Jr., & Moyers, R. E. (1973). Electromyography of the oral phase of deglutition in the rhesus monkey (*Macaca mulatta*). Archives of Oral Biology, 18, 995-1002.
- Mermelstein, P. (1973). Articulatory model for the study of speech production. Journal of the Acoustical Society of America, 53, 1070-1082.
- Meyer, D. E., Smith, J. E. K., & Wright, C. E. (1982). Models for the speed and accuracy of aimed movements. Psychological Review, 89, 449-482.
- Meyer, G. W., Gerhardt, D. C., & Castell, D. O. (1981). Human esophageal response to rapid swallowing: Muscle refractory period or neural inhibition? American Journal of Physiology, 241, G129-G136.
- Milidonis, M. K., Kraus, S. L., Segal, R. L., & Widmer, C. G. (1993). Genioglossi muscle activity in response to changes in anterior/neutral head posture. American Journal of Orthodontics and Dentofacial Orthopedics, 103, 39-44.

- Miller, A. J. (1972a). Characteristics of the swallowing reflex induced by peripheral nerve and brainstem stimulation. Experimental Neurology, 34, 210-222.
- Miller, A. J. (1972b). Significance of sensory inflow to the swallowing reflex. Brain Research, 43, 147-159.
- Miller, A. J. (1982). Deglutition. Physiological Reviews, 62, 129-184.
- Miller, A. J. (1986). Neurophysiological basis of swallowing. Dysphagia, 1, 91-100.
- Miller, A. J. (1993). The search for the central swallowing pathway: The quest for clarity. Dysphagia, 8, 185-194.
- Miller, A. J., & Bowman, J. P. (1974). Divergent synaptic influences affecting discharge patterning of genioglossus motor units. Brain Research, 78, 179-191.
- Miller, A. J., & Bowman, J. P. (1977). Precentral cortical modulation of mastication and swallowing. Journal of Dental Research, 56, 1154.
- Miller, F. R. (1920). The cortical paths for mastication and deglutition. Journal of Physiology, London, 53, 473-478.
- Miller, F. R., & Sherrington, C. S. (1916). Some observations on the bucco-pharyngeal stage of reflex deglutition in the cat. Quarterly Journal of Experimental Physiology, 9, 147-186.
- Milner, T. E. (1986). Controlling velocity in rapid movements. Journal of Motor Behavior, 18, 147-161.
- Miyawaki, K. (1974). A study of the musculature of the human tongue. Annual Bulletin, Research Institute of Logopedics and Phoniatics (University of Tokyo), 8, 23-49.
- Miyawaki, K., Hirose, H., Ushijima, T., & Sawashima, M. (1975). A preliminary report on the electromyographic study of the activity of lingual muscles. Annual Bulletin, Research Institute of Logopedics and Phoniatics (University of Tokyo), 9, 91-106.
- Miyawaki, K., Kiritani, S., Tatsumi, I. F., & Fujimura, O. (1974). Palatographic observation of VCV articulations in Japanese. Annual Bulletin, Research Institute of Logopedics and Phoniatics (University of Tokyo), 8, 51-57.

- Mizutani, T., & Hashimoto, K. (1988, November). Analysis of tongue motion for the dental consonants based on the high-speed palatographic data. Paper presented at the second joint meeting of the Acoustical Society of America and the Acoustical Society of Japan, Honolulu, HI.
- Morimoto, T., Inoue, T., Nakamura, T., & Kawamura, Y. (1984). Frequency-dependent modulation of rhythmic human jaw movements. Journal of Dental Research, *63*, 1310-1314.
- Morrish, K. A., Stone, M., Shawker, T. H., & Sonies, B. C. (1985). Distinguishability of tongue shape during vowel production. Journal of Phonetics, *13*, 189-203.
- Mueller, A. (1992). Percent. Unpublished computer program written for the Department of Linguistics, University of California, Los Angeles.
- Munhall, K. G., Ostry, D. J., & Parush, A. (1985). Characteristics of velocity profiles of speech movements. Journal of Experimental Psychology: Human Perception and Performance, *11*, 457-474.
- Murray, G. M., & Sessle, B. J. (1990). Neurones in primate tongue motor cortex alter their firing rates during swallow. Neuroscience Abstract, *16*, 1221.
- Murray, G. M., & Sessle, B. J. (1992a). Functional properties of single neurons in the face primary motor cortex of the primate. I. Input and output features of tongue motor cortex. Journal of Neurophysiology, *67*, 747-758.
- Murray, G. M., & Sessle, B. J. (1992b). Functional properties of single neurons in the face primary motor cortex of the primate. II. Relations with trained orofacial motor behavior. Journal of Neurophysiology, *67*, 759-774.
- Murray, G. M., & Sessle, B. J. (1992c). Functional properties of single neurons in the face primary motor cortex of the primate. III. Relations with different directions of trained tongue protrusion. Journal of Neurophysiology, *67*, 775-785.
- Nakayama, S., Neya, T., Watanabe, K., & Tsuchiya, K. (1974). Effects of electrical stimulation and local destruction on the medulla oblongata on swallowing movements in dogs. Rendiconti di Gastro-enterologia, *6*, 6-11.
- Negus, V. E. (1948). The second stage of swallowing. Acta-Otolaryngologica, Supplementum *78*, 78-82.

- Neya, T., Watanabe, K., & Yamasato, T. (1974). Localization of potentials in medullary reticular formation relevant to swallowing. Rendiconti di Gastro-enterologia, 6, 107-110.
- Nelson, J. B., & Castell, D. O. (1988). Esophageal motility disorders. Disease-a-Month, 34, 299-389.
- Newell, K. M. (1980). The speed-accuracy paradox in movement control: Error of time and space. In G. E. Stelmach, & J. Requin (Eds.), Tutorials in Motor Behavior (pp. 501-510). Amsterdam: Elsevier-North Holland.
- Newman, L. A., Cleveland, R. H., Blickman, J. G., Hillman, R. E., & Jaramillo, D. (1991). Videofluoroscopic analysis of the infant swallow. Investigative Radiology, 26, 870-873.
- Niimi, K., Kishi, S., Miki, M., & Fujita, S. (1963). An experimental study of the course and termination of the projection fibers from cortical areas 4 and 6 in the cat. Folia Psychiatrica et Neurologica Japonica, 17, 167-216.
- Öhman, S. E. G. (1966). Coarticulation in VCV utterances: Spectrographic measurements. Journal of the Acoustical Society of America, 39, 151-168.
- Ostry, D. J., Cooke, J. D., & Munhall, K. G. (1987). Velocity curves of human arm and speech movements. Experimental Brain Research, 68, 37-46.
- Ostry, D. J., & Flanagan, J. R. (1989). Human jaw movement in mastication and speech. Archives of Oral Biology, 34, 685-693.
- Ostry, D. J., Keller, E., & Parush, A. (1983). Similarities in the control of the speech articulators and the limbs: Kinematics of tongue dorsum movement in speech. Journal of Experimental Psychology: Human Perception and Performance, 9, 622-636.
- Ostry, D. J., & Munhall, K. G. (1985). Control of rate and duration of speech movements. Journal of the Acoustical Society of America, 77, 640-648.
- Palmer, J. B., Tanaka, E., & Siebens, A. A. (1988). Motions of the posterior pharyngeal wall in swallowing. Laryngoscope, 98, 414-417.
- Palmer, J. M. (1973). Dynamic palatography. Phonetica, 28, 76-85.

- Pearson, K. G. (1987). Central pattern generation: A concept under scrutiny. In H. McLennan, J. R. Ledson, C. H. S. McIntosh, & D. R. Jones (Eds.), Advances in physiological research (pp. 167-185). New York: Plenum Press.
- Pearson, K. G. (1991). Sensory elements in pattern-generating networks. In N. I. Badler, B. A. Barsky, & D. Zeltzer (Eds.), Making them move. Mechanics, control and animation of articulated figures (pp. 111-127). San Mateo: Morgan Kaufmann.
- Penfield, W., & Rasmussen, T. (1950). The cerebral cortex of man: A clinical study of localization of function. New York: Macmillan.
- Perkell, J. S. (1969). Physiology of speech production: Results and implications of a quantitative cineradiographic study (Research Monograph No. 53). Cambridge, MA: M.I.T. Press.
- Plesh, O., Bishop, B., & McCall, W. (1987). Mandibular movements and jaw muscles' activity while voluntarily chewing at different rates. Experimental Neurology, 98, 285-300.
- Pommerenke, W. T. (1928). A study of the sensory areas eliciting the swallowing reflex. American Journal of Physiology, 84, 36-41.
- Porter, R. (1966). Lingual mechanoreceptors activated by muscle twitch. Journal of Physiology, London, 183, 101-111.
- Porter, R. (1967). Cortical actions on hypoglossal motoneurons in cats: A proposed role for a common internuncial cell. Journal of Physiology, London, 193, 295-308.
- Pouderous, P., & Kahrilas, P. J. (1995). Deglutitive tongue force modulation by volition, volume, and viscosity in humans. Gastroenterology, 108, 1418-1426.
- Rasband, W. (1994). NIH Image, Version 1.55 [Computer program]. Bethesda, MD: The National Institutes of Health.
- Recasens, D. (1991). On the production characteristics of apicoalveolar taps and trills. Journal of Phonetics, 19, 267-280.
- Recasens, D., Farnetani, E., Fontdevila, J., & Pallarès, M. D. (1993). An electropalatographic study of alveolar and palatal consonants in Catalan and Italian. Language and Speech, 36, 213-234.
- Roberts, R. I. (1957). A cineradiographic investigation of pharyngeal deglutition. British Journal of Radiology, 30, 449-460.

- Robbins, J., Hamilton, J. W., Lof, G. L., & Kempster, G. B. (1992). Oropharyngeal swallowing in normal adults of different ages. Gastroenterology, 103, 823-829.
- Robbins, J. A., Sufit, R., Rosenbek, J., Levine, R., & Hyland, J. (1987). A modification of the modified barium swallow. Dysphagia, 2, 83-86.
- Robbins, K. T., Bowman, J. B., & Jacob, R. F. (1987). Postglossectomy deglutitory and articulatory rehabilitation with palatal augmentation prostheses. Archives of Otolaryngology - Head and Neck Surgery, 113, 1214-1218.
- Roman, C. (1986). Contrôle nerveux de la déglutition et de la motricité oesophagienne chez les Mammifères. Journal of Physiology, Paris, 81, 118-131.
- Rossi, G. F., & Brodal, A. (1956). Corticofugal fibers to the brain-stem reticular formation. An experimental study in the cat. Journal of Anatomy, 90, 42-62.
- Rossignol, S., Lund, J. P., & Drew, T. (1988). The role of sensory inputs in regulating patterns of rhythmical movements in higher vertebrates. In A. Cohen, S. Rossignol, & S. Grillner (Eds.), Neural control of rhythmic movements in vertebrates (pp. 201-283). New York: J. Wiley.
- Sakoe, H., & Chiba, S. (1978). Dynamic programming algorithm optimization for spoken word recognition. IEEE Transactions on Acoustics, Speech, and Signal Processing, 26, 43-49.
- SAS Institute, Inc. (1992). SAS system for Windows, version 3.95, release 6.08 [Computer program]. Cary, NC: SAS Institute, Inc.
- Schmidt, R. A., Sherwood, D. E., Zelaznik, H. N., & Leikind, B. J. (1985). Speed-accuracy trade-offs in motor behavior: theories of impulse variability. In H. Heuer, U. Keinbeck, & K.-H. Schmidt (Eds.), Motor behavior: Programming, control, and acquisition (pp. 153-188). New York: Springer-Verlag.
- Selley, W. G., Ellis, R. E., Flack, F. C., & Brooks, W. A. (1990). Coordination of sucking, swallowing and breathing in the newborn: Its relationship to infant feeding and normal development. British Journal of Disorders of Communication, 25, 311-327.
- Selley, W. G., Ellis, R. E., Flack, F. C., Curtis, H., & Callon, M. (1986). Ultrasound study of sucking and swallowing by newborn infants (letter to the editor). Developmental Medicine & Child Neurology, 28, 821-823.

- Sessle, B. J., & Henry, J. L. (1989). Neural mechanisms of swallowing: Neurophysiological and neurochemical studies on brain stem neurons in the solitary tract region. Dysphagia, 4, 61-75.
- Shaiman, S. (1989). Kinematic and electromyographic responses to perturbation of the jaw. Journal of the Acoustic Society for America, 86, 78-88.
- Shaker, R., Cook, I. J. S., Dodds, W. J., & Hogan, W. J. (1988). Pressure-Flow dynamics of the oral phase of swallowing. Dysphagia, 3, 79-84.
- Shaker, R., Dodds, W. J., Dantas, R. O., Hogan, W. J., & Arndorfer, R. C. (1990). Coordination of deglutitive glottic closure with oropharyngeal swallowing. Gastroenterology, 98, 1478-1484.
- Shawker, T. H., Sonies, B., Hall, T. E., & Baum, B. F. (1984). Ultrasound analysis of tongue, hyoid, and larynx activity during swallowing. Investigative Radiology, 19, 82-86.
- Shawker, T. H., Sonies, B., Stone, M., & Baum, B. J. (1983). Real-time ultrasound visualization of tongue movement during swallowing. Journal of Clinical Ultrasound, 11, 485-490.
- Shedd, D. P., Scatliff, J. H., & Kirchner, J. A. (1960). The buccopharyngeal propulsive mechanism in human deglutition. Surgery, 48, 846-853.
- Shingai, T., & Shimada, K. (1976). Reflex swallowing elicited by water and chemical substances applied in the oral cavity, pharynx, and larynx of the rabbit. Japanese Journal of Physiology, 26, 455-469.
- Shprintzen, R. J., Lencione, R. M., McCall, G. N., & Skolnick, M. L. (1974). A three dimensional cinefluoroscopic analysis of velopharyngeal closure during speech and nonspeech activities in normals. Cleft Palate Journal, 11, 412-428.
- Sinclair, W. J. (1970). Initiation of reflex swallowing from the naso- and oropharynx. American Journal of Physiology, 218, 956-960.
- Sinclair, W. J. (1971). Role of the pharyngeal plexus in initiation of swallowing. American Journal of Physiology, 221, 1260-1263.
- Sirisko, M. A., & Sessle, B. J. (1983). Corticobulbar projections and orofacial and muscle afferent inputs of neurons in primate sensorimotor cerebral cortex. Experimental Neurology, 82, 716-720.

- Smith, A., Goffman, L., Zelaznik, H. N., Ying, G., & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. Experimental Brain Research, 104, 493-501.
- Smith, K. K., & Kier, W. M. (1989). Trunks, tongues, and tentacles: Moving with skeletons of muscle. American Scientist, 77, 29-35.
- Smith, T. S. (1971). A phonetic study of the function of the extrinsic tongue muscles (UCLA Working Papers in Phonetics No. 18). Los Angeles: University of California.
- Sonies, B. C. (1991). Ultrasound imaging and swallowing. In M. W. Donner & B. Jones (Eds.), Normal and abnormal swallowing: Imaging in diagnosis and therapy (pp. 109-117). New York: Springer.
- Sonies, B. C., Parent, L. J., Morrish, K., & Baum, B. (1988). Durational aspects of the oral-pharyngeal phase of swallow in normal adults. Dysphagia, 3, 1-10.
- Sonies, B. C., Weiffenbach, J., Atkinson, J. C., Brahim, J., Macynski, A., & Fox, P. C. (1987). Clinical examination of motor and sensory functions of the adult oral cavity. Dysphagia, 1, 178-186.
- Statistical Sciences. (1991). S-Plus, version 3.0 [Computer program]. Seattle, WA: Statistical Sciences.
- Stetson, R. H. (1951). Motor phonetics: A study of speech movements in action. Amsterdam: North-Holland.
- Stone, M. (1981). Evidence for a rhythm pattern in speech production: Observations of jaw movement. Journal of Phonetics, 9, 109-120.
- Stone, M. (1990). A three-dimensional model of tongue movement based on ultrasound and x-ray microbeam data. Journal of the Acoustical Society of America, 87, 2207-2217.
- Stone, M. (1991). Toward a model of three-dimensional tongue movement. Journal of Phonetics, 19, 309-320.
- Stone, M. (1995). How the tongue takes advantage of the palate during speech. In F. Bell-Berti & L. J. Raphael (Eds.), Producing speech: Contemporary issues (pp. 143-153). New York: American Institute of Physics.

- Stone, M. (1996). Instrumentation for the study of speech physiology. In N. J. Lass (Ed.), Principles of experimental phonetics (pp. 495-524). St. Louis: Mosby.
- Stone, M., Faber, A., Cordaro, M. (1991). Cross-sectional tongue movement and tongue-palate movement patterns in [s] and [ʃ] syllables. Proceedings of the XIIth International Congress of the Phonetic Sciences, 2, 354-357.
- Stone, M., & Lundberg, A. (1996). Three-dimensional tongue surface shapes of English consonants and vowels. Journal of the Acoustical Society of America, 99, 3728-3737.
- Stone, M., & Shawker, T. H. (1986). An ultrasound examination of tongue movement during swallowing. Dysphagia, 1, 78-83.
- Stone, M., Sonies, B. C., Shawker, T. H., Weiss, G., Nadel, L. (1983). Analysis of real-time ultrasound images of tongue configuration using a grid-digitizing system. Journal of Phonetics, 11, 207-218.
- Storey, A. T. (1968). Laryngeal initiation of swallowing. Experimental Neurology, 20, 359-365.
- Sumi, T. (1964). Neuronal mechanisms in swallowing. Pflügers Archiv, 278, 467-477.
- Sumi, T. (1969a). Some properties of cortically-evoked swallowing and chewing in rabbits. Brain Research, 15, 107-120.
- Sumi, T. (1969b). Synaptic potentials of hypoglossal motoneurons and their relation to reflex deglutition. Japanese Journal of Physiology, 19, 68-79.
- Sumi, T. (1970a). Activity in single hypoglossal fibers during cortically induced swallowing and chewing in rabbits. Pflügers Archiv, 314, 329-346.
- Sumi, T. (1970b). Changes of hypoglossal nerve activity during inhibition of chewing and swallowing by lingual nerve stimulation. Pflügers Archiv, 317, 303-309.
- Sumi, T. (1971). Modification of cortically evoked rhythmic chewing and swallowing from midbrain and pons. Japanese Journal of Physiology, 21, 489-506.
- Sumi, T. (1972a). Reticular ascending activation of frontal cortical neurons in rabbits, with special reference to the regulation of deglutition. Brain Research, 46, 43-54.
- Sumi, T. (1972b). Role of the pontine reticular formation in the neural organization of deglutition. Japanese Journal of Physiology, 22, 295-314.

- Suzuki, N. (1989). Application of EPG to cleft palate and glossectomee cases. Clinical Linguistics & Phonetics, 3, 127-136.
- Sweazey, R. D., & Bradley, R. M. (1986). Central connections of the lingual-tonsillar branch of the glossopharyngeal nerve and the superior laryngeal nerve in lamb. Journal of Comparative Neurology, 245, 471-482.
- Sze, C.-F. (1996). Image processing package [Unpublished computer program].
- Tatton, W. G., & Bruce, I. C. (1981). Comment: A schema for the interactions between motor programs and sensory input. Canadian Journal of Physiology and Pharmacology, 59, 691-699.
- Thexton, A. J. (1992). Mastication and swallowing: An overview. British Dental Journal, 173, 197-206.
- Tomura, Y., Ide, Y., & Kamijo, Y. (1981). Studies on the morphological changes of the tongue movements during mastication by x-ray TV cinematography. In Y. Kawamura, & R. Dubner (Eds.), Oral-facial sensory and motor functions (pp. 45-52). Tokyo: Quintessence.
- Tuller, B., Harris, K. S., & Kelso, J. A. S. (1982). Stress and rate: Differential transformation of articulation. Journal of the Acoustical Society of America, 71, 1534-1543.
- Vanek, A. W., & Diamant, N. E. (1987). Responses of the human esophagus to paired swallows. Gastroenterology, 92, 643-650.
- Veis, S. L., & Logemann, J. A. (1985.) Swallowing disorders in persons with cerebrovascular accident. Archives of Physical Medicine and Rehabilitation, 66, 372-375.
- Vitti, M., Basmajian, J. V., Ouellette, P. L., Mitchell, D. L., Eastman, W. P., & Seaborn, R. D. (1975). Electromyographic investigations of the tongue and circumoral muscular sling with fine-wire electrodes. Journal of Dental Research, 54, 844-849.
- Walberg, F. (1957). Do the motor nuclei of the cranial nerves receive corticofugal fibers? An experimental study in the cat. Brain, 80, 597-605.
- Walker, A. E., & Green, H. D. (1938). Electrical excitability of the motor face area: A comparative study in primates. Journal of Neurophysiology, 1, 152-165.

- Weber, F., Woolridge, M. W., & Baum, J. D. (1986). An ultrasonographic study of the organisation of sucking and swallowing by newborn infants. Developmental Medicine & Child Neurology, 28, 19-24.
- Weerasuriya, A., Bieger, D., & Hockman, C. H. (1979). Basal forebrain facilitation of reflex swallowing in the cat. Brain Research, 174, 119-133.
- Weerasuriya, A., Bieger, D., & Hockman, C. H. (1980). Interaction between primary afferent nerves in the elicitation of reflex swallowing. American Journal of Physiology, 239, R407-R414.
- Wein, B., Böckler, R., Klajman, S. (1991). Temporal reconstruction of sonographic imaging of disturbed tongue movements. Dysphagia, 6, 135-139.
- Wheeler, R. L., Logemann, J. A., & Rosen, M. S. (1980). Maxillary reshaping prostheses: Effectiveness in improving speech and swallowing of postsurgical oral cancer patients. Journal of Prosthetic Dentistry, 43, 313-319.
- Wieneke, G., Janssen, P., & Belderbos, H. (1987). The influence of speaking rate on the duration of jaw movements. Journal of Phonetics, 15, 111-126.
- Wilson, J. A., Pryde, A., MacIntyre, C. C. A., & Heading, R. C. (1989). Normal pharyngoesophageal motility: A study of 50 healthy subjects. Digestive Diseases and Sciences, 34, 1590-1599.
- Wright, S., & Kerswill, P. (1989). Electropalatography in the analysis of connected speech processes. Clinical Linguistics & Phonetics, 3, 49-57.