Advancing Our Understanding of Speech Motor Control Through an Investigation of Intermuscular Coherence in Typical Speakers

by

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Abstract

There is a need to characterize intermuscular coherence (IMC) in selected muscles of the speech mechanism in order to establish its utility as a tool to study speech motor control. IMC is a correlation in the frequency domain that provides information about whether two signals (i.e., electromyographic (EMG)) are firing at the same frequency. Two muscles firing across the same frequency spectrum are thought to be receiving the same neural signaling or common neural drive. IMC measurements remain a largely unused method for studying speech motor control. However, initial studies using IMC to describe muscle activity in muscles of the speech mechanism suggest that this measurement may be sensitive to certain non-speech and speech requirements. Questions remain about IMC sensitivity to various speaking demands across the lifespan.

In the first two studies, I compared the effects of lung volume, laryngeal demands, articulatory complexity, and cognitive linguistic demands on IMC in the respiratory (Study 1) and articulatory (Study 2) subsystems. Studies involved secondary analysis of surface electromyography (EMG) recordings from the intercostals, obliques, and orbicularis oris in healthy younger and older adults to determine the presence of task- or age-related differences in IMC. These data also included acoustic and respiratory kinematic recordings to provide context for IMC findings. In Study 3, intercostal and oblique IMC measurements on four tasks were compared across children, adolescents, younger adults, and older adults to investigate whether established developmental patterns of respiratory kinematics would be accompanied by age-related differences in IMC.

This work adds to a growing body of literature supporting the utility of IMC in the study of speech motor control. In all three studies, the results revealed several differences in IMC values across the lifespan as well as key task-related differences within the respiratory and articulatory subsystems. The dissertation concludes with a summary of these findings, as well as a discussion of the limitations and future research directions.

Preface

This thesis is an original work by Alesha Reed under the supervision of Carol A. Boliek, Professor Emerita in the Department of Communication Sciences and Disorders at the University of Alberta; Jacqueline Cummine, Professor in the Department of Communication Sciences and Disorders at the University of Alberta; Nicole Etter, Associate Professor in the Department of Communication Sciences and Disorders at Pennsylvania State University; John Misiaszek, Professor, Department of Occupational Therapy and Vice Dean of the Faculty of Rehabilitation Medicine at the University of Alberta.

The University of Alberta's Health Research Ethics Board approved the research studies used in Chapters 3, 4 and 5 (Study IDs Pro00055070, Pro00054045, Pro00061081 and Pro00092065).

Dedication

In loving memory of my mother

Brenda Stewart

July 26, 1962 - December 5th, 2014

Loving you from here.

Acknowledgments

I would like to begin by thanking my supervisors Drs. Carol Boliek and Jacqueline Cummine for their support and guidance. I am eternally grateful to have had a supervisory team that supported my exploration of both academic and extracurricular interests throughout my graduate training. Your mentorship has made me a better person and a better researcher. To my committee members, Dr. Nicole Etter and Dr. John Misiaszek, thank you for your time, expertise and practical guidance that helped shape the theoretical foundation of this dissertation. To my friends, colleagues, and mentors within the Faculty, I am so thankful to have met and worked with you during my graduate training. Thank you for making my experience as a student and staff member so rich.

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ABBREVIATIONS

EMG	Electromyography
IC	Intercostal Muscle Group
IMC	Intermuscular Coherence
DDK	Diadochokinetic Task
MPD	Maximum Phonation Duration Task
OB	Oblique Muscle Group
OO	Orbicularis Oris
PN	Picture Naming Task
RB	Rest Breathing Task
SP	Speech Task
TT	Tongue Twister Task
VC	Vital Capacity Task
WR	Word Reading Task
%RC	Percentage of rib cage contribution to total lung volume expenditure
%VC	Lung volume expenditure expressed as a percentage of predicted vital capacity
%VC/SYLL	Lung volume expenditure per syllable expressed as a percentage of predicted vital capacity

Chapter 1: Introduction

Overview of Speech Motor Control

Speech production requires a highly complex set of movements that are not fully understood in terms of neuromuscular control. Disruptions to speech production occur as a result of a breakdown in how the brain formulates a motor speech plan and/or signals the peripheral sensorimotor system for execution (Duffy, 2013). Disorders resulting in an impaired ability to speak and be understood affect over 350,000 people in Canada (Statistics Canada, 2002).

Speech motor control is unique from other forms of motor control in that the target is primarily auditory, and the muscles used to produce speech must be coordinated bilaterally. This highly intricate process requires coordination of up to 100 muscles in the face, neck and chest (Darley et al., 1975). The production of speech requires muscle activation across four subsystems (Hixon et al., 2014). The first is the *respiratory subsystem* which generates the flow of air necessary to produce the pressure needed for sound production. Movement of the chest wall (i.e., the abdomen and rib cage) causes air to be displaced from the lungs towards the *laryngeal subsystem.* Here, with enough tracheal pressure, the vocal folds are repeatedly opened and closed, producing a sinusoidal wave (buzzing noise) which then resonates in the vocal tract (supralaryngeal structures) ultimately radiating from the mouth and nose for speech production. More specifically, the sound wave resonates through the vocal tract via the *velopharyngeal and articulatory subsystems.* The structures within these subsystems move in certain ways in order to control the flow of air into the oral and nasal cavity (velopharyngeal), thus changing the acoustic characteristics of the sound wave. This basic understanding of speech production (i.e., that sounds occur as a result of air moving down the vocal tract, vibration of vocal folds and changing the vocal tract configuration) has been well studied, however the complex intricacies of each system and their overall coordination are still widely researched.

Speech Motor Control Research Across the lifespan

To date, a variety of techniques and measurements of speech production have been used to further our understanding of speech production across the lifespan. These investigations have included kinematic analysis of articulation and respiratory patterns (e.g., Boliek et al., 2009; Hixon et al., 1973; Hoit et al., 1990; Rowe et al., 2021), EMG activity (e.g., Hoit et al., 1988; McClean & Tasko, 2002; Mendes Balata et al., 2013; Sasaki & Leder, 2013; Stepp, 2012), acoustic recordings (e.g., Stathopoulos et al., 2011; Stathopoulos & Sapienza, 2005; Tang & Stathopoulos, 2005) and behavioural measurements such as duration and articulatory rate (Bóna, 2014; Jacewicz et al., 2009; Smith et al., 1987). This information has led to several advances in our understanding of developmental and senescent changes in the respiratory, laryngeal and articulatory speech subsystems.

Changes in Respiratory Subsystem

In the respiratory system, changes in breathing patterns across the lifespan are well documented. For example, developmental patterns of chest wall kinematics are thought to be related to changes in chest wall compliance. Greater compliance of the chest wall in the early years is thought to contribute to the variable respiratory patterns for speech during development, which become stable by around the age of 10 years when we observe maturational decreases in overall respiratory compliance (i.e., decrease compliance in lung and chest wall) (Boliek et al., 2009; Hoit et al., 1990; Stathopoulos & Sapienza, 2005). By the age of 10 years, children have some adult-like speech breathing behaviours such as initiating speech in the biomechanically efficient midrange of the vital capacity (VC: maximum amount of air expired after a maximum inhalation). Variability is observed in contribution of the rib cage to total lung volume excursion and percentage of the VC used per breath group. Children also demonstrate fewer syllables per breath group and use more air per syllable. Breathing patterns associated with speech remain stable until approximately the seventh and eighth decade of life, when changes are observed as an increase in lung volume excursion during speech and higher rib cage initiations (Hoit & Hixon, 1987; Huber, 2008; Huber & Spruill, 2008; Sperry & Klich, 1992). Older adults exhibit a decrease in the number of syllables per breath group and more air expended (relative to VC) per syllable (Hoit & Hixon, 1987). These behavioural changes in older adults are thought to be partly due to a decrease in chest wall compliance associated with calcification of intercostal cartilages and changes in connective tissue (Hoit et al., 1990).

Changes in Laryngeal Subsystem

Changes in the laryngeal structures are also thought to underlie the behavioural changes observed in speech production. In the first decade of life, the larynx triples in size, the laryngeal cartilages begin to ossify and it descends to the 7th cervical vertebrae (Bosma, 1985). Low muscle mass in the intrinsic laryngeal musculature results in children having a high fundamental frequency (F0) (i.e., pitch), which subsequently declines with the increase in mass observed during puberty (Stathopoulos et al., 2011; Tang & Stathopoulos, 2005).

Changes in laryngeal structures may also contribute to the kinematic changes observed in respiration. With age, the musculature of the larynx begins to atrophy, and joints begin to ossify (Kahane & Kahn, 1984). These changes lead to an eventual rise in F0 during the 6th and 7th decade of life (Stathopoulos et al., 2011; Tang & Stathopoulos, 2005). Changes also result in a decreased ability of laryngeal structures (e.g., thyroarytenoid muscles) to resist the tracheal pressures and airflow needed for speech. It is possible that some of the changes in chest wall kinematics, such as increased initiation of breath groups, are used to compensate for the loss of air at the level of the larynx.

Changes in Articulatory Subsystem

While velopharyngeal function is generally thought to remain stable across the lifespan (Hoit et al., 1994; Zajac, 1997), the articulatory subsystem experiences changes. As the oral cavity grows, children develop muscle synergies needed to control the articulators across a wider range of movements. Children are observed to speak slower and show more variability in the amplitude, velocity and timing of articulatory movements relative to adults (Green et al., 2000, 2002; Steeve et al., 2008). Acoustically, this variability stabilizes at approximately 12 years old, although the underlying movement of the articulators does not stabilize until later in adolescence (Smith & Zelaznik, 2004; Walsh & Smith, 2002; Wohlert & Smith, 2002). In older adults, a decline in articulator endurance, sensitivity, strength and mobility contribute to a variety of changes in speech production(Amerman & Parnell, 1992; Bilodeau-Mercure & Tremblay, 2016; Bronson-Lowe et al., 2013; Dietsch et al., 2015; Etter et al., 2018; Liss et al., 1990; Liu et al., 2011; Peladeau-Pigeon & Steele, 2017; Sonies et al., 1984; Stathopoulos et al., 2011; Vanderwegen et al., 2013; Wohlert & Smith, 1998, 2002). For example, older adults display increased variability in articulator movement (Wohlert & Smith, 1998). Older adults also tend to speak slower (longer individual phonemes and syllables) and have more pauses during speech (Bilodeau-Mercure & Tremblay, 2016; Bóna, 2014; Hoit & Hixon, 1987; Huber et al., 2012).

Limitations

To date, measurements of speech production have been largely restricted to kinematic analysis of articulation and respiratory patterns (e.g., Hixon et al., 1973; Rowe et al., 2021), EMG activity (e.g., Hoit et al., 1988; McClean & Tasko, 2002; Mendes Balata et al., 2013; Sasaki & Leder, 2013; Stepp, 2012), acoustic recordings (e.g., Stathopoulos et al., 2011; Stathopoulos & Sapienza, 2005; Tang & Stathopoulos, 2005) and behavioural measurements such as duration and articulatory rate (Bóna, 2014; Jacewicz et al., 2009; Smith et al., 1987). Characterization of these indirect measures of motor function have provided valuable advances to our understanding of speech motor control, such as understanding how the system responds to auditory or somatosensory perturbation ((De Miranda Marzullo et al., 2010; Lametti et al., 2012; Nasir & Ostry, 2006; Purcell & Munhall, 2006; Villacorta et al., 2007), as well as changing task requirements such as vocal loudness or rate (Dromey & Ramig, 1998; Huber, 2008; Kuhlmann & Iwarsson, 2021; McClean & Tasko, 2006). A logical next step to advance our understanding of speech motor control is to implement a multi-measurement approach, which would serve to provide a more dynamic and comprehensive understanding about the speech motor control mechanisms and their relation to physiological measures of muscular control.

Muscle Activity in the Speech Mechanism

Motor programming signals for speech descend from cortical and subcortical structures via pyramidal and extrapyramidal tracts (Lemon, 2008; Purves, 2018). These neurons project to the cell body of the lower motor neuron pools in the brainstem or spinal cord (Lemon, 2008; Purves, 2018). Together, the information from pyramidal and extrapyramidal tracts, in addition to information from local circuit neurons, modulates the control of the muscles involved in speech production. The summed input of these connections is transmitted to the muscle via the lower motor neuron’s axon (Purves, 2018). The arrival of an action potential at the neuromuscular junction depolarizes the muscle fiber’s membrane, causing it to contract.

This change in electrical activity generated by the muscles can be recorded through the use of electromyography (EMG) recordings (Jeffery R. Cram, 2011). Early methodological approaches were developed to record this change in electrical activity *in vivo* using metal wires inserted directly into a muscle fiber. More recently, surface electromyography has been developed as a non-invasive way of investigating activity from muscle groups. The EMG signal represents activity across multiple motor units within the target muscle. EMG activity can be used to characterize the amount of activation that occurs throughout a task, which has a linear relationship with muscle force (although the strength of this relationship changes as a function of muscle type, training experience, fatigue, among others) (Kuriki et al., 2012). This measurement of EMG amplitude can be made in reference to a voluntarily produced *maximum muscle contraction* level to determine relative activation of a muscle during a given movement or task (Kuriki et al., 2012). Researchers have used this measure to elucidate the individual contribution of muscles in the head, neck and chest to speech motor control.

Respiratory System

To date, research on chest wall muscle activation during speech production has primarily been conducted in healthy, young adults. This research shows that during tasks spanning the entire range of the vital capacity, the abdominal wall is active throughout the entire utterance (Hixon et al., 1976, 2014; Hoit et al., 1988; McFarland & Smith, 1989). This activity is done in concert with muscles of the rib cage. During speech production, the expiration is controlled again by the abdominal wall and rib cage, although lower muscular pressures are needed. As tracheal pressure increases, muscular activity in the rib cage and abdomen increases (Clair-Auger et al., 2015; Hixon & Weismer, 1995; McFarland & Smith, 1989). Few studies have investigated these changes across the lifespan. Preliminary work suggests that children do not show a systematic change in EMG amplitude as a function of task requirement like that observed in adults (Clair-Auger et al., 2015). Moreover, children have higher levels of activation relative to adults (Clair-Auger et al., 2015). While studies investigating inspiratory and expiratory pressure generation have reported decreased inspiratory and expiratory muscle strength in older adults ((Berry et al., 1996; Black & Hyatt, 1969; Enright et al., 1994), no studies have investigated chest wall muscle activity associated with speech in an ageing population.

Laryngeal and Articulatory subsystems

Studies using hook-wire EMG in the laryngeal and articulatory subsystems during speech have demonstrated that measurements of muscle activation can contribute to our understanding of motor control across different tasks and across the lifespan. In the laryngeal subsystem, EMG studies have developed our understanding of the contribution of intrinsic and extrinsic laryngeal musculature in speech production (Boucher, Ahmarani & Ayad, 2006; Faaborg-andersen et al., 1958; Khoddami et al., 2013; Manda et al., 2016; McClean & Tasko, 2002; Mendes Balata et al., 2013; Poletto et al., 2004; Smith et al., 1993).

EMG alone and in combination with kinematic measurements, have been observed in muscles of the face in relation to manipulation of vocal loudness and increasing rate (McClean & Tasko, 2006), as well as during speech and non-speech tasks across the lifespan (Boucher, 2001; Huang et al., 2005; McClean & Tasko, 2006; Ruark & Moore, 1997; Smith, 2006; Steeve, Moore, Green, Reilly, & Mcmurtrey, 2008; Wohlert & Smith, 2002)

Intermuscular Coherence

Beyond measures of muscle activity, other variables of interest may be extracted from the EMG signal in order to further characterize how muscles carry out the movements needed for speech. Intermuscular coherence (IMC) is a measurement of the similarities between the electrical activity of two sets of muscles (Farina, Merletti, et al., 2014; Grosse et al., 2002) by performing a cross-correlation in the frequency domain (see Equation 1). This calculation yields a value between 0 and 1. Here, a value of 1 suggests that the two signals are firing at the same frequency (i.e., are highly correlated), whereas a value of 0 indicates no relationship between the frequency firing patterns. In other words, a high value of IMC indicates that, at any given time, one signal can predict the other. However, it is also important to note that, depending on the nature of the task, two muscles may be necessary to achieve an outcome but yield a low value of IMC.

$$Coh_{XY}(f) = \left|C_{xy}(w)\right|^2 = \frac{\left|\overline{G_{xy}(w)}\right|^2}{\overline{G_{xx}(w)}\cdot\overline{G_{yy}(w)}}$$

Equation 1 . Intermuscular coherence calculation where Coh=magnitude square coherence; Gxx(w) and Gyy(w)= averaged power spectra of the x and y muscles of interest, for a given frequency (w); Gxy=averaged cross-power spectrum of x and y signals at frequency w (Norton & Gorassini, 2006; Rosenberg et al., 1989).

A basic interpretation of this value allows researchers to infer whether or not there is similarity in common neural drive to the muscles of interest. Here, neural drive is defined as common input into the motor neuron pools of two separate muscles resulting in the generation of motor unit action potentials (Farina, Merletti, et al., 2014; Farina, Negro, et al., 2014). The mechanism leading to an increase in coupling between signals has been proposed to be the result of an increase in cortico-motoneuronal drive to the periphery (Boonstra, 2013; Farina, Merletti, et al., 2014; Farina, Negro, et al., 2014; Kattla & Lowery, 2010). This increase in common synaptic input has been demonstrated to be triggered in response to a number of factors, including increased contraction level (Boonstra et al., 2007; Castronovo et al., 2015), fatigue (Kattla & Lowery, 2010; Semmler et al., 2013), and sensory feedback (Fisher et al., 2002; Kilner et al., 2003; Nguyen et al., 2017). IMC can be calculated at any given frequency, however the frequency bandwidths most commonly studied are the beta bandwidth (~15-30 Hz) and the gamma bandwidth (31-60 Hz). Although each bandwidth is associated with sensitivity to different types of motor tasks and demands, changes in both bandwidths are thought to represent corticomuscular drive (Boonstra, 2013; Boonstra et al., 2016; Boonstra & Breakspear, 2012; Farina, Negro, et al., 2014; Farina & Negro, 2015; Mima & Hallett, 1999; Negro & Farina, 2011; Reyes et al., 2017).

Traditionally, beta bandwidth IMC has been thought to increase in functionally coordinated muscles during static phases of movement, with decreases observed during dynamic phases of movement (Kilner et al., 1999; Reyes et al., 2017). More recently, however, this interpretation has been reframed to account for increases in beta IMC reported during dynamic movement. Within the new interpretation, beta bandwidth IMC can be viewed as representing neuromuscular strategy shifting between synergistic and individuated control. For example, when comparing beta bandwidth IMC between finger muscles applying pressure to a flexible object (i.e., a spring) compared to an inflexible object (i.e., a dowel), researchers found decreased IMC in the flexible object condition (Reyes et al., 2017). The difference in IMC was interpreted as an “unbinding” of synergistic control used in the flexible object condition, as each individual finger responded to changing demands in order to maintain control (i.e., individuated control) (Laine & Valero-Cuevas, 2017). Conversely, in a study investigating IMC between bilateral leg muscles during a bipedal squat, an increase in IMC was observed in the dynamic phase (i.e., bending knees to achieve position) as muscles theoretically relied on increased synergistic control to execute the movement, relative to static phase (i.e., holding position) (Kenville et al., 2020). Together these studies have extended our understanding of changes in the beta bandwidth, providing valuable insights into neuromuscular control strategies.

Gamma bandwidth IMC has primarily been associated with changes in the processing and integration of somatosensory information (Chang et al., 2012; De Marchis et al., 2015; Mohr et al., 2015; Omlor et al., 2007; von Tscharner et al., 2018). This interpretation is built upon repeated observations of changes in gamma bandwidth IMC when somatosensory information is manipulated. For example, when participants performing a symmetrical elbow flexion/extension were provided with somatosensory information via a balancing apparatus, researchers observed significant increases in IMC relative to the same task performed with varying degrees of visual information alone (Nguyen et al., 2017). Increased gamma bandwidth IMC has also been observed across novel and highly complex tasks (Chang et al., 2012; De Marchis et al., 2015; Mohr et al., 2015; Omlor et al., 2007; von Tscharner et al., 2018), further supporting the existing interpretation of the relationship between this bandwidth and somatosensory integration.

Intermuscular Coherence in the Speech Mechanism

To date, IMC in the speech mechanism has been investigated in only a few studies. These studies have provided preliminary evidence that IMC in the speech mechanism is sensitive to manipulation of tasks associated with speech.

Respiratory system

Early research focused on high frequency (60-110 Hz) IMC in the diaphragm and intercostal muscles (Ackerson & Bruce, 1983; Bruce & Ackerson, 1986; Bruce & Goldman, 1983). This preliminary research made attempts to link IMC in this frequency bandwidth to the activity of central pattern generators, which are responsible for the reflexive breathing controlled via the brainstem (Guyenet & Bayliss, 2016; Smith et al., 2014). Unfortunately, the tasks used in these studies were *voluntary* breathing tasks, mediated by supraspinal control and thus, cannot be used to make inferences regarding the frequency of brainstem control. Therefore, conclusions that IMC in the 60-110 Hz frequency band is representative of central pattern generator control are limited.

More recent research began to expand our knowledge of the IMC sensitivity to changing task demands. Smith and Denny (1990) were the first to show a systematic change in chest wall IMC in response to a change in lung volume. They found that bilateral diaphragm IMC in the high frequency band (60-110 Hz) decreased during mid-range lung volume tasks compared to large lung volume tasks. IMC in the beta-bandwidth and low gamma-bandwidth (20-60 Hz), did not change as a function of lung volume (Smith & Denny, 1990). These patterns of IMC were derived from recordings during inspiratory and expiratory phases. Later, the same research group investigated muscle activity of the diaphragm during the inspiratory phase only and found that high frequency IMC (60-110 Hz) increased for mid-range lung volume tasks compared to large lung volume tasks (Denny & Smith, 2000).

Nearly a decade later, research has shifted to investigating muscles of the chest wall during expiratory phases of speech production. For example, expiratory muscles of the chest wall (intercostals and obliques) show change in IMC as a result of lung volume and tracheal pressure requirements (Boliek et al., 2019; Tomczak et al., 2013). IMC in the beta-bandwidth appears to increase for mid-range lung volume tasks relative to large lung volume tasks (Tomczak et al., 2013). More recent work has found higher levels of 15-60 Hz IMC in the chest wall during tasks requiring pressure generation against resistance at the oral airway (Boliek et al., 2019), and during the execution phase of speech production (Reed et al., 2021).

Laryngeal System

Extrinsic laryngeal muscles (sternothyroid and sternohyoid) provide further evidence of a modulation of IMC as a function of speech-related task demands (Stepp et al., 2010, 2011). Beta-bandwidth IMC of external laryngeal musculature has been investigated twice in healthy adults. A study conducted in 2010 compared IMC between bilateral strap muscles of the neck (sternothyroid and sternohyoid) in individuals with vocal hyperfunction to a group of control subjects (Stepp et al., 2010). IMC was measured during spontaneous speech (i.e., *tell me about a holiday you've been on*) and during a standardized passage reading task. Neither group showed a change in IMC as a function of task, however their results showed a decrease in beta-bandwidth IMC (15-35 Hz) in the vocal hyperfunction group relative to healthy controls. A follow up to this study was published in 2011 and demonstrated that IMC decreased during divided attention (counting backwards from 100 by 7), singing and mimicking hyperfunctional speech (Stepp et al., 2011). IMC did not change during non-speech tasks (tongue retraction and static-resistant force), or clear speech tasks (i.e., over enunciated productions). Together, these studies provide preliminary evidence that IMC between bilateral extrinsic laryngeal muscles is sensitive to task demands associated with speech. IMC in this subsystem appears to decrease in response to increased cognitive load (divided attention, singing, mimicked hyperfunctional speech), however, changes between types of high cognitive load tasks is not yet known.

Articulatory System

Limited research using IMC exists for articulatory muscles. Early studies reported low levels of bilateral masseter IMC in frequencies below 60 Hz during a clenching task relative to IMC of bilateral diaphragm recordings during a breathing task (Bruce & Ackerson, 1986). Other studies have since extended these findings to include comparisons of masseter IMC across tasks such as chewing and speech (Smith & Denny, 1990). These comparisons across tasks suggest that IMC in the masseter may be sensitive to task requirements, with IMC decreasing during clenching and speech relative to chewing (Smith & Denny, 1990; Steeve & Price, 2010). More recently, studies have reported decreases in the beta bandwidth in rapid syllable repetition tasks compared to chewing tasks (Usler et al., 2020).

Three studies have investigated IMC between left versus right orbicularis-oris. Initial findings reported that, across a wide range of tasks, IMC was only detected in a sustained pucker task in healthy adults (Caviness et al., 2006; Goffman & Smith, 1994). More recent studies, however, have reported significant levels of IMC during a speech task, and changes in IMC across phase of speech production (Reed et al., 2021). Last, studies conducted in the genioglossus muscle during inspiratory loading suggest that IMC increases in response to increased inspiratory loading (Woods et al., 2015).

Limitations

Preliminary studies of IMC suggest that this is a promising tool for investigations of speech motor control. To determine its utility in the characterization of neuromuscular control of speech, studies must address several limitations to the existing research base.

First, a wider variety of task specifications must be explored to understand the sensitivity of this measure to factors relevant to speech motor control. Studies examining chest wall IMC have manipulated lung volume and laryngeal requirements but did not systematically manipulate articulatory targets (Boliek et al., 2019; Denny & Smith, 2000; Smith & Denny, 1990; Tomczak et al., 2013). In contrast, researchers measuring laryngeal and orbicularis oris IMC did manipulate articulation targets but did not systematically vary laryngeal and lung volume targets (Caviness et al., 2006; Goffman & Smith, 1994; Reed et al., 2021; Stepp et al., 2010, 2011). In order to deepen our understanding of IMC in typically developing individuals it is essential to systematically manipulate lung volume as well as laryngeal and articulatory complexity.

Second, future work conducted across the lifespan is needed to understand to what extent this measure is sensitive to age-related changes documented in the speech mechanism. Whereas many behavioural changes have been tied to these maturational changes in the nervous system and speech mechanism, there is still much to be learned about changes in speech motor control as a function of typical development and healthy aging. Investigations employing the use of IMC as a relatively novel measurement tool would further our understanding about the underlying mechanisms employed by motor speech networks. IMC presents as a unique tool to investigate the coupling of muscle activation patterns that may be associated with the maturational changes outlined above. Studies investigating lifespan changes in IMC in the limbs have yielded mixed results, with some studies showing an increase (Castronovo et al., 2018; Farmer et al., 2007; Semmler et al., 2000, 2006) or no change (Jaiser et al., 2016) in IMC with age. These heterogeneous results may, in part, be due to differences in signal processing (e.g., signal rectification) and task targets. Preliminary work in the speech mechanism suggests similar degrees of chest wall IMC and orbicularis oris IMC across phase of speech production in younger and older adults , however no studies to date have investigated this relationship in the speech mechanism across more than two age ranges or in a wide variety of tasks. In order to fully characterize IMC in the speech mechanism, it is necessary to assess how it changes across the lifespan.

Rationale

Establishing a concrete understanding of neuromuscular control measures such as intermuscular coherence is essential in order to use these measures to advance existing models of speech motor control. For example, a commonly used theoretical model of speech motor control is the Directions Into Velocities of Articulators (DIVA) (Guenther, 2014; Guenther & Vladusich, 2012; Tourville & Guenther, 2011). This computational model of speech motor control proposes two control systems for the production of speech, a *feedforward* and a *feedback* system, each being represented by a network of brain regions. Over time, the authors of the DIVA model have built a considerable amount of evidence validating this model by using a combination of behavioural and neuroimaging studies. Researchers use this model to account for, and can make accurate predictions about, how perturbations to afferent auditory and somatosensory information can impact efferent adjustments in speech motor control (Tourville, Reilly, & Guenther, 2008). Despite these advancements, this model lacks consideration of how the speech motor control system integrates the respiratory system in order to make adjustments such as breath group length, vocal loudness modulation, or inspiratory duration. While there exists a considerable amount of evidence regarding the reflexive regulation of the respiratory system by brainstem central pattern generators (Smith, Abdala, Borgmann, Rybak, & Paton, 2014), little research exists regarding the integration of cortical control of respiration during speech. Incorporation of signals to the respiratory subsystem are important as they play an essential role in the air flow and pressures required for speech production, as well as adjustments for vocal duration and loudness. Furthermore, the DIVA model, and other existing theories of speech motor control, do not include detailed peripheral measures of neuromuscular control such as respiratory, laryngeal, and articulatory movements associated with speaking. A logical next step to advance our understanding of speech motor control is to implement a multi-measurement approach of peripheral aspects of the speech mechanism, which would serve to provide a more dynamic and comprehensive understanding of the complex speech mechanism.

Beyond the potential utility of IMC as a tool to expand existing models of speech motor control, IMC may also have potential to inform clinical investigations of motor speech disorders, which occur as a result of a breakdown in how the brain formulates a motor speech plan and/or signals the peripheral sensorimotor system for execution (Duffy, 2013). Disorders resulting in an impaired ability to speak and be understood affect over 350,000 people in Canada (Statistics Canada, 2002). To date, differential diagnosis of motor speech disorder subtypes remains challenging. Whereas certain “gold standard” approaches to diagnosis exist, they are often based on perceptual measurements, which can be subjective and have limited inter-assessor reliability (Duffy, 2013). Further complicating the diagnostic process, is a high degree of heterogeneity of behavioural sequelae within a given disordered subgroup, which, in turn, increases difficulty for determining treatment targets, dosage and predicted outcomes. Response to intervention is dependent upon several factors including the nature and severity of the disorder, treatment timing and saliency, environmental support structures and motivation. Because of our somewhat limited understanding of speech motor control in general, it seems reasonable to first study these dynamics in healthy speakers before tackling the diverse symptoms observed in populations with motor speech disorders. Given the proposed ability of IMC to inform neuromuscular control, it presents as a potentially unique tool to researchers to monitor a return to post-injury function

(Norton & Gorassini, 2006), habilitation of function (i.e., in the case of developmental neurogenic communication disorders), and perhaps serve as a biomarker for disease (Velázquez-Pérez et al., 2017) in disorders of speech motor control. Critically, before this measure can be used in these capacities, it is essential that systematic investigations of how IMC changes in response to changing demands across the speech mechanism must be investigated.

Dissertation Objectives

The main objective of this doctoral research was to characterize IMC for selected muscle groups used during non-speech and speech tasks in typically developing individuals. The specific aims were to:

1. Describe changes in IMC between the intercostals and obliques in response to varying lung volume demands, laryngeal requirements, articulatory complexity and cognitive-linguistic demands
2. Describe changes in IMC between the left and right orbicularis oris in response to varying lung volume demands, laryngeal requirements, articulatory complexity and cognitive-linguistic demands
3. Describe age-related differences in IMC

Investigating IMC within the speech mechanism will inform our understanding of speech motor control and establish IMC's utility in future investigations of typical and disordered speech. These aims were investigated in a series of three studies.

Structure of the Dissertation

The main body of the thesis consists of three chapters, one for each study described below (Chapters 2-4). Chapter 5 contains a summary of contributions made by this dissertation, an overview of the limitations of the studies presented and an exploration of future directions of this work. All studies involved secondary analysis of previously collected data, however the candidate was involved in aspects of the original study designs, was present for collection of data for all three studies and participated in data analysis of the original measurements.

Study 1 and Study 2

These studies involved a secondary analysis of previously collected data, and were designed to investigate the effects of task specifications and age on IMC of the chest wall (Aim 1 & 3; Study 1) and articulators (Aim 2 & 3; Study 2). Data for both studies were collected simultaneously, and included recordings of chest wall kinematics, acoustic and EMG activity from the intercostals, external obliques and orbicularis oris. Chest wall IMC between the intercostals and external obliques are presented in Study 1, and articulatory IMC between the left and right orbicularis oris are presented in Study 2. Participants include 30 young adults between the ages of 18-44 years and 30 older adults between the ages of 50-77 years.

Both studies included six tasks that manipulate lung volume requirements, laryngeal function (i.e., maintenance of subglottal pressure), articulatory function (e.g., DDK, word reading, tongue twisters) and cognitive load (e.g., labeling a picture vs reading single words). These tasks included rest breathing (RB), word reading (WR), picture naming (PN), tongue twisters (TT), maximum phonation duration (PHON), and a diadochokinetic repetition task (DDK). The first study also included a vital capacity (VC) task. See Appendices 1-3 for stimuli used in WR, PN and TT tasks, respectively. Relevant ethics approvals are listed in Appendix 4.

Study 3

The third study employed a cross-sectional design to evaluate IMC across the lifespan (Aim 3). Secondary analyses were performed on data from three separate studies. The data analyzed in Study 1 and 2 was included in the third study. All studies used the same data acquisition protocols to acquire chest wall kinematics, EMG recordings from the intercostals and external obliques and acoustic recordings. Participants included 120 typically developing children and adults ranging in age from 6 to 77 years old.

Four tasks designed to manipulate lung volume requirements and laryngeal function (i.e., maintenance of subglottal pressure) were included in this study. Two were non-speech tasks requiring no maintenance of subglottal pressure: a vital capacity (VC) maneuver (large lung volume) and rest breathing (RB) (small lung volume). Two tasks involving generation of tracheal pressure for sound production were also included: a maximum phonation duration (PHON) task and a small lung volume task requiring maintenance of subglottal pressure (i.e., speech task (SP). In two of the three studies included in the present analyses, data from a sentence repetition task were used (e.g., *Buy bobby a puppy*, *the blue spot is on the key,* and *the potato stew is in the pot*) and in the third study included a single word overt reading task will serve as the midrange lung volume task involving speech.

References

Ackerson, L. M., & Bruce, E. N. (1983). Bilaterally synchronized oscillations in human diaphragm and intercostal EMGs during spontaneous breathing. *Brain Research*, *271*(2), 346–348. https://doi.org/10.1016/0006-8993(83)90299-8

Amerman, J. D., & Parnell, M. M. (1992). Speech Timing Strategies in Elderly Adults. *Journal of Phonetics*, *20*(1), 65–76.

Berry, J. K., Vitalo, C. A., Larson, J. L., Patel, M., & Kim, M. J. (1996). Respiratory muscle strength in older adults. *Nursing Research*, *45*(3), 154–159. https://doi.org/10.1097/00006199-199605000-00006

Bilodeau-Mercure, M., & Tremblay, P. (2016). Age Differences in Sequential Speech Production: Articulatory and Physiological Factors. *Journal of the American Geriatrics Society*, *64*(11), e177–e182. https://doi.org/10.1111/jgs.14491

Black, L. F., & Hyatt, R. E. (1969). Maximal respiratory pressures: normal values and relationship to age and sex. *The American Review of Respiratory Disease*, *99*(5), 696–702. https://doi.org/10.1164/ARRD.1969.99.5.696

Boliek, C. A., Bakhtiari, R., Pedersen, L., Esch, J., & Cummine, J. (2019). Differential cortical control of chest wall muscles during pressure- and volume-related expiratory tasks and the effects of acute expiratory threshold loading. *Motor Control*, *23*(1), 13–33. https://www.ncbi.nlm.nih.gov/pubmed/29902955

Boliek, C. A., Hixon, T. J., Watson, P. J., & Jones, P. B. (2009). Refinement of speech breathing in healthy young children ages 4 to 6 years of life. *Journal of Speech, Language and Hearing Research*, *52*(August), 990–1008.

Bóna, J. (2014). Temporal characteristics of speech: The effect of age and speech style. *The Journal of the Acoustical Society of America*, *136*(2), EL116–EL121. https://doi.org/10.1121/1.4885482

Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. *Frontiers in Human Neuroscience*, *7*(DEC), 1–2. https://doi.org/10.3389/FNHUM.2013.00855

Boonstra, T. W., & Breakspear, M. (2012). Neural mechanisms of intermuscular coherence: implications for the rectification of surface electromyography. *Journal of Neurophysiology*, *107*(3), 796–807. https://doi.org/10.1152/jn.00066.2011

Boonstra, T. W., Daffertshofer, A., van As, E., van der Vlugt, S., & Beek, P. J. (2007). Bilateral motor unit synchronization is functionally organized. *Experimental Brain Research*, *178*, 79–88. https://doi.org/10.1007/s00221-006-0713-2

Boonstra, T. W., Farmer, S. F., & Breakspear, M. (2016). *Using Computational Neuroscience to Define Common Input to Spinal Motor Neurons*. *10*(June), 2013–2016. https://doi.org/10.3389/fnhum.2016.00313

Boucher, V. J. (2001). A stumbling block in the development of motor theories of speech: Relating EMG to force-related changes in articulation. *Clinical Linguistics and Phonetics*, *15*(1–2), 123–127. https://doi.org/10.1080/026992001461433

Boucher, V. J., Ahmarani, C., & Ayad, T. (2006). Physiologic features of vocal fatigue: Electromyographic Spectral-Compression in laryngeal muscles. *The Laryngoscope*, *116*(6), 959-965.

Bronson-Lowe, C. R., Loucks, T., Ofori, E., & Sosnoff, J. J. (2013). Aging Effects on Sensorimotor Integration: A Comparison of Effector Systems and Feedback Modalities. *Article in Journal of Motor Behavior*. https://doi.org/10.1080/00222895.2013.784239

Bruce, E. N., & Ackerson, L. M. (1986). High-frequency oscillations in human electromyograms during voluntary contractions. *Journal of Neurophysiology*, *56*(2), 542–553. http://www.ncbi.nlm.nih.gov/pubmed/3760934

Bruce, E. N., & Goldman, M. D. (1983). High-frequency oscillations in human respiratory electromyograms during voluntary breathing. *Brain Research*, *269*(2), 259–265. https://doi.org/10.1016/0006-8993(83)90135-X

Castronovo, A. M., Mrachacz-Kersting, N., Stevenson, A. J. T., Holobar, A., Enoka, R. M., & Farina, D. (2018). Decrease in force steadiness with aging is associated with increased power of the common but not independent input to motor neurons. *Journal of Neurophysiology*, *120*(4), 1616–1624. https://doi.org/10.1152/JN.00093.2018/ASSET/IMAGES/LARGE/Z9K0091847490005.JPEG

Castronovo, A. M., Negro, F., Conforto, S., & Farina, D. (2015). The proportion of common synaptic input to motor neurons increases with an increase in net excitatory input. *Journal of Applied Physiology*, *119*, 1337–1346. https://doi.org/10.1152/japplphysiol.00255.2015

Caviness, J. N., Liss, J. M., Evidente, C., & Adler, V. (2006). *Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson's Disease*. *49*(April), 424–439.

Chang, Y. J., Chou, C. C., Chan, H. L., Hsu, M. J., Yeh, M. Y., Fang, C. Y., Chuang, Y. F., Wei, S. H., & Lien, H. Y. (2012). Increases of Quadriceps Inter-Muscular Cross-Correlation and Coherence during Exhausting Stepping Exercise. *Sensors 2012, Vol. 12, Pages 16353-16367*, *12*(12), 16353–16367. https://doi.org/10.3390/S121216353

Clair-Auger, J. M., Gan, L. S., Norton, J. A., & Boliek, C. A. (2015). Simultaneous Measurement of Breathing Kinematics and Surface Electromyography of Chest Wall Muscles during Maximum Performance and Speech Tasks in Children: Methodological Considerations. *Folia Phoniatrica et Logopaedica*, *67*(4), 202–211. https://doi.org/10.1159/000441326

Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders*. Saunders.

De Marchis, C., Severini, G., Castronovo, A. M., Schmid, M., & Conforto, S. (2015). Intermuscular coherence contributions in synergistic muscles during pedaling. *Experimental Brain Research*, *233*(6), 1907–1919. https://doi.org/10.1007/S00221-015-4262-4/METRICS

De Miranda Marzullo, A. C., Neto, O. P., Ballard, K. J., Robin, D. A., Chaitow, L., & Christou, E. A. (2010). Neural control of the lips differs for young and older adults following a perturbation. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *206*(3), 319. https://doi.org/10.1007/S00221-010-2411-3

Denny, M., & Smith, A. (2000). Respiratory control in stuttering speakers: evidence from respiratory high-frequency oscillations. *Journal of Speech, Language, and Hearing Research*, *43*(4), 1024–1037. http://www.ncbi.nlm.nih.gov/pubmed/11386469

Dietsch, A. M., Clark, H. M., Steiner, J. N., & Solomon, N. P. (2015). Effects of Age, Sex, and Body Position on Orofacial Muscle Tone in Healthy Adults. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1145–1150. https://doi.org/10.1044/2015_JSLHR-S-14-0325

Dromey, C., & Ramig, L. O. (1998). Intentional Changes in Sound Pressure Level and Rate: Their Impact on Measures of Respiration, Phonation, and Articulation. In *Journal of Speech Language and Hearing Research* (Vol. 41, Issue October, pp. 1003–1018). https://doi.org/10.1044/jslhr.4105.1003

Duffy, J. R. (2013). *Motor Speech Disorders : Substrates, Differential Diagnosis, and Management* (3rd ed.). Elsevier Mosby. https://search.library.ualberta.ca/catalog/5911036

Enright, P. L., Kronmal, R. A., Manolio, T. A., Schenker, M. B., & Hyatt, R. E. (1994). Respiratory muscle strength in the elderly. Correlates and reference values. Cardiovascular Health Study Research Group. *American Journal of Respiratory and Critical Care Medicine*, *149*(2), 430–438. https://www.academia.edu/12497747/Respiratory_muscle_strength_in_the_elderly_Correlates_and_reference_values_Cardiovascular_Health_Study_Research_Group

Etter, N. M., McKeon, P. O., Dressler, E. V., & Andreatta, R. D. (2018). Effects of ageing on orofacial fine force control and its relationship with parallel change in sensory perception. *International Journal of Speech-Language Pathology*, *20*(5), 502–515. https://doi.org/10.1080/17549507.2017.1318303

Faaborg-andersen, K., Edfeldt, Å. W., & Nykøbing, F. (1958). Electromyography of intrinsic and extrinsic laryngeal muscles during silent speech: Correlation with Reading activity: Preliminary report. *Acta Oto-Laryngologica*, *49*(1), 478–482. https://doi.org/10.3109/00016485809134778

Farina, D., Merletti, R., & Enoka, R. M. (2014). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, *114*, 1215–1230. https://doi.org/10.1152/japplphysiol.01070.2003

Farina, D., & Negro, F. (2015). Common Synaptic Input to Motor Neurons , Motor Unit Synchronization , and Force Control. *Exercise and Sport Sciences Reviews*, *43*(1), 23–33.

Farina, D., Negro, F., & Dideriksen, J. L. (2014). *The effective neural drive to muscles is the common synaptic input to motor neurons*. *16*, 3427–3441. https://doi.org/10.1113/jphysiol.2014.273581

Farmer, S. F., Gibbs, J., Halliday, D. M., Harrison, L. M., James, L. M., Mayston, M. J., & Stephens, J. A. (2007). Changes in EMG coherence between long and short thumb abductor muscles during human development. *Journal of Physiology*, *579*(2), 389–402. https://doi.org/10.1113/jphysiol.2006.123174

Fisher, R. J., Galea, M., Brown, P., & Lemon, R. N. (2002). Digital nerve anaesthesia decreases EMG-EMG coherence in a human precision grip task. *Experimental Brain Research*, *145*, 207–214. https://doi.org/10.1007/s00221-002-1113-x

Goffman, L., & Smith, A. (1994). Motor Unit Territories in the Human Perioral Musculature. *Journal of Speech and Hearing Research*, *37*(5), 975–984. https://doi.org/10.1044/JSHR.3705.975

Green, J. R., Moore, C. A., Higashikawa, M., & Steeve, R. W. (2000). The Physiologic Development of Speech Motor Control: Lip and Jaw Coordination. *Journal of Speech Language and Hearing Research*, *43*, 239–255. https://doi.org/10.1037//1082-989X.5.2

Green, J. R., Moore, C. A., & Reilly, K. J. (2002). The Sequential Development of Jaw and Lip Control for Speech. *Journal of Speech, Language and Hearing Research*, *45*, 66–79.

Grosse, P., Cassidy, M. J., & Brown, P. (2002). EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: Physiological principles and clinical applications. *Clinical Neurophysiology*, *113*, 1523–1531. https://doi.org/10.1016/S1388-2457(02)00223-7

Guyenet, P. G., & Bayliss, D. A. (2016). *Neural control of breathing and CO2 homeostasis*. *25*(3), 289–313. https://doi.org/10.1007/s11065-015-9294-9.Functional

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the Chest Wall during Speech Production: Volume Displacements of the Rib Cage, Abdomen, and Lung. *Journal of Speech and Hearing Research*, *16*(1), 78–115. https://doi.org/10.1044/jshr.1601.78

Hixon, T. J., Mead, J., & Goldman, M. D. (1976). Dynamics of the chest wall during speech production: function of the thorax, rib cage, diaphragm, and abdomen. *Journal of Speech and Hearing Research*, *19*(2), 297–356. https://doi.org/10.1044/jshr.1902.297

Hixon, T. J., & Weismer, G. (1995). Perspectives on the Edinburgh Study of Speech Breathing. *Journal of Speech, Language, and Hearing Research*, *38*(1), 42–60. https://doi.org/10.1044/jshr.3801.42

Hixon, T. J., Weismer, G., & Hoit, J. D. (2014). *Preclinical Speech Science : Anatomy, Physiology, Acoustics, Perception* (2nd ed.). Plural Publishing. https://search.library.ualberta.ca/catalog/6111374

Hoit, J. D., & Hixon, T. J. (1987). Age and Speech Breathing. *Journal of Speech and Hearing Research*, *30*, 351–366.

Hoit, J. D., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1990). Speech Breathing in Children and Adolescents. *Journal of Speech and Hearing Research*, *33*, 51–69.

Hoit, J. D., Plassman, B. L., Lansing, R. W., & Hixon, T. J. (1988). Abdominal muscle activity during speech production. *Journal of Applied Physiology*, *65*(6), 2656–2664. https://doi.org/10.1152/jappl.1988.65.6.2656

Hoit, J. D., Watson, P. J., Hixon, K. E., McMahon, P., & Johnson, C. L. (1994). Age and Velopharyngeal Function During Speech Production. *Journal of Speech, Language, and Hearing Research*, *37*(2), 295–302. https://doi.org/10.1044/jshr.3702.295

Huang, C. N., Chen, C. H., & Chung, H. Y. (2005). The review of applications and measurements in facial electromyography. *Journal of Medical and Biological Engineering*, *25*(1), 15–20.

Huber, J. E. (2008). Effects of Utterance Length and Vocal Loudness on Speech Breathing in Older Adults. *Respiratory, Physiology and Neurobiology*, *164*(3), 323–330. https://doi.org/10.1016/j.resp.2008.08.007.Effects

Huber, J. E., Darling, M., Francis, E. J., & Zhang, D. (2012). Impact of typical aging and Parkinson's disease on the relationship among breath pausing, syntax, and punctuation. *American Journal of Speech-Language Pathology*, *21*(4), 368–379. https://doi.org/10.1044/1058-0360(2012/11-0059)

Huber, J. E., & Spruill, J. (2008). Age-Related Changes to Speech Breathing With Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047)

Jacewicz, E., Fox, R. A., O'Neill, C., & Salmons, J. (2009). Articulation rate across dialect, age, and gender. *Language Variation and Change*, *21*(2), 233–256. https://doi.org/10.1017/S0954394509990093

Jaiser, S. R., Baker, M. R., & Baker, S. N. (2016). Intermuscular coherence in normal adults: Variability and changes with age. *PLoS ONE*, *11*(2), 1–16. https://doi.org/10.1371/journal.pone.0149029

Jeffery R. Cram. (2011). *Cram's Introduction to Surface Electromyography* (E. Eleanor Criswell, Ed.; Second Edition). https://books.google.ca/books/about/Cram_s_Introduction_to_Surface_Electromy.html?id=RgfX5jXrmzMC&printsec=frontcover&source=kp_read_button&redir_esc=y#v=onepage&q&f=false

Kahane, J. C., & Kahn, A. R. (1984). Weight measurements of infant and adult intrinsic laryngeal muscles. *Folia Phoniatrica*, *36*(3), 129–133. http://www.ncbi.nlm.nih.gov/pubmed/6469156

Kattla, S., & Lowery, M. M. (2010). *Fatigue related changes in electromyographic coherence between synergistic hand muscles*. 89–99. https://doi.org/10.1007/s00221-009-2110-0

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020). Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, *124*(4), 1045–1055. https://doi.org/10.1152/JN.00231.2020

Khoddami, S. M., Nakhostin Ansari, N., Izadi, F., & Talebian Moghadam, S. (2013). The assessment methods of laryngeal muscle activity in muscle tension Dysphonia: A review. *The Scientific World Journal*, *2013*(1). https://doi.org/10.1155/2013/507397

Kilner, J. M., Baker, S. N., Salenius, S., Jousmäki, V., Hari, R., & Lemon, R. N. (1999). Task-dependent modulation of 15-30 Hz coherence between rectified EMGs from human hand and forearm muscles. *The Journal of Physiology*, *516.2*, 559–570. http://www.ncbi.nlm.nih.gov/pubmed/10087353

Kilner, J. M., Fisher, R. J., & Lemon, R. N. (2003). *Coupling of Oscillatory Activity Between Muscles Is Strikingly Reduced in a Deafferented Subject Compared With Normal Controls*. 790–796.

Kuhlmann, L. L., & Iwarsson, J. (2021). Effects of Speaking Rate on Breathing and Voice Behavior. *Journal of Voice*. https://doi.org/10.1016/J.JVOICE.2021.09.005

Kuriki, H. U., Mícolis De Azevedo, F., Sanae, L., Takahashi, O., & Mello, M. (2012). The Relationship Between Electromyography and Muscle Force. In M. Schwartz (Ed.), *EMG Methods for Evaluating Muscle and Nerve Function* (pp. 31–52). www.intechopen.com

Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, *118*(3), 1775–1783. https://doi.org/10.1152/jn.00204.2017

Lametti, D. R., Nasir, S. M., & Ostry, D. J. (2012). Sensory Preference in Speech Production Revealed by Simultaneous Alteration of Auditory and Somatosensory Feedback. *Journal of Neuroscience*, *32*(27), 9351–9358. https://doi.org/10.1523/jneurosci.0404-12.2012

Lemon, R. N. (2008). *Descending Pathways in Motor Control. Cm*. https://doi.org/10.1146/annurev.neuro.31.060407.125547

Liss, J. M., Weismer, G., & Rosenbek, J. C. (1990). Selected Acoustic Characteristics of Speech Production in Very Old Males. *Journal of Gerontology*, *45*(2), P35–P45. https://doi.org/10.1093/geronj/45.2.P35

Liu, P., Chen, Z., Jones, J. A., Huang, D., & Liu, H. (2011). Auditory feedback control of vocal pitch during sustained vocalization: A Cross-Sectional study of adult aging. *PLoS ONE*, *6*(7), 0–7. https://doi.org/10.1371/journal.pone.0022791

Manda, Y., Maeda, N., Pan, Q., Sugimoto, K., Hashimoto, Y., Tanaka, Y., Kodama, N., & Minagi, S. (2016). New method of neck surface electromyography for the evaluation of tongue-lifting activity. *Journal of Oral Rehabilitation*, *43*(6), 417–425. https://doi.org/10.1111/joor.12389

McClean, M. D., & Tasko, S. M. (2002). Association of orofacial with laryngeal and respiratory motor output during speech. *Experimental Brain Research*, *146*(4), 481–489. https://doi.org/10.1007/s00221-002-1187-5

McClean, M. D., & Tasko, S. M. (2006). Association of Orofacial Muscle Activity and Movement During Changes in Speech Rate and Intensity. *Journal of Speech, Language, and Hearing Research*, *46*(6), 1387–1400. https://doi.org/10.1044/1092-4388(2003/108)

McFarland, D. H., & Smith, A. (1989). Surface recordings of respiratory muscle activity during speech: some preliminary findings. *Journal of Speech and Hearing Research*, *32*(3), 657–667. http://www.ncbi.nlm.nih.gov/pubmed/2779209

Mendes, A., Ferreira, L., Jorge, A., Rothman, H., Tavares, D., & Garcez, I. (2017). Respiratory physiology during reading aloud tasks. *Distúrbios Da Comunicação*, *29*(3), 519–528. https://doi.org/10.23925/2176-2724.2017v29i3p519-528

Mendes Balata, P. M., Da Silva, H. J., Rocha De Moraes, K. J., De Araújo Pernambuco, L., & Arruda De Moraes, S. R. A. (2013). Use of surface electromyography in phonation studies: An integrative review. *International Archives of Otorhinolaryngology*, *17*(3), 329–339. https://doi.org/10.7162/S1809-977720130003000014

Mima, T., & Hallett, M. (1999). Corticomuscular coherence: a review. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *16*(6), 501–511. https://doi.org/10.1097/00004691-199911000-00002

Mohr, M., Nann, M., Von Tscharner, V., Eskofier, B., & Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *PLOS ONE*, *10*(11), e0142048. https://doi.org/10.1371/JOURNAL.PONE.0142048

Nasir, S. M., & Ostry, D. J. (2006). Somatosensory Precision in Speech Production. *Current Biology*, *16*(19), 1918–1923. https://doi.org/10.1016/j.cub.2006.07.069

Negro, F., & Farina, D. (2011). *Linear transmission of cortical oscillations to the neural drive to muscles is mediated by common projections to populations of motoneurons in humans*. *3*, 629–637. https://doi.org/10.1113/jphysiol.2010.202473

Nguyen, H. B., Lee, S. W., Harris-love, M. L., & Lum, P. S. (2017). Control of Movement Neural coupling between homologous muscles during bimanual tasks : effects of visual and somatosensory feedback. *Journal of Neurophysiology*, *117*, 655–664. https://doi.org/10.1152/jn.00269.2016

Omlor, W., Patino, L., Hepp-Reymond, M. C., & Kristeva, R. (2007). Gamma-range corticomuscular coherence during dynamic force output. *NeuroImage*, *34*(3), 1191–1198. https://doi.org/10.1016/J.NEUROIMAGE.2006.10.018

Peladeau-Pigeon, M., & Steele, C. M. (2017). Age-Related Variability in Tongue Pressure Patterns for Maximum Isometric and Saliva Swallowing Tasks. *Journal of Speech, Language, and Hearing Research*, *60*(11), 3177–3184. https://doi.org/10.1044/2017_jslhr-s-16-0356

Poletto, C. J., Verdun, L. P., Strominger, R., & Ludlow, C. L. (2004). Correspondence between laryngeal vocal fold movement and muscle activity during speech and nonspeech gestures. *Journal of Applied Physiology*, *97*(3), 858–866. https://doi.org/10.1152/japplphysiol.00087.2004

Purcell, D. W., & Munhall, K. G. (2006). Adaptive control of vowel formant frequency: Evidence from real-time formant manipulation. *The Journal of the Acoustical Society of America*, *120*(2), 966–977. https://doi.org/10.1121/1.2217714

Purves, D. (2018). *Neuroscience* (D. Purves, G. J. Augustine, D. Fitzpatrick, W. C. Hall, A.-S. LaMantia, R. D. Mooney, M. L. Platt, & L. E. White, Eds.; Sixth edition). Oxford University Press. https://search.library.ualberta.ca/catalog/8297154

Reed, A., Cummine, J., Bhat, N., Jhala, S., Bakhtiari, R., & Boliek, C. A. (2021). Changes in Intermuscular Coherence as a Function of Age and Phase of Speech Production During an Overt Reading Task. *Motor Control*, *25*(2), 295–314. https://doi.org/10.1123/MC.2020-0003

Reyes, A., Laine, C. M., Kutch, J. J., & Valero-Cuevas, F. J. (2017). Beta Band Corticomuscular Drive Reflects Muscle Coordination Strategies. *Frontiers in Computational Neuroscience*, *11*(April), 1–10. https://doi.org/10.3389/fncom.2017.00017

Rowe, H. P., Stipancic, K. L., Lammert, A. C., & Green, J. R. (2021). Validation of an Acoustic-Based Framework of Speech Motor Control: Assessing Criterion and Construct Validity Using Kinematic and Perceptual Measures. *Journal of Speech, Language, and Hearing Research*, *64*(12), 4736–4753. https://doi.org/10.1044/2021_JSLHR-21-00201

Ruark, J. L., & Moore, C. A. (1997). Coordination of Lip Muscle Activity by 2-Year-Old Children During Speech and Nonspeech Tasks. *Journal of Speech, Language, and Hearing Research : JSLHR*, *40*(6), 1373. https://doi.org/10.1044/JSLHR.4006.1373

Sasaki, C. T., & Leder, S. B. (2013). Surface electromyography for speech and swallowing systems: Measurement, analysis, and interpretation: Comment. *Dysphagia*, *28*(1), 116–117. https://doi.org/10.1007/s00455-012-9431-z

Semmler, J. G., Ebert, S. A., & Amarasena, J. (2013). Eccentric muscle damage increases intermuscular coherence during a fatiguing isometric contraction. *Acta Physiologica*, *208*(4), 362–375. https://doi.org/10.1111/apha.12111

Semmler, J. G., Kornatz, K. W., & Enoka, R. M. (2006). Motor-Unit Coherence During Isometric Contractions Is Greater in a Hand Muscle of Older Adults. *Journal of Neurophysiology*, *90*(2), 1346–1349. https://doi.org/10.1152/jn.00941.2002

Semmler, J. G., Steege, J. W., Kornatz, K. W., & Enoka, R. M. (2000). Motor-Unit Synchronization Is Not Responsible for Larger Motor-Unit Forces in Old Adults. *Journal of Neurophysiology*, *84*(1), 358–366. https://doi.org/10.1152/jn.2000.84.1.358

Smith, A. (2006). Speech motor development: Integrating muscles, movements, and linguistic units. *Journal of Communication Disorders*, *39*(5), 331–349. https://doi.org/10.1016/j.jcomdis.2006.06.017

Smith, A., & Denny, M. (1990). High-frequency oscillations as indicators of neural control mechanisms in human respiration, mastication, and speech. *Journal of Neurophysiology*, *63*(4), 745–758.

Smith, A., Luschei, E., Denny, M., Wood, J., & Hirano, M. (1993). Spectral Analyses of Activity of Laryngeal and Orofacial Muscles in Stutters. *Journal of Neurology, Neurosurgery and Psychiatry*, *56*, 1303–1311.

Smith, A., & Zelaznik, H. N. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology*, *45*(1), 22–33. https://doi.org/10.1002/dev.20009

Smith, J. C., Abdala, A. P. L., Borgmann, A., Rybak, I. A., & Paton, J. F. R. (2014). Brainstem respiratory networks: building blocks and microcircuits. *Trends in Neurosciences*, *36*(3), 152–162. https://doi.org/10.1016/j.pain.2013.06.005.Re-Thinking

Smith, Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech and Hearing Research*, *30*(4), 522–529. http://www.ncbi.nlm.nih.gov/pubmed/3695445

Sonies, B. C., Baum, B. J., & Shawker, T. H. (1984). Tongue Motion in Elderly Adults: Initial in Situ Observations. *Journal of Gerontology*, *39*(3), 279–283. https://doi.org/10.1093/geronj/39.3.279

Sperry, E. E., & Klich, R. J. (1992). Speech breathing in senescent and younger women during oral reading. *Journal of Speech and Hearing Research*, *35*(6), 1246–1255. https://doi.org/10.1044/JSHR.3506.1246

Stathopoulos, E. T., Huber, J. E., Sussman, J. E., & Lafayette, W. (2011). *Changes in Acoustic Characteristics of the Voice Across Life Span*. *54*(August), 1011–1021. https://doi.org/10.1044/1092-4388(2010/10-0036)b

Stathopoulos, E. T., & Sapienza, C. (2005). Respiratory and laryngeal measures of children during vocal intensity variation. *The Journal of the Acoustical Society of America*, *94*(5), 2531–2543. https://doi.org/10.1121/1.407365

Statistics Canada. (2002). *2001 Participation and Activity Limitation Survey*.

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & McMurtrey, J. R. (2008). Babbling, chewing, and sucking: oromandibular coordination at 9 months. *Journal of Speech, Language, and Hearing Research : JSLHR*, *51*(6), 1390–1404. https://doi.org/10.1044/1092-4388(2008/07-0046)

Steeve, R. W., & Price, C. M. (2010). Investigating the use of coherence analysis on mandibular electromyograms to investigate neural control of early oromandibular behaviours: A pilot study. *Clinical Linguistics & Phonetics*, *24*(6), 485–501. https://doi.org/10.3109/02699200903506312

Stepp, C. E. (2012). Surface Electromyography for Speech and Swallowing Systems: Measurement, Analysis, and Interpretation. *Journal of Speech, Language and Hearing*, *55*, 1232–1247. https://doi.org/10.1044/1092-4388(2011/11-0214)a

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2010). Use of Neck Strap Muscle Intermuscular Coherence as an Indicator of Vocal Hyperfunction. *IEEE Trans Neural Syst Rehabil Eng.EEE Trans Neural Syst Rehabil Eng.*, *18*(3), 329–335. https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2011). Modulation of neck intermuscular Beta coherence during voice and speech production. *Journal of Speech, Language, and Hearing Research*, *54*, 836–844. https://doi.org/10.1044/1092-4388(2010/10-0139)

Tang, J., & Stathopoulos, E. T. (2005). Vocal efficiency as a function of vocal intensity: A study of children, women, and men. *The Journal of the Acoustical Society of America*, *97*(3), 1885–1892. https://doi.org/10.1121/1.412062

Tomczak, C. R., Greidanus, K. R., & Boliek, C. A. (2013). Modulation of chest wall intermuscular coherence: effects of lung volume excursion and transcranial direct current stimulation. *Journal of Neurophysiology*, *110*, 680–687. https://doi.org/10.1152/jn.00723.2012

Usler, E. R., Wei, X., Simione, M., Richburg, B., Stipancic, K. L., & Green, J. R. (2020). Modulation of Intermuscular Beta Coherence in Different Rhythmic Mandibular Behaviors.

Frontiers in Human Neuroscience, *14*, 302. https://doi.org/10.3389/FNHUM.2020.00302/BIBTEX

Vanderwegen, J., Guns, C., Van Nuffelen, G., Elen, R., & De Bodt, M. (2013). The influence of age, sex, bulb position, visual feedback, and the order of testing on maximum anterior and posterior tongue strength and endurance in healthy Belgian adults. *Dysphagia*, *28*(2), 159–166. https://doi.org/10.1007/s00455-012-9425-x

Villacorta, V. M., Perkell, J. S., & Guenther, F. H. (2007). Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception. *The Journal of the Acoustical Society of America*, *122*(4), 2306–2319. https://doi.org/10.1121/1.2773966

von Tscharner, V., Ullrich, M., Mohr, M., Comaduran Marquez, D., & Nigg, B. M. (2018). Beta, gamma band, and high-frequency coherence of EMGs of vasti muscles caused by clustering of motor units. *Experimental Brain Research*, *236*(11), 3065–3075. https://doi.org/10.1007/S00221-018-5356-6/METRICS

Walsh, B., & Smith, A. (2002). Articulatory Movements in Adolescents: Evidence for Protracted Development of Speech Motor Control Processes. *Journal of Speech, Language and Hearing Research*, *45*, 1119–1133.

Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *Journal of Speech, Language, and Hearing Research : JSLHR*, *41*(1), 41–50. http://www.ncbi.nlm.nih.gov/pubmed/9493732

Wohlert, A. B., & Smith, A. (2002). Developmental Change in Variability of Lip Muscle Activity During Speech. *Journal of Speech, Language, and Hearing Research*, *45*(6), 1077–1087. https://doi.org/10.1044/1092-4388(2002/086)

Woods, M. J., Nicholas, C. L., Semmler, J. G., Chan, J. K. M., Jordan, A. S., & Trinder, J. (2015). Common drive to the upper airway muscle genioglossus during inspiratory loading. *Journal of Neurophysiology*, *114*(5), 2883–2892. https://doi.org/10.1152/jn.00738.2014

Zajac, D. J. (1997). Velopharyngeal function in young and older adult speakers: Evidence from aerodynamic studies. *The Journal of the Acoustical Society of America*, *102*(3), 1846–1852. https://doi.org/10.1121/1.42009

Chapter 2: Task and Age-Related Sensitivities in the Chest Wall

The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Chest Wall

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AR was responsible for study design, data collection and analysis and wrote the manuscript, RB was involved in data analysis and development of custom Matlab scripts for analysis, and authors JC and CB supervised all stages of the project. All authors reviewed the final manuscript.

Introduction

Speech production requires a highly complex set of movements to coordinate muscles among the head, neck and chest wall (Kent, 2000). For speech to occur, the motor system must coordinate activity across the four subsystems involved in speech production. Speech must be executed on exhalation (respiratory subsystem), while the vocal folds (phonatory subsystem) and vocal tract (i.e., tongue, lips, jaw, soft palate) (articulatory subsystem), and velopharynx (velopharyngeal subsystem) execute a series of movements to produce specific speech sounds. Disruptions to an individual's ability to speak occur as a result of a breakdown in the planning, programming and/or execution stages of speech production. The speech system has been studied using a variety of methods resulting in aerodynamic, kinematic and acoustic measurements of speech and non-speech tasks. In order to study the neuromuscular control responsible for the execution of speech movements, researchers use electromyographic (EMG) recordings of muscular activity.

Traditionally EMG recordings have been used by speech physiologists to characterize the timing (i.e., onset and offset of muscle activation) and degree of contraction within the muscles used to produce speech. Information derived from EMG recordings has significantly advanced our understanding of the complexities and flexibility of muscle activation patterns associated with speech production (e.g., Clair-Auger et al., 2015; Hoit et al., 1988; McFarland & Smith, 1989; Poletto et al., 2004; Steeve et al., 2008). Beyond analysis of timing and amplitude of muscle contraction, signal frequency analyses between two muscles facilitates insight into the neuromuscular control of movement. This measurement is referred to as intermuscular coherence (IMC), and is accomplished by performing a cross-correlation in the observed EMG frequency domain (Grosse et al., 2002). Briefly, IMC is the degree to which the frequency activity in one muscle predicts that of the other at any given time throughout the analysis window. IMC is studied within distinct frequency bandwidths, which provides researchers with additional information about the neuromuscular control for a given task. Commonly studied are the beta frequency bandwidth (~15-30 Hz) and the gamma bandwidth (~30-60hz). Although both bandwidths are thought to be related to corticomuscular drive (Boonstra, 2013; Mima & Hallett, 1999; Reyes et al., 2017), IMC within each bandwidth is associated with, and sensitive to, different types of motor tasks and demands. For example, changes in IMC in the beta bandwidth may indicate whether observed coordinated muscle activity is under individuated vs synergistic control (de Vries et al., 2016; Laine & Valero-Cuevas, 2017; Nazarpour et al., 2012; Reyes et al., 2017). IMC in the gamma bandwidth however, is thought to be associated with coordination of muscles during novel and/or more complex, dynamic movement sequences (Chang et al., 2012; De Marchis et al., 2015; Mohr et al., 2015, 2018; Omlor et al., 2007; von Tscharner et al., 2018).

Preliminary studies have explored the sensitivity of IMC to varying factors and task demands across speech subsystems. For example, in the respiratory system, chest wall IMC may be sensitive to changes in lung volume (Denny & Smith, 2000; Smith & Denny, 1990; Tomczak et al., 2013), varying muscular demands (Boliek et al., 2019), voluntary vs involuntary tasks (Ackerson & Bruce, 1983; Bruce & Ackerson, 1986), absence or presence of tracheal pressure (i.e., needed for phonation) (Boliek et al., 2019; Tomczak et al., 2013) and phase of speech planning and production (i.e., pre-production planning phase, production phase or the onset of speech) (Reed et al., 2021).

Although those previous studies have been critically informative about methodological approaches for capturing IMC and providing preliminary evidence of its sensitivity to speech and non-speech targets, researchers using IMC must now investigate the impact of a wider variety of task demands on speech motor control. Specifically, little is known about the role of cognitive or articulatory demands of the speech task on IMC in the chest wall. Differences in “upstream” (i.e., pre-phonological encoding and articulation) and cognitive-linguistic demands require careful consideration when examining neuromuscular control for speaking as these factors have been shown to impact multiple measures of speech motor control (Mitchell & Hoit, 1996; Nip & Green, 2013; Wang et al., 2010). For example, while it is widely accepted that vocal reaction times are longer in picture naming tasks versus single word reading tasks, there is evidence to suggest that the articulatory movements associated with these tasks are also impacted (Riès et al., 2012). Manipulation of cognitive-linguistic demands provides insight into how underlying neuromuscular control of speech subsystems may be altered even when producing similar movement patterns. Initial studies have examined increased cognitive demands on extrinsic laryngeal IMC (Stepp et al., 2011), however the impact of increased cognitive-linguistic demands on chest wall IMC has yet to be described.

Last, in order to become a relevant and generalizable measure of speech motor control, studies of IMC in the speech mechanism must consider the impact of aging. The global population of adults ages 60 years and older is estimated to reach 22% by the year 2050 (United Nations, 2015). To adequately make statements about speech motor control in this growing population, we need to understand the role of physical and cognitive degeneration on measures of speech motor control. Studies investigating lifespan changes in IMC in the limbs have yielded mixed results, with some studies showing an increase (Castronovo et al., 2015; Farmer et al., 2007; Semmler et al., 2006) or no change (Jaiser et al., 2016) in IMC with age. Preliminary work within the respiratory and articulatory subsystems suggest that there are no changes in IMC between young and older adults, at least for certain phase elements of planning and speech production (Reed et al., 2021).

The respiratory system is ideal for further exploration of IMC as there is a well-established literature on speech breathing kinematics that describes the effects of age, lung volume manipulation, laryngeal coordination, articulatory behaviours, and cognitive-linguistic demands (e.g., Dromey & Ramig, 1998b, 1998a; Hixon et al., 1976; Huber, 2008; Mitchell & Hoit, 1996; Wang et al., 2010). Respiratory kinematic studies also suggest that when compared to younger adults, older adults demonstrate decreased biomechanical efficiency, lung volume excursion and breath group length (Hoit et al., 1989; Hoit & Hixon, 1987; Huber & Spruill III, 2012; Sperry & Klich, 1992). Despite this wealth of information regarding respiratory kinematics, few studies have collected information regarding the muscle activity underlying these movements. The pairing of traditional measures of speech motor control (i.e., kinematics) with unique peripheral measures of muscle firing (i.e., IMC) allows for a more comprehensive understanding of speech motor control.

In summary, despite several advances in our understanding of the complex movements needed for speech production, the neuromuscular control that underlies these movements remains poorly understood. Preliminary investigations of IMC in the speech mechanism indicate that it may be a promising measure for advancing our understanding of speech motor control. In order to determine its utility in the characterization of speech motor control, studies must consider an expanded range of speech and non-speech tasks in both younger and older populations.

Present Study

The present study seeks to further characterize the neuromuscular control of speech using IMC measurements derived from EMG recordings in the respiratory subsystem. Building on existing work in the field, younger and older adults were asked to perform a series of seven tasks, which will be described below in the context of specific requirements within, and demands across, speech subsystems. This study is designed to address five key objectives, specifically how IMC as a measure of neuromuscular control changes when (1) lung volume, (2) laryngeal engagement, (3) articulatory demands, and (4) cognitive linguistic demands are manipulated for speech and non-speech tasks in younger and older adults (5). Previous work has informed two specific hypotheses relating to objectives (1) and (2). First we hypothesize that within the beta frequency bandwidth, tasks using smaller lung volumes would be associated with higher chest wall IMC (Tomczak et al., 2013). Second, we hypothesize that in the gamma frequency bandwidth, large lung volume tasks with additional tracheal pressure requirements (i.e., maximum phonation duration and diadochokinetic productions) would yield higher chest wall IMC compared to large lung volume tasks without tracheal pressure requirements (i.e., vital capacity) (Boliek et al., 2019). The remainder of the objectives are exploratory in nature and will be interpreted in the context of available literature.

Materials and Methods

Participants

Thirty English speaking younger adults (age: 26.97 years old ± 6.04; age range: 18-43 years old; sex: 8 men, 22 women) and thirty English speaking older adults (age: 66.37 years old ± 6.83; age range: 54-77 years old; sex: 7 men, 23 women) were recruited. Participants were required to have a negative history of neurological conditions (e.g., epilepsy, migraines, movement disorders), acute or chronic muscle conditions or surgeries affecting the head, neck, chest or abdomen; history of speech, language or learning delays or disorders. All participants had normal or corrected to normal hearing and vision. All study protocols received approval through the University of Alberta Research Ethics Board.

Tasks

The data presented in this study were collected using seven tasks designed to manipulate activity within and across speech subsystems. Table 2.1 provides an overview of each task and its associated requirement from the speech mechanism. Task descriptions are outlined in the procedures section below. With respect to the respiratory system, tasks are categorized as requiring large or small lung volumes. In the laryngeal system, subglottal pressure was either not generated (i.e., in the case of rest breathing and vital capacity), or maintained at a constant level as in the case of sustained phonation, or was variably produced (i.e., for voiced versus voiceless sounds within word productions). Articulator movement demands were considered to be either low (i.e., for neutral vowels), similar to habitual speech demands or involve maximum performance (i.e., normal or accelerated rate of speech). The final column of the table includes a description of the cognitive-linguistic considerations for each task.

Table 2.1 *Description of the lung volume requirements, laryngeal engagement, articulatory demands and cognitive-linguistic considerations of each task.*

Task	Lung Volume Requirements (respiratory subsystem)	Tracheal Pressure Requirements (laryngeal subsystem) Status of larynx	Articulatory demands (Articulation Subsystem)	Cognitive-linguistic considerations
Vital Capacity Maneuver (VC)	Range of Large Lung Volumes	None	None	Novel non speech
Maximum Phonation Duration (MPD)	Range of Large Lung Volumes	Sustained	Low demand	Novel non speech
Sequential Diadochokinetic (DDK)	Range of Large Lung Volumes	Alternating	High demand	Novel non speech
Rest Breathing (RB)	Range of Small Lung Volumes	None	None	None
Word Reading (WR)	Small Range of Lung Volumes	Alternating	Habitual Speech	Reading
Picture Naming (PN)	Small Range of Lung Volumes	Alternating	Habitual Speech	Naming
Tongue Twister Repetition (TT)	Small Range of Lung Volumes	Alternating	High Demand	Reading

Procedures

Upon arriving at the Speech Physiology Laboratory at the University of Alberta, participants provided written and informed consent and were formally admitted to the study. Once consented, chest wall EMG electrodes, inductance plethysmography bands and an omni-directional microphone were placed and tested. Following respiratory kinematic calibration procedures (including the vital capacity (VC) task), data for the rest breathing (RB) task was collected. This involved informing the participants to relax while researchers checked equipment (approximately two minutes or until 10-20 sequential rest breaths with no movement artifact were collected).

The remaining large lung volume tasks were then elicited: the maximum phonation duration (MPD) and sequential diadochokinetic (DDK). In all three large lung volume tasks, participants were asked to begin with a maximum inspiration and to continue until all air was expelled. In the VC task, participants were required to blow out all air through their mouth. In the MPD participants were asked to produce an open vowel ("ah") and in the DDK task, they were asked to repeat three syllables ("pataka") at a maximum articulatory rate. Three consistent trials of each task were elicited.

Following VC, RB, MPD and DDK tasks, participants completed word reading (WR), picture naming (PN) and tongue twister (TT) tasks in a randomized order, with instructions and stimuli presented by E-prime software (Psychology Software Tools, Pittsburgh, PA, USA). In the WR task, participants were asked to read aloud a list of forty, four-letter, monosyllabic words. Two word lists balanced for onset phoneme and word type (i.e., regular exception, nonwords, and pseudohomophones) were used. In the PN task, participants were asked to name the images presented as quickly and accurately as possible. Two matched sets were used during this task containing 20 object and 20 action stimuli each (10 low frequency and 10 high frequency items of each). In the TT task, participants were asked to read aloud the words on the screen as quickly and accurately as possible. Two matched sets of 15 tongue twisters, controlled for length and lexical qualities were used.

In total, the protocol was approximately 2 hours from time of consent to departure. Participants received a small honorarium for participation. A subset of these data has previously been published (Reed et al., 2021).

Data Acquisition and Signal Analysis

In addition to IMC, a series of descriptive variables were collected to confirm successful variable manipulation across tasks and to provide context to IMC. Acquisition and analysis of descriptive (i.e., kinematic, EMG amplitude and task performance) and dependent variables (i.e., chest wall IMC) are described below.

Kinematics. Two variable inductance plethysmography bands were used to detect movement of the chest wall (Respitrace, Ambulatory Monitoring Company, NY). One band was placed around the rib cage and one around the abdomen. Signals were sampled at 10 kHz and displayed in real time with time-locked EMG recordings using PowerLab (ADInstruments, Colorado Springs, CO). These measurements were calibrated offline using two maneuvers performed by the participants (as previously described by Hixon, 1973; Hoit & Hixon, 1987): an isovolume maneuver (alternating between movements to contract and relax abdominal wall with airway closed) and a rest breathing task performed using a mouthpiece attached to a calibrated pneumotachometer and differential pressure transducer (nares occluded) (Validyne model DP45-14; Validyne Model CD15). The pneumotachometer was calibrated prior to each data collection session. During the calibration process, estimates of vital capacity based on age, sex and height were used to confirm conversion of summed movement of the rib cage and abdomen into lung volume.

Signals were analyzed using a custom Matlab program. For each task, all trials were segmented from the peak of inspiration to the end of expiration. Three descriptive measures were derived from kinematic recordings. First, lung volume excursion in percent vital capacity (%VC) was calculated by dividing lung volume excursion for the event by the participant's vital capacity. This allowed for normalization across participants. For the majority of participants vital capacity was the largest lung volume excursion across the three vital capacity trials. In the event that participants demonstrated lung volumes below age, height and sex predictions, (i.e., due to poor performance) a predicted value was substituted (ten participants) (Quanjer et al., 2012). Next, percent rib cage contribution to total lung volume excursion (%RC) was calculated to quantify the relative contribution of the rib cage to the lung volume event. This measure provides insight into biomechanical efficiency and has previously been demonstrated to change as a function of age (Hoit & Hixon, 1987; Huber & Spruill, 2008). Lastly, lung volume excursion per syllable in percent vital capacity/syllable (%VC/SYLL) was calculated to provide additional insight into the joint efficiency of the respiratory and laryngeal subsystems for controlling expiratory flow during phonation. This measure was calculated for DDK and TT tasks. All three measures were generated for each trial and averaged within the task.

EMG data. EMG data for the intercostal and oblique muscles of the chest wall were collected using previous published protocols (Boliek et al., 2019; Reed et al., 2021; Tomczak et al., 2013). Surface EMG recordings were collected from paired electrodes on the right intercostals (6-7th intercostal space) and obliques (10 cm from midline at the level of the umbilicus), with a ground electrode placed midline on the clavicle. Pre-gelled surface electrodes were used (Kendal Soft-E H69P, Tyco Healthcare Group). Correct placement of EMG electrodes was confirmed using a vital capacity maneuver with a brief breath hold (intercostals), a trunk rotation task against external resistance applied by experimenter hand on opposite shoulder (obliques). These two manuevers also served to capture maximum voluntary muscle contraction (MVC) used to normalize EMG amplitudes across tasks and participants described below. EMG signals were collected using a sampling rate of 10 kHz. Signals were amplified (Grass P511; Astro-Med, Inc., Quincy, MA) and band-pass filtered (3–3000 Hz). Power line interference was minimized using a 60-Hz notch filter. All EMG signals were acquired using a multichannel acquisition system (PowerLab 16SP ML795; ADInstruments, Colorado Springs, CO). Digital recordings were saved using LabChart software (version 5.5.6; ADInstruments) time-locked with kinematic signal acquisition.

Custom Matlab scripts were used to calculate EMG amplitude (descriptive variable) relative to baseline task (i.e., rest breathing) and IMC (dependent variable) from EMG signals (see protocols Boliek et al., 2019; Reed et al., 2021; Tomczak et al., 2013 for further details). For each task, both measures were derived from the expiratory limb of trials (peak inspiration to end expiration) as indicated using the summed rib cage and abdomen kinematic signals. For the rest breathing task, a period of ~10 sequential breaths was segmented (i.e., inspiration and expiration) and used for both IMC and EMG amplitude. Signal amplitude provides insight into the degree of muscle contraction during a task relative to the muscle's maximum voluntary contraction (%MVC). %MVC is calculated using reference values from resting EMG and tasks designed to elicit maximum voluntary contraction (i.e., tasks used to confirm electrode placement, as described previously). Using custom Matlab scripts (See Boliek et al., 2019 and Tomczak et al., 2013 for further details), data were high-pass filtered using a cut off frequency of 60 Hz (intercostals and obliques), prior to rectification and smoothing. Values were generated for each trial and averaged within each task. Individual trial values resulting in % MVC values over 200% were removed due to the likelihood of movement artifact (<1% of data). Separate values were calculated for intercostals (IC) and for obliques (OB).

Data processing for IMC within the chest wall included filtering using a 30 Hz high-pass Butterworth filter and a 300 Hz low-pass filter and rectification of signals. IMC (Equation 1) was calculated using a frequency resolution of 2.44 Hz and segment length of 2,048 points. IMC values were normalized for the number of segments (Equation 2) prior to statistical analysis. For each task, intercostal-oblique IMC was calculated in the beta (15-30 Hz) and gamma (31-60Hz) frequency bandwidths.

$$Coh_{XY}(f) = \left|C_{xy}(w)\right|^2 = \frac{\left|\overline{G_{xy}(w)}\right|^2}{\overline{G_{xx}(w)}\cdot\overline{G_{yy}(w)}}$$

Equation 1 . Intermuscular coherence calculation where Coh=magnitude square coherence; Gxx(w) and Gyy(w)= averaged power spectra of the x and y muscles of interest, for a given frequency (w); Gxy=averaged cross-power spectrum of x and y signals at frequency w (Norton & Gorassini, 2006; Rosenberg et al., 1989).

$$Z\,(f) = \operatorname{atanh}\left(\sqrt{Coh\,(f)}\,\right) / \sqrt{1/(2 * L)}$$

Equation 2. Standardized Z score transformation of intermuscular coherence at frequency (f), given L segments (Rosenberg et al., 1989, as used by Baker, Pinches, & Lemon, 2003)

Measures of Task performance. Time locked audio recordings were made using TF32, a Windows based version of CSpeech software (Milenkovic, 2001), and a small omni-directional condenser microphone (Audio-Technica, Model AT 803b) with amplification (M-Audiobuddy Pre-Amplifier). These recordings were used to calculate four measures of task performance using PRATT (Boersma & Weenink, 2013) software. Task duration for MPD and DDK tasks were calculated as the difference between voice onset and offset within each trial. Measures of rate for the DDK and TT tasks were derived by dividing task duration (i.e., voice onset-offset) by the number of syllables. Inaccurate trials (i.e., phoneme substitutions or repetitions) were excluded from rate measurements for the tongue twister task.

Statistics

Statistical analysis was conducted using JASP (version 0.16.3; JASP Team, 2022). For all variables, values more than 1.5 *SD*s from the mean of each age group were excluded from the analysis (<1% of data). The Shapiro-Wilk test of normality was significant across all measures, therefore repeated measures ANOVAs were used to investigate the effect of tasks within each age group for both frequency bandwidths. Homogeneity of variance was confirmed using Mauchly's test of sphericity. When a violation of sphericity occurred, a Greenhouse-Geisser corrected value was reported (denoted using $^{+}$). *Post hoc* analyses were conducted using a Holm correction for multiple comparisons. Between group differences were investigated using independent samples t-tests or Mann-Whitney U tests using a Holm correction for multiple comparisons. Corrected *p*-values are reported throughout the manuscript. Descriptive variables including respiratory kinematics (%VC, %RC, %VC/SYLL), EMG amplitude (%MVC for IC, OB), performance measures (task duration and rate) were subjected to the same statistical routine. Exploratory Pearson correlations between IMC and descriptive variables were conducted using a Bonferroni correction.

Results

Uncorrected kinematic and raw EMG signals of a representative participant are shown in Figure 2.1. IMC findings are presented below (see Figure 2.2 for IMC in a representative participant during the DDK task) and respiratory kinematic, EMG amplitude variables and exploratory correlations are presented in the Supplementary materials by task and by age.

Respiratory kinematic variables included lung volume excursion in percent vital capacity (%VC), percent rib cage contribution to total lung volume excursion (%RC) and lung volume excursion (in percent vital capacity) per syllable (%VC/SYLL) are presented in Supplemental Materials: Figures S2.1, S2.2 and S2.3, respectively. EMG amplitude variables include degree of contraction relative to the muscle's maximum voluntary contraction (%MVC) for both the intercostal and oblique muscles can be found in Supplemental Materials: Figures S2.4A and S2.4B, respectively. Exploratory correlations include Pearson correlations between IMC and respiratory kinematics, EMG amplitude variables and behavioural measures can be found in Supplemental Materials: Figures S2.5A-C. Statistical significance of task and age-related differences are denoted within figures and reported in figure captions.

The findings confirmed successful manipulation of lung volume excursion: all smaller lung volume excursion tasks (RB, WR, PN, TT) had significantly lower lung volume excursions (%VC) and demonstrated lower EMG amplitude (%MVC) relative to larger lung volume excursion tasks (VC, MPD, DDK).

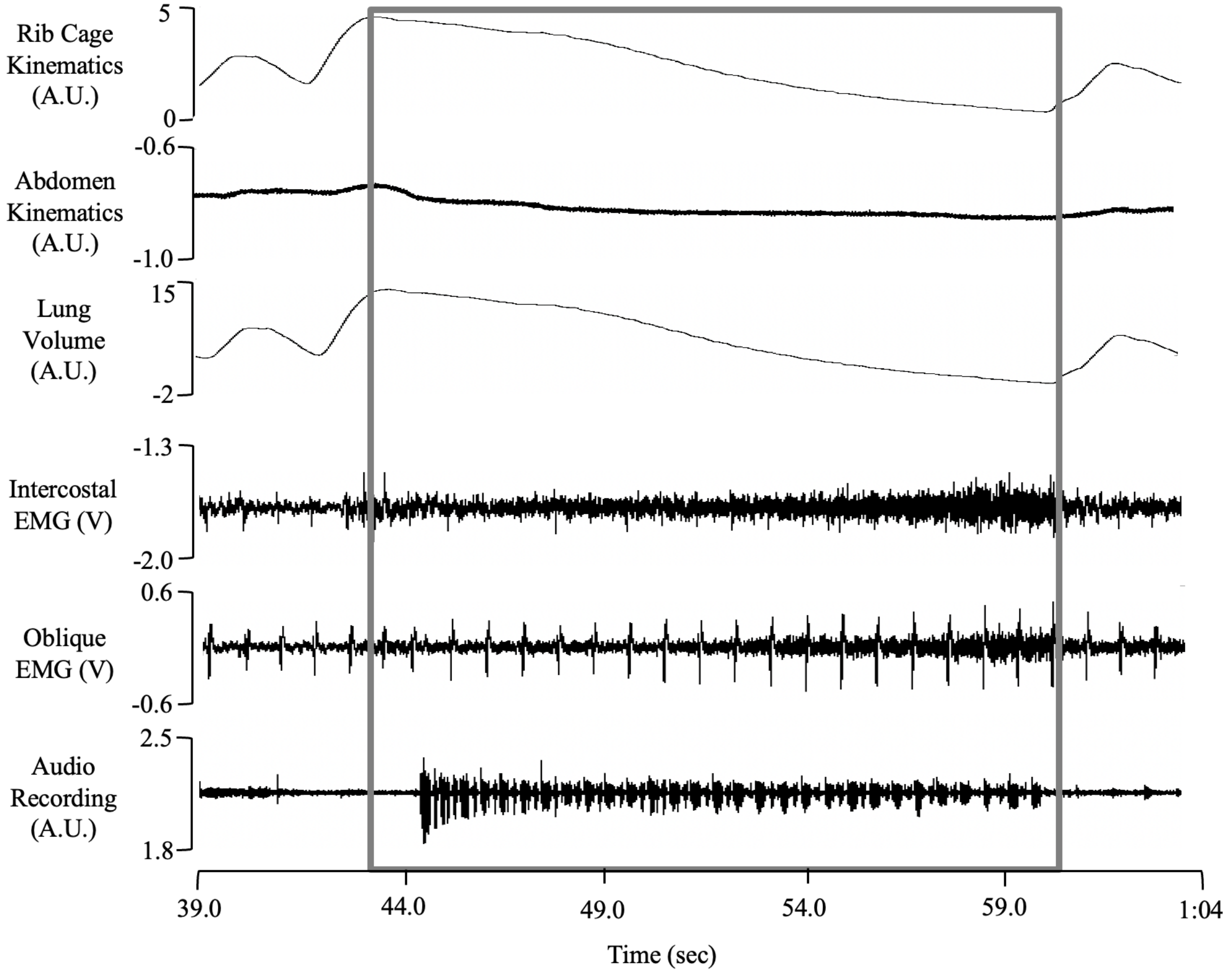

Figure 2.1 Unfiltered data from a representative subject. Simultaneously recorded rib cage (RC) and abdominal (AB) kinematic signals, uncalibrated lung volume (LV) signal used for file segmentation in LabChart (corrected for RC and AB contributions), intercostal (IC) oblique (OB), upper left, lower left, upper right and lower right orbicularis oris (OO) EMG activity, and the acoustic recording during the diadochokinetic task. Expiratory window denoted using box overlay (as measured by the LV signal). A.U. = arbitrary units, V = volts IC = intercostal muscle group; OB = oblique muscle group.

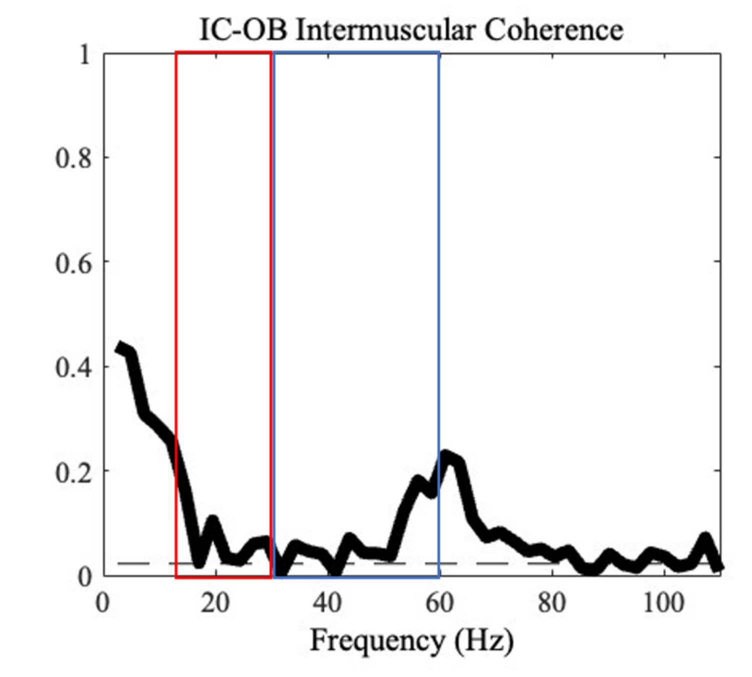

Figure 2.2 Intercostal – Oblique intermuscular coherence for a representative subject for the diadochokinetic (DDK) task. The y and x axes represent intermuscular coherence strength and frequency (Hz), respectively. The red and blue rectangles indicate the 15-30 Hz and 31-60 Hz frequency bandwidths, respectively. The dotted line represents the 95% confidence interval.

Task Performance

Duration and rate measurements of MPD, DDK and TT tasks are reported in Table 2.2. Paired t-tests indicated that a faster rate was achieved in the DDK task relative to TT for both the younger ($p < .002$) and older adults ($p < .002$). Paired t-tests also indicated a significantly longer duration for the MPD task relative to DDK for both younger ($p < .016$) and older ($p < .016$) adults. Mann-Whitney U tests revealed a significantly faster rate in the TT task of younger adults relative to older adults ($p < .004$). No other age related differences were detected.

Table 2.2 *Mean Duration (in seconds) and rate (syllables per second) for maximum phonation duration (MPD) task, diadochokinetic task (DDK) and tongue twisters (TT) task.*

	MPD Duration (sec)	DDK Duration (sec)	DDK Rate (syll/sec)	TT Rate (syll/sec)
Younger adults	20.42 (5.09)	16.87 (5.77)	5.83 (0.74)	3.49 (0.53)
Older adults	19.67 (6.77)	16.17 (3.52)	5.54 (0.91)	2.96 (0.34)

Intermuscular Coherence

Values within beta (15-30 Hz) and gamma (31-60 Hz) frequency bandwidths are reported in Figure 2.3a and 2.3b. Data are presented by task separately for both younger and older adults. As previously stated, violations of normality resulted in the need to conduct separate repeated measures ANOVAs to investigate task related differences in each age group. Between group differences were investigated using independent samples t-tests and Mann Whitney-U tests. Differences between younger and older adult's patterns of IMC across tasks are highlighted below and explored in further detail in the discussion section.

Beta Frequency Bandwidth. In younger adults, repeated measures ANOVA detected a main effect of task ($F_{6,114}$=4.291, *p*< .001). Post hoc testing revealed significantly higher coherence in the PN task relative to VC and DDK tasks (all *p*<0.05). The RB task also had significantly higher coherence than the VC task (*p*< .039).

Repeated measures ANOVA also detected a main effect of task for older adults ($F_{3.77,64.06}$=4.03^{+}, *p*< .006), with post hoc testing revealing significantly higher coherence in the PN task relative to the TT and DDK tasks (all *p*<0.05). The RB task also had significantly higher coherence than the DDK task (*p* < .02) within this age group.

Despite these differences in patterns of IMC between age groups, independent samples t-tests and Mann Whitney-U tests did not detect significant differences between groups.

Gamma Frequency Bandwidth. In younger adults, repeated measures ANOVA detected a main effect of task ($F_{3.42,71.80}$=4.43^{+}, p < .005). Similar to the 15-30 Hz frequency bandwidth, post hoc testing revealed higher IMC in the PN task relative to the VC and DDK tasks (both *p*<0.05).

Repeated measures ANOVA and post hoc testing revealed a similar pattern in older adults. Following a main effect of task ($F_{3.39,74.52}$=4.36^{+}, p < .005), post hoc testing detected significantly higher IMC in the PN task relative to VC and DDK tasks (both *p*<0.05). RB also displayed higher IMC relative to the VC task (*p*<0.05).

Similar to the beta bandwidth, independent samples t-tests and Mann Whitney-U tests did not detect significant differences between age groups in any task.

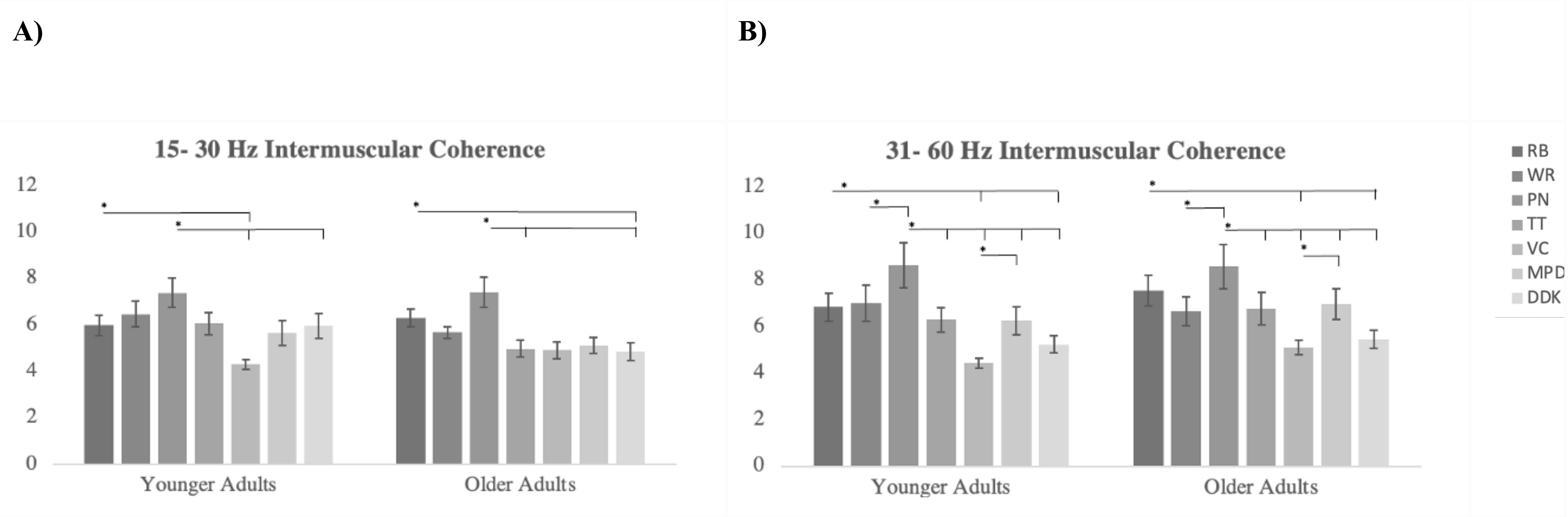

Figure 2.3 *Chest wall Intermuscular coherence (IMC) in younger and older adults. Transformed intermuscular coherence values are represented on the y axis; values are graphed separately by frequency bandwidth. Panels A and B depict intercostal-oblique IMC in the 15-30 Hz and 31-60 Hz frequency bands, respectively. Panels A and B depict intercostal oblique IMC in the 15-30 Hz and 31-60 Hz frequency bands, respectively. Error bars indicate standard deviation of the mean. Asterisks denote significant task related differences within younger and older adult age groups. IC= Intercostals, OB=Obliques, RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, VC=Vital Capacity, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*

Discussion

The purpose of the present study was to examine the effects of varying task demands on IMC of the respiratory subsystem in younger and older healthy adults. Seven speech and nonspeech tasks requiring varying lung volume excursions, tracheal pressures, articulatory demands, and cognitive requirements were used. IMC of intercostals and oblique chest wall muscles in both beta and gamma bandwidths were sensitive to task manipulation with patterns of sensitivity differing for IMC bandwidth and age. In the beta bandwidth, IMC in younger adults showed evidence of a sensitivity to lung volume manipulation, with some small lung volume tasks demonstrating higher coherence relative to some large lung volume tasks. Older adults, however, showed sensitivity in the beta bandwidth to articulatory demands, with high demand tasks such as DDK and TT demonstrating lower coherence relative to some no/low or habitual demand tasks such as RB and PN. In the gamma bandwidth, IMC in both age groups also appeared to be sensitive to lung volume demands, as the RB and PN task demonstrated higher coherence relative to VC and DDK tasks. We describe these differences in IMC from a speech-breathing subsystem perspective and provide interpretation through the lens of what is currently known about neuromuscular control and how these findings expand our existing knowledge of speech motor control in younger and older healthy adults.

Beta Bandwidth (15-30 Hz)

Younger Adults. Previous findings informed our initial hypothesis that tasks requiring larger lung volume excursions would be associated with lower chest wall beta IMC compared to tasks requiring smaller lung volume excursions (Tomczak et al., 2013). Overall, the pattern of findings in younger adults confirms this hypothesis and suggests that the IMC in the beta bandwidth is primarily sensitive to lung volume manipulation. Although there was not a systematic effect of lung volume excursion on IMC across tasks, younger adults demonstrated higher IMC during the RB task compared to the VC task, and higher IMC in the PN versus the VC and DDK tasks.

The mechanism underlying the decrease in IMC with increased lung volume is not well understood. Studies of IMC in the limbs have not shown force-related changes in this frequency bandwidth (Castronovo et al., 2015; Poston et al., 2010; Reyes et al., 2017) as might be involved in larger and smaller lung volume tasks here (See EMG data, Supplemental Materials: Figures S2.4A-B). Studies of limb motor control suggest that beta IMC decreases when the coordinated movement of two muscles requires individuated rather than synergistic control (Laine & Valero-Cuevas, 2017; Reyes et al., 2017). For example, IMC between finger muscles decreases when a person applies pressure to a flexible object (i.e., a spring) compared to an inflexible object (i.e., a dowel) (Laine & Valero-Cuevas, 2017). In that study, the observed decrease in IMC was interpreted as an "unbinding" of motor control as the two fingers must individually respond to changing demands when pressing on a spring in order to maintain control (i.e., individuated control). Conversely, when applying pressure to an inflexible object, researchers propose that the similar motor commands are accomplished using synergistic control by the motor control system. It may be that in the case of the speech breathing, our observed changes in beta band IMC reflect, in part, synergistic muscular control for tasks requiring smaller lung volumes and individuated control for tasks requiring larger lung volumes. This interpretation is supported by our understanding of chest wall mechanics related to small and large lung volume tasks and further described by the present kinematic and EMG results (Supplemental Materials: Figure S2.4A-B). Consistent with previous findings, the small lung volume tasks expended similar amounts of lung volume (i.e., %VC) using similar degrees of muscle contraction (%MVC)

(Hixon et al., 1973, 1976). For tasks requiring small lung volumes, muscle activation patterns of the rib cage and abdomen are distinct from one another, however their peak EMG amplitude (%MVC) is significantly lower than that observed for large lung volume tasks (Clair-Auger et al., 2015; Hixon et al., 1976; Hoit et al., 1988; Mendes et al., 2017). Interpreted within the context of limb literature, this may suggest that the system is able to rely on synergistic neuromuscular control during small lung volume tasks. Although patterns of activation (i.e., onset and offset) were not examined in the present study, existing literature suggests that during the large lung volume tasks such as those included here, the rib cage and abdominal muscles engage in coordinated but distinct patterns of activation as the task transitions from peak expiratory pressures to peak inspiratory pressures (i.e., the top and bottom of the vital capacity, respectively) (Clair-Auger et al., 2015; Hixon et al., 1976; Mendes et al., 2017). Large lung volume maximum performance tasks require neuromuscular regulation of expiration against the backdrop of significantly changing chest wall recoil pressures (Hixon et al., 1976). It follows that individuated muscular control of the intercostal and oblique muscles for these large lung volume maximum performance tasks is reflected in the observed lower IMC here. Moreover, the absence of ICOB beta band sensitivity to manipulations of laryngeal, articulatory and cognitive-linguistic demands further suggests that in younger adults, the respiratory system is able to coordinate these demands without a meaningful shift between individuated versus synergistic control.

Older Adults. The pattern of IMC observed in older adults did not align with the proposed lung volume hypothesis and the patterns observed in younger adults. Instead, beta-band IMC changed relative to articulatory demands. We show higher IMC values for older adults in PN (habitual articulatory demands) relative to TT and DDK (high demand tasks) and higher IMC for RB (no articulatory demands) compared to DDK.

Lower beta IMC values associated with more complex articulatory demands aligns with previous studies of extrinsic laryngeal beta IMC in healthy young adults(Stepp et al., 2011). In that study, decreased laryngeal beta IMC was observed for tasks requiring increased articulatory complexity. More specifically, Stepp and colleagues (2011) found that "hyperfunctional speech" (i.e., speaking as though it were difficult to produce voice) had decreased beta bandwidth IMC relative to "normal speech" in the laryngeal subsystem. As discussed, beta bandwidth IMC is thought represent cortical control of movement, and decreases in this bandwidth have been linked to dynamic movements that require a shift from synergistic to individuated muscle control (de Vries et al., 2016; Laine & Valero-Cuevas, 2017; Nazarpour et al., 2012; Reyes et al., 2017). Interpreted within this context, our data suggest that in older adults, increasing articulatory demands result in a shift in neuromuscular control of the respiratory subsystem.

The mechanism underlying this shift is unclear, however valuable context is gained from the descriptive kinematic and EMG variables presented in Supplementary Materials (Figures S2.1-S2.5). As can be seen in Supplementary Materials Figure S2.2, there may be an overall pattern of decreased speech breathing efficiency in older adults. For example, older adults had higher %VC in the RB, PN and TT tasks relative to younger adults. Consistent with available literature, older adults also had higher %VC/Syll in the WR, TT and DDK tasks (Supplemental Materials: Figures S2.3) and slower articulation rates than younger adults in the TT and DDK tasks (Bilodeau-Mercure & Tremblay, 2016; Bóna, 2014; Hartman & Danhauer, 1976; Hoit & Hixon, 1987; Liss et al., 1990; Ryan, 1972; Smith et al., 1987; Wohlert & Smith, 1998). Increased lung volume excursion per trial and per syllable and slower articulation rates suggest a decline in respiratory and articulatory subsystem efficiency during high articulatory (TT and DDK) tasks (Hoit & Hixon, 1987; Huber & Spruill, 2008). With increasing age, these behavioural changes are also accompanied by changes in signal transmission, characterized by a decrease in the number of motor units(Campbell et al., 1973), changes in neuronal size (Haug & Eggers, 1991), and glutamate uptake capacity (Segovia et al., 2001). Interpreted within these findings, the pattern of IMC observed within older adults suggests that these behavioural and physiological changes are accompanied by changes in neuromuscular control of the respiratory subsystem within the speech mechanism.

Gamma Bandwidth (31-60 Hz)

Based on previous work, it was hypothesized that large lung volume tasks produced with tracheal pressure requirements (i.e., MPD and DDK) would have higher chest wall IMC compared to large lung volume tasks without tracheal pressure requirements (i.e., VC) (Boliek et al., 2019). The results of the present study did not reveal any differences in gamma bandwidth IMC between the large lung volume tasks used. Thus, our initial hypothesis was not supported. The difference between the present and Boliek et al., 2019 study may be analysis-based in nature. Boliek and colleagues (2019) analyzed chest wall IMC across beta and gamma frequency bandwidths (i.e., 15-60Hz) and did not include a correction for task duration. By analyzing the two frequency bandwidths separately, we may gain additional insight into neuromuscular control of the chest wall.

The absence of a difference between large lung volume tasks with and without tracheal pressure requirements provides further insight into our understanding of chest wall coordination. The gamma bandwidth is thought to represent subcortical involvement in motor control (De Marchis et al., 2015; Kenville et al., 2020; Mohr et al., 2015, 2018; Nishimura et al., 2009; von Tscharner et al., 2018). These studies of limb motor control suggest that higher IMC values in this frequency are associated with novel and/or more complex tasks mediated by the integrative subcortical processes needed for these movements. Interpreted within this context, the present results suggest that coordination between laryngeal and respiratory subsystems may not result in increased involvement of subcortical systems as demonstrated by similar IMC values across these tasks in younger adults. This interpretation aligns with our current understanding of the high degree of integration between respiratory and laryngeal subsystems (Davis et al., 1992; Dromey & Ramig, 1998b, 1998a; Peters & Boves, 1988; Stathopoulos & Sapienza, 1993). Indeed, these systems exhibit considerable overlap in their neural control mechanisms, with both being commanded via central pattern generators during metabolic breathing and cortical control centers coordinating speech production (Guyenet & Bayliss, 2016; Levitzky, 2017; Loucks et al., 2007). It is possible then, that the integration between these two subsystems allows for the speech mechanism to mediate the shift between tasks with and without tracheal pressure demands without a significant change in sensory information integration, as measured by gamma bandwidth IMC.

Lung Volume Effects. Consistent with patterns detected in the beta bandwidth for younger adults, younger and older adults demonstrated changes in gamma bandwidth IMC associated with lung volume manipulation. In younger and older adults, IMC during the PN task was higher than during VC and DDK. Older adults also had significantly higher gamma bandwidth IMC in the RB task relative to the VC task. The pattern of higher IMC for small lung volume tasks does not align with our existing understanding of the effects of task novelty and/or complexity on gamma bandwidth IMC (De Marchis et al., 2015; Kenville et al., 2020; Mohr et al., 2015, 2018; Nishimura et al., 2009; von Tscharner et al., 2018). Our understanding of gamma bandwidth sensitivity is based on limb motor control literature, where complexity is used as a descriptor for tasks that are motorically difficult to execute. Applied to the context of the respiratory system, we would have expected the more complicated large lung volume tasks to have higher IMC than the motorically less complex small lung volume tasks.

The higher IMC observed in small lung volume tasks also does not align with our knowledge of subcortical involvement in small versus large lung volume tasks. Although subcortical structures have been demonstrated to play a role in both the voluntary and involuntary control of breathing (Mckay et al., 2003; Pattinson, 2008), neuroimaging studies suggest that larger lung volume tasks produced with and without phonation or articulatory demands, result in increases in subcortical activation relative to rest breathing (Loucks et al., 2007).

Role of Cognitive Linguistic Factors. An alternative explanation to the gamma bandwidth findings involves separate consideration of the contribution of lung volume versus cognitive-linguistic load. In other words, it is possible that the difference between RB versus VC and DDK observed in older adults is driven by lung volume differences, whereas the differences observed between PN versus VC and DDK tasks are the result of a separate phenomena, namely cognitive-linguistic load. It may be that the difference in IMC during the PN task suggests a difference in neuromuscular drive in response to the unique cognitive-linguistic demands of the PN task (i.e., naming an object or action). Interpreted within existing limb literature, this finding may suggest that the PN task is associated with an increase in subcortical involvement and/or sensorimotor integrative processes, as has previously been hypothesized to occur during novel or complex tasks (De Marchis et al., 2015; Kenville et al., 2020; Mohr et al., 2015, 2018; Nishimura et al., 2009; von Tscharner et al., 2018). This interpretation would be in line with the current understanding of the neurological underpinnings of picture naming tasks relative to word reading tasks. More specifically, it has long been established that reaction times for picture naming tasks are significantly longer than word reading tasks and, although the intricacies continue to be debated, the difference in reaction time is generally thought to be attributable to the need to retrieve semantic information prior to initiating the appropriate lexical target (Cattell, 1885; Coltheart et al., 1993; Glaser, 1992; Price et al., 2006). Neuroimaging studies suggest that both tasks involve overlapping regions of activation of cortical and subcortical areas; however each task is linked to differences in amount and/or timing of activity (Price, 2012; Valente et al., 2016). The pattern of IMC observed in the present study may provide preliminary evidence that this distal measure of neuromuscular control is sensitive to the upstream processes involved in executing task performance.

Conclusion

The present findings suggest that IMC warrants further investigation as a tool to understand speech motor control. Building on existing work in the respiratory subsystem, we demonstrated that beta and gamma frequency bandwidths are primarily sensitive to the demands of lung volume, although important differences related to articulatory demand and cognitive-linguistic load were also explored. Our work also established key age-related differences in patterns of chest wall IMC in the beta bandwidth. Future studies investigating the reliability of IMC of the chest wall and establishing its relationship to performance are needed.

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References

Ackerson, L. M., & Bruce, E. N. (1983). Bilaterally synchronized oscillations in human diaphragm and intercostal EMGs during spontaneous breathing. *Brain Research*, *271*(2), 346–348. https://doi.org/10.1016/0006-8993(83)90299-8

Bilodeau-Mercure, M., & Tremblay, P. (2016). Age Differences in Sequential Speech Production: Articulatory and Physiological Factors. *Journal of the American Geriatrics Society*, *64*(11), e177–e182. https://doi.org/10.1111/jgs.14491

Boliek, C. A., Bakhtiari, R., Pedersen, L., Esch, J., & Cummine, J. (2019). Differential cortical control of chest wall muscles during pressure- and volume-related expiratory tasks and the effects of acute expiratory threshold loading. *Motor Control*, *23*(1), 13–33. https://www.ncbi.nlm.nih.gov/pubmed/29902955

Bóna, J. (2014). Temporal characteristics of speech: The effect of age and speech style. *The Journal of the Acoustical Society of America*, *136*(2), EL116–EL121. https://doi.org/10.1121/1.4885482

Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. *Frontiers in Human Neuroscience*, *7*(DEC), 1–2. https://doi.org/10.3389/FNHUM.2013.00855

Bruce, E. N., & Ackerson, L. M. (1986). High-frequency oscillations in human electromyograms during voluntary contractions. *Journal of Neurophysiology*, *56*(2), 542–553. http://www.ncbi.nlm.nih.gov/pubmed/3760934

Campbell, M. J., McComas, A. J., & Petito, F. (1973). Physiological changes in ageing muscles. *Journal of Neurology, Neurosurgery, and Psychiatry*, *36*(2), 174–182. https://doi.org/10.1136/JNNP.36.2.174

Castronovo, A. M., Negro, F., Conforto, S., & Farina, D. (2015). The proportion of common synaptic input to motor neurons increases with an increase in net excitatory input. *Journal of Applied Physiology*, *119*(11), 1337–1346. https://doi.org/10.1152/japplphysiol.00255.2015

Cattell, J. M. (1885). Ueber die Zeit der Erkennung und Benennung von Schriftzeichen, Bildern und Farben. *Philosophische Studien*, *2*, 635–650. https://www.mpi.nl/publications/item2309357/ueber-die-zeit-der-erkennung-und-benennung-von-schriftzeichen-bildern-und

Chang, Y. J., Chou, C. C., Chan, H. L., Hsu, M. J., Yeh, M. Y., Fang, C. Y., Chuang, Y. F., Wei, S. H., & Lien, H. Y. (2012). Increases of Quadriceps Inter-Muscular Cross-Correlation and Coherence during Exhausting Stepping Exercise. *Sensors 2012, Vol. 12, Pages 16353-16367*, *12*(12), 16353–16367. https://doi.org/10.3390/S121216353

Clair-Auger, J. M., Gan, L. S., Norton, J. A., & Boliek, C. A. (2015). Simultaneous Measurement of Breathing Kinematics and Surface Electromyography of Chest Wall Muscles during Maximum Performance and Speech Tasks in Children: Methodological Considerations. *Folia Phoniatrica et Logopaedica*, *67*(4), 202–211. https://doi.org/10.1159/000441326

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of Reading Aloud: Dual-Route and Parallel-Distributed-Processing Approaches. *Psychological Review*, *100*(4), 589–608. https://doi.org/10.1037/0033-295X.100.4.589

Davis, P. J., Bartlett, D., & Luschei, E. S. (1992). Coordination of the Respiratory and Laryngeal Systems in Breathing and Vocalization. *NCVC Status and Progress Report*, 59–81.

De Marchis, C., Severini, G., Castronovo, A. M., Schmid, M., & Conforto, S. (2015). Intermuscular coherence contributions in synergistic muscles during pedaling. *Experimental Brain Research*, *233*(6), 1907–1919. https://doi.org/10.1007/S00221-015-4262-4/METRICS

de Vries, I. E. J., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, *116*(6), 2576–2585. https://doi.org/10.1152/jn.00460.2016

Denny, M., & Smith, A. (2000). Respiratory control in stuttering speakers: evidence from respiratory high-frequency oscillations. *Journal of Speech, Language, and Hearing Research*, *43*(4), 1024–1037. http://www.ncbi.nlm.nih.gov/pubmed/11386469

Dromey, C., & Ramig, L. O. (1998a). Intentional Changes in Sound Pressure Level and Rate: Their Impact on Measures of Respiration, Phonation, and Articulation. In *Journal of Speech Language and Hearing Research* (Vol. 41, Issue October, pp. 1003–1018). https://doi.org/10.1044/jslhr.4105.1003

Dromey, C., & Ramig, L. O. (1998b). The Effect of Lung Volume on Selected Phonatory and Articulatory Variables. *Journal of Speech, Language, and Hearing Research*, *41*(3), 491–502. https://doi.org/10.1044/jslhr.4103.491

Farmer, S. F., Gibbs, J., Halliday, D. M., Harrison, L. M., James, L. M., Mayston, M. J., & Stephens, J. A. (2007). Changes in EMG coherence between long and short thumb abductor muscles during human development. *Journal of Physiology*, *579*(2), 389–402. https://doi.org/10.1113/jphysiol.2006.123174

Glaser, W. R. (1992). Picture naming. *Cognition*, *42*(1–3), 61–105. https://doi.org/10.1016/0010-0277(92)90040-O

Grosse, P., Cassidy, M. J., & Brown, P. (2002). EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: Physiological principles and clinical applications. *Clinical Neurophysiology*, *113*, 1523–1531. https://doi.org/10.1016/S1388-2457(02)00223-7

Guyenet, P. G., & Bayliss, D. A. (2016). Neural control of breathing and CO2 homeostasis. 25(3), 289–313. https://doi.org/10.1007/s11065-015-9294-9.Functional

Hartman, D. E., & Danhauer, J. L. (1976). Perceptual features of speech for males in four perceived age decades. *The Journal of the Acoustical Society of America*, *59*(3), 713–715. https://doi.org/10.1121/1.380894

Haug, H., & Eggers, R. (1991). Morphometry of the human cortex cerebri and corpus striatum during aging. *Neurobiology of Aging*, *12*(4), 336–338. http://www.ncbi.nlm.nih.gov/pubmed/1961364

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the Chest Wall during Speech Production: Volume Displacements of the Rib Cage, Abdomen, and Lung. *Journal of Speech and Hearing Research*, *16*(1), 78–115. https://doi.org/10.1044/jshr.1601.78

Hixon, T. J., Mead, J., & Goldman, M. D. (1976). Dynamics of the chest wall during speech production: function of the thorax, rib cage, diaphragm, and abdomen. *Journal of Speech and Hearing Research*, *19*(2), 297–356. https://doi.org/10.1044/jshr.1902.297

Hoit, J. D., & Hixon, T. J. (1987). Age and Speech Breathing. *Journal of Speech and Hearing Research*, *30*, 351–366.

Hoit, J. D., Hixon, T. J., Altman, M. E., & Morgan, W. J. (1989). Speech breathing in women. *Journal of Speech and Hearing Research*, *32*(2), 353–365. https://doi.org/10.1044/JSHR.3202.353

Hoit, J. D., Plassman, B. L., Lansing, R. W., & Hixon, T. J. (1988). Abdominal muscle activity during speech production. *Journal of Applied Physiology*, *65*(6), 2656–2664. https://doi.org/10.1152/jappl.1988.65.6.2656

Huber, J. E. (2008). Effects of Utterance Length and Vocal Loudness on Speech Breathing in Older Adults. *Respiratory, Physiology and Neurobiology*, *164*(3), 323–330. https://doi.org/10.1016/j.resp.2008.08.007.Effects

Huber, J. E., & Spruill III, J. (2012). Age-Related Changes to Speech Breathing with Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047).Age-Related

Huber, J. E., & Spruill, J. (2008). Age-Related Changes to Speech Breathing With Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047)

Jaiser, S. R., Baker, M. R., & Baker, S. N. (2016). Intermuscular coherence in normal adults: Variability and changes with age. *PLoS ONE*, *11*(2), 1–16. https://doi.org/10.1371/journal.pone.0149029

Kent, R. D. (2000). Research on Speech Motor Control and Its Disorders: a Review and Prospective. *Journal of Communication Disorders*, *33*, 391–428. https://doi.org/10.1016/S0021-9924(00)00023-X

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020). Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, *124*(4), 1045–1055. https://doi.org/10.1152/JN.00231.2020

Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, *118*(3), 1775–1783. https://doi.org/10.1152/jn.00204.2017

Liss, J. M., Weismer, G., & Rosenbek, J. C. (1990). Selected Acoustic Characteristics of Speech Production in Very Old Males. *Journal of Gerontology*, *45*(2), P35–P45. https://doi.org/10.1093/geronj/45.2.P35

Levitzky M.G.(Ed.), (2017). *Pulmonary Physiology, 9e*. McGraw Hill. https://accessmedicine-mhmedical-com.login.ezproxy.library.ualberta.ca/content.aspx?bookid=2288&sectionid=178857560

Loucks, T. M. J., Poletto, C. J., Simonyan, K., Reynolds, C. L., & Ludlow, C. L. (2007). Human brain activation during phonation and exhalation : Common volitional control for two upper airway functions. *Human Brain Mapping Journal*, *36*, 131–143. https://doi.org/10.1016/j.neuroimage.2007.01.049

McFarland, D. H., & Smith, A. (1989). Surface recordings of respiratory muscle activity during speech: some preliminary findings. *Journal of Speech and Hearing Research*, *32*(3), 657–667. http://www.ncbi.nlm.nih.gov/pubmed/2779209

Mckay, L. C., Evans, K. C., Frackowiak, R. S. J., & Corfield, D. R. (2003). *Neural correlates of voluntary breathing in humans*. 1170–1178.

Mendes, A., Ferreira, L., Jorge, A., Rothman, H., Tavares, D., & Garcez, I. (2017). Respiratory physiology during reading aloud tasks. *Distúrbios Da Comunicação*, *29*(3), 519–528. https://doi.org/10.23925/2176-2724.2017v29i3p519-528

Mima, T., & Hallett, M. (1999). Corticomuscular coherence: a review. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *16*(6), 501–511. https://doi.org/10.1097/00004691-199911000-00002

Mitchell, H. L., & Hoit, J. D. (1996). Cognitive-Linguistic Demands and Speech Breathing. *Journal of Speech, Language, and Hearing Research*, *39*(1), 93–104. https://doi.org/10.1044/jshr.3901.93

Mohr, M., Nann, M., Von Tscharner, V., Eskofier, B., & Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *PLOS ONE*, *10*(11), e0142048. https://doi.org/10.1371/JOURNAL.PONE.0142048

Mohr, M., Schön, T., von Tscharner, V., & Nigg, B. M. (2018). Intermuscular coherence between surface EMG signals is higher for monopolar compared to bipolar electrode configurations. *Frontiers in Physiology*, *9*(MAY), 566. https://doi.org/10.3389/FPHYS.2018.00566/BIBTEX

Nazarpour, K., Barnard, A., & Jackson, A. (2012). Flexible cortical control of task-specific muscle synergies. *Journal of Neuroscience*, *32*(36), 12349–12360. https://doi.org/10.1523/JNEUROSCI.5481-11.2012

Nip, I. S. B., & Green, J. R. (2013). Increases in Cognitive and Linguistic Processing Primarily Account for Increases in Speaking Rate With Age. *Child Development*, *84*(4), 1324–1337. https://doi.org/10.1111/CDEV.12052

Nishimura, Y., Morichika, Y., & Isa, T. (2009). A subcortical oscillatory network contributes to recovery of hand dexterity after spinal cord injury. *Brain*, *132*(3), 709. https://doi.org/10.1093/BRAIN/AWN338

Norton, J. A., & Gorassini, M. (2006). Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *Journal of Neurophysiology*, *95*, 2580–2589. https://doi.org/10.1152/jn.01289.2005

Omlor, W., Patino, L., Hepp-Reymond, M. C., & Kristeva, R. (2007). Gamma-range corticomuscular coherence during dynamic force output. *NeuroImage*, *34*(3), 1191–1198. https://doi.org/10.1016/J.NEUROIMAGE.2006.10.018

Pattinson, K. T. S. (2008). Opioids and the control of respiration. *British Journal of Anaesthesia*, *100*(6), 747–758. https://doi.org/10.1093/BJA/AEN094

Peters, H. F. M., & Boves, L. (1988). Coordination of Aerodynamic and Phonatory Processes in Fluent Speech Utterances of Stutterers. *Journal of Speech and Hearing Research*, *31*(3), 352–361. https://doi.org/10.1044/JSHR.3103.352

Poletto, C. J., Verdun, L. P., Strominger, R., & Ludlow, C. L. (2004). Correspondence between laryngeal vocal fold movement and muscle activity during speech and nonspeech gestures. *Journal of Applied Physiology*, *97*(3), 858–866. https://doi.org/10.1152/japplphysiol.00087.2004

Poston, B., Santos, A. D. Dos, Jesunathadas, M., Hamm, T. M., & Santello, M. (2010). Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping. *Journal of Neurophysiology*, *104*(2), 1141–1154. https://doi.org/10.1152/JN.00185.2010/ASSET/IMAGES/LARGE/Z9K0081002390008.JPEG

Price, C. J. (2012). A review and synthesis of the first 20years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, *62*(2), 816–847. https://doi.org/10.1016/j.neuroimage.2012.04.062

Price, C. J., McCrory, E., Noppeney, U., Mechelli, A., Moore, C. J., Biggio, N., & Devlin, J. T. (2006). How reading differs from object naming at the neuronal level. *NeuroImage*, *29*(2), 643–648. https://doi.org/10.1016/J.NEUROIMAGE.2005.07.044

Quanjer, P. H., Stanojevic, S., Cole, T. J., Baur, X., Hall, G. L., Culver, B. H., Enright, P. L., Hankinson, J. L., Ip, M. S. M., Zheng, J., Stocks, J., & Schindler, C. (2012). Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. *The European Respiratory Journal*, *40*(6), 1324–1343. https://doi.org/10.1183/09031936.00080312

Reed, A., Cummine, J., Bhat, N., Jhala, S., Bakhtiari, R., & Boliek, C. A. (2021). Changes in Intermuscular Coherence as a Function of Age and Phase of Speech Production During an Overt Reading Task. *Motor Control*, *25*(2), 295–314. https://doi.org/10.1123/MC.2020-0003

Reyes, A., Laine, C. M., Kutch, J. J., & Valero-Cuevas, F. J. (2017). Beta Band Corticomuscular Drive Reflects Muscle Coordination Strategies. *Frontiers in Computational Neuroscience*, *11*(April), 1–10. https://doi.org/10.3389/fncom.2017.00017

Riès, S., Legou, T., Burle, B., Alario, F. X., & Malfait, N. (2012). Why does picture naming take longer than word reading? The contribution of articulatory processes. *Psychonomic Bulletin & Review*, *19*(5), 955–961. https://doi.org/10.3758/S13423-012-0287-X

Rosenberg, J. R., Amjad, A. M., Breeze, P., Brillinger, D. R., & Halliday, D. M. (1989). The Fourier approach to the identification of functional coupling between neuronal spike trains. *Progress in Biophysics and Molecular Biology*, *53*(1), 1–31. https://doi.org/10.1016/0079-6107(89)90004-7

Ryan, W. J. (1972). Acoustic aspects of the aging voice. *Journal of Gerontology*, *27*(2), 265–268. https://doi.org/10.1093/geronj/27.2.265

Segovia, G., Porras, A., Del Arco, A., & Mora, F. (2001). Glutamatergic neurotransmission in aging: A critical perspective. *Mechanisms of Ageing and Development*, *122*, 1–29. https://doi.org/10.1016/S0047-6374(00)00225-6

Semmler, J. G., Kornatz, K. W., & Enoka, R. M. (2006). Motor-Unit Coherence During Isometric Contractions Is Greater in a Hand Muscle of Older Adults. *Journal of Neurophysiology*, *90*(2), 1346–1349. https://doi.org/10.1152/jn.00941.2002

Smith, A., & Denny, M. (1990). High-frequency oscillations as indicators of neural control mechanisms in human respiration, mastication, and speech. *Journal of Neurophysiology*, *63*(4), 745–758.

Smith, Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech and Hearing Research*, *30*(4), 522–529. http://www.ncbi.nlm.nih.gov/pubmed/3695445

Sperry, E. E., & Klich, R. J. (1992). Speech breathing in senescent and younger women during oral reading. *Journal of Speech and Hearing Research*, *35*(6), 1246–1255. https://doi.org/10.1044/JSHR.3506.1246

Stathopoulos, E. T., & Sapienza, C. (1993). Respiratory and laryngeal function of women and men during vocal intensity variation. *Journal of Speech and Hearing Research*, *36*(1), 64–75. https://doi.org/10.1044/JSHR.3601.64

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & Mcmurtrey, J. R. (2008). Babbling, Chewing, and Sucking: Oromandibular Coordination at 9 Months. *Journal of Speech Language and Hearing Research*, *51*(December), 1390–1405.

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2011). Modulation of neck intermuscular Beta coherence during voice and speech production. *Journal of Speech, Language, and Hearing Research*, *54*, 836–844. https://doi.org/10.1044/1092-4388(2010/10-0139)

Tomczak, C. R., Greidanus, K. R., & Boliek, C. A. (2013). Modulation of chest wall intermuscular coherence: effects of lung volume excursion and transcranial direct current stimulation. *Journal of Neurophysiology*, *110*, 680–687. https://doi.org/10.1152/jn.00723.2012

United Nations. (2015). *World Population Ageing United Nations*.

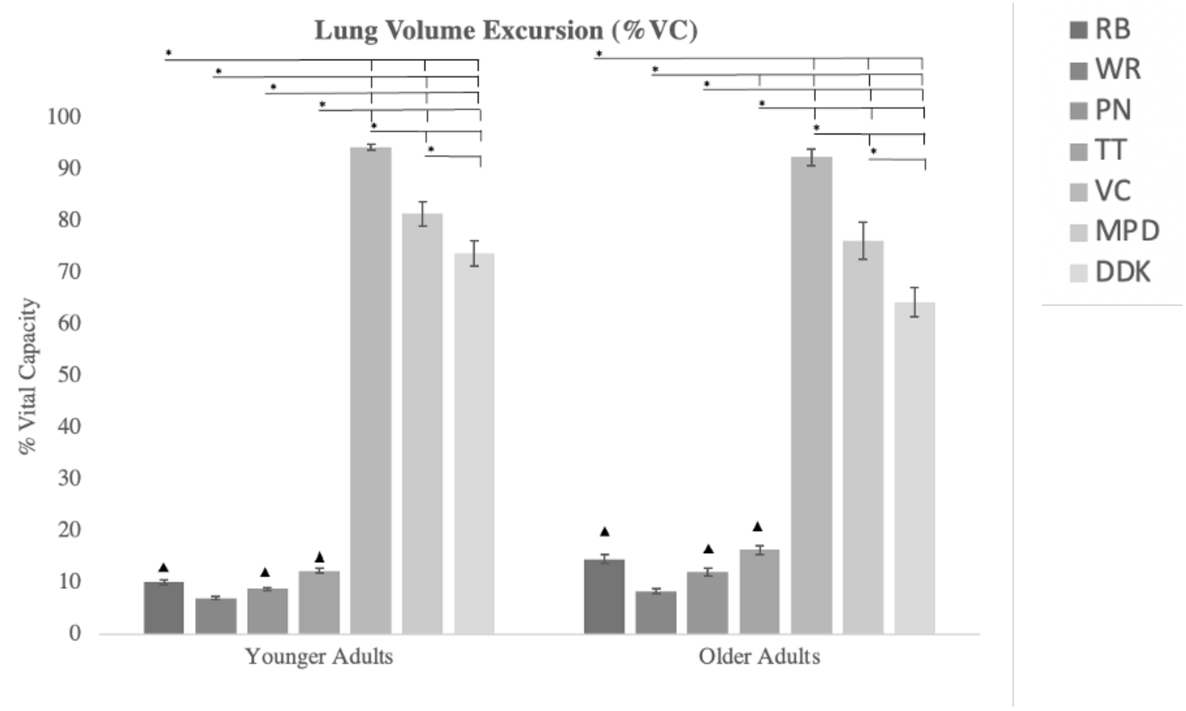
Valente, A., Pinet, S., Alario, F. X., & Laganaro, M. (2016). “When” does picture naming take longer than word reading? *Frontiers in Psychology*, *7*(JAN), 31. https://doi.org/10.3389/FPSYG.2016.00031/BIBTEX

von Tscharner, V., Ullrich, M., Mohr, M., Comaduran Marquez, D., & Nigg, B. M. (2018). Beta, gamma band, and high-frequency coherence of EMGs of vasti muscles caused by clustering of motor units. *Experimental Brain Research*, *236*(11), 3065–3075. https://doi.org/10.1007/S00221-018-5356-6/METRICS

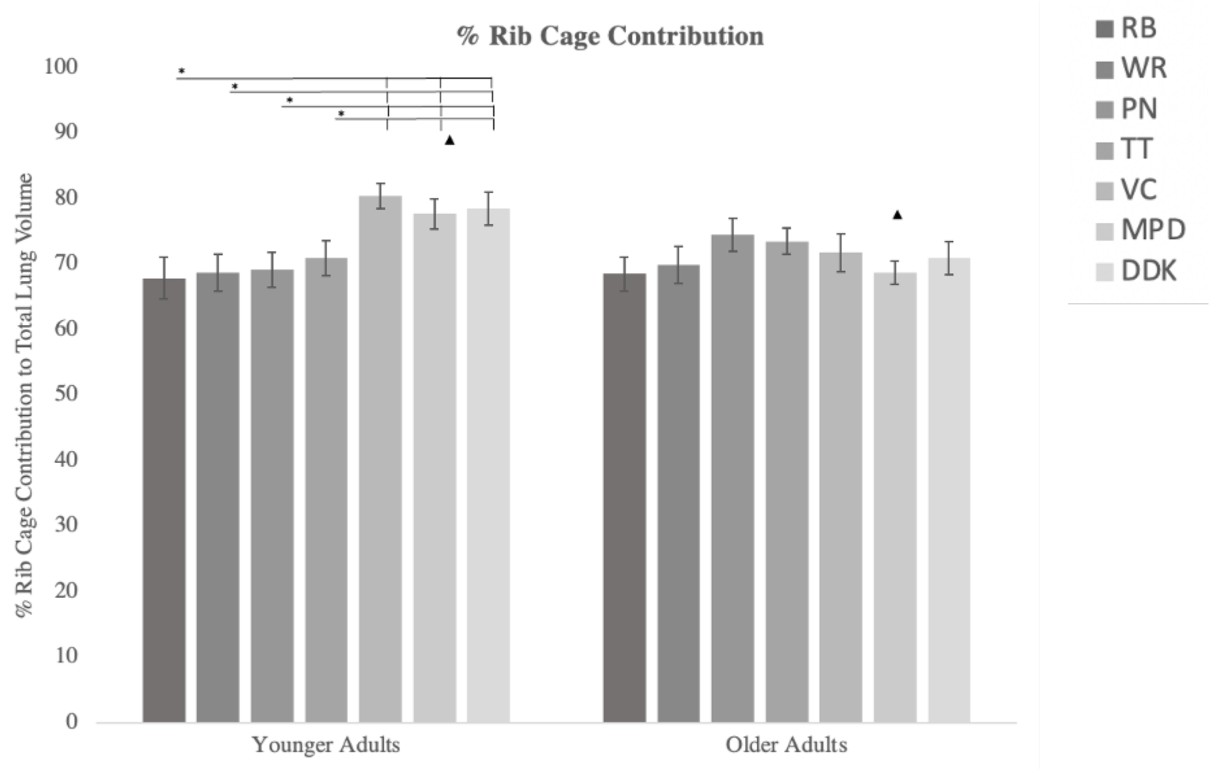
Wang, Y. T., Green, J. R., Nip, I. S. B., Kent, R. D., & Kent, J. F. (2010). Breath Group Analysis for Reading and Spontaneous Speech in Healthy Adults. *Folia Phoniatrica et Logopaedica*, *62*(6), 297–302. https://doi.org/10.1159/000316976

Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *Journal of Speech, Language, and Hearing Research : JSLHR*, *41*(1), 41–50. http://www.ncbi.nlm.nih.gov/pubmed/9493732

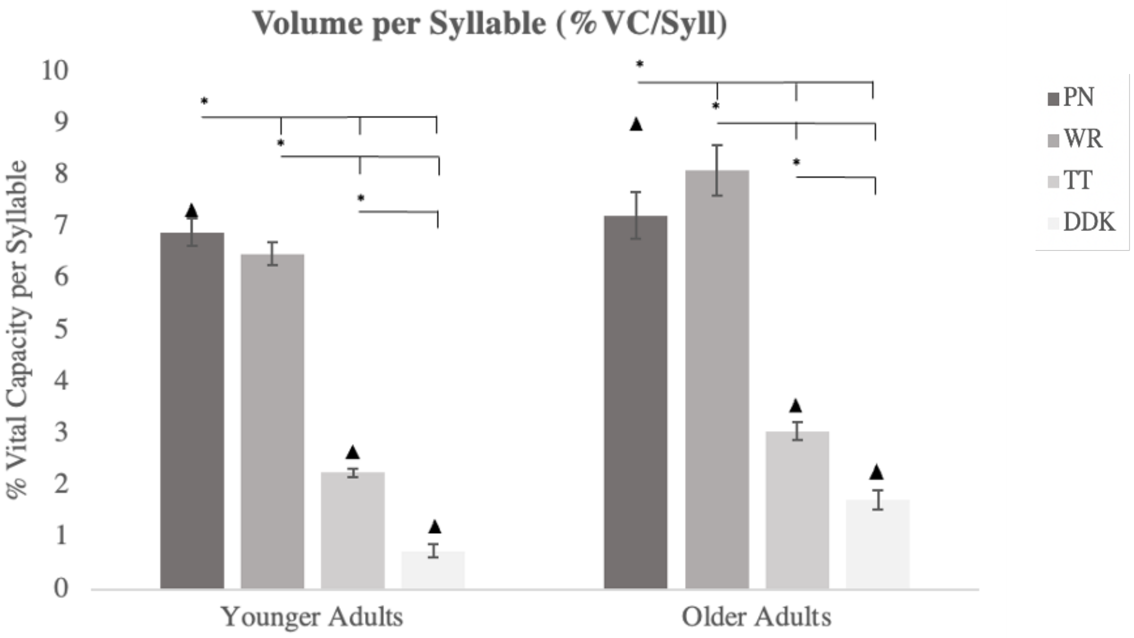
Supplemental Documents



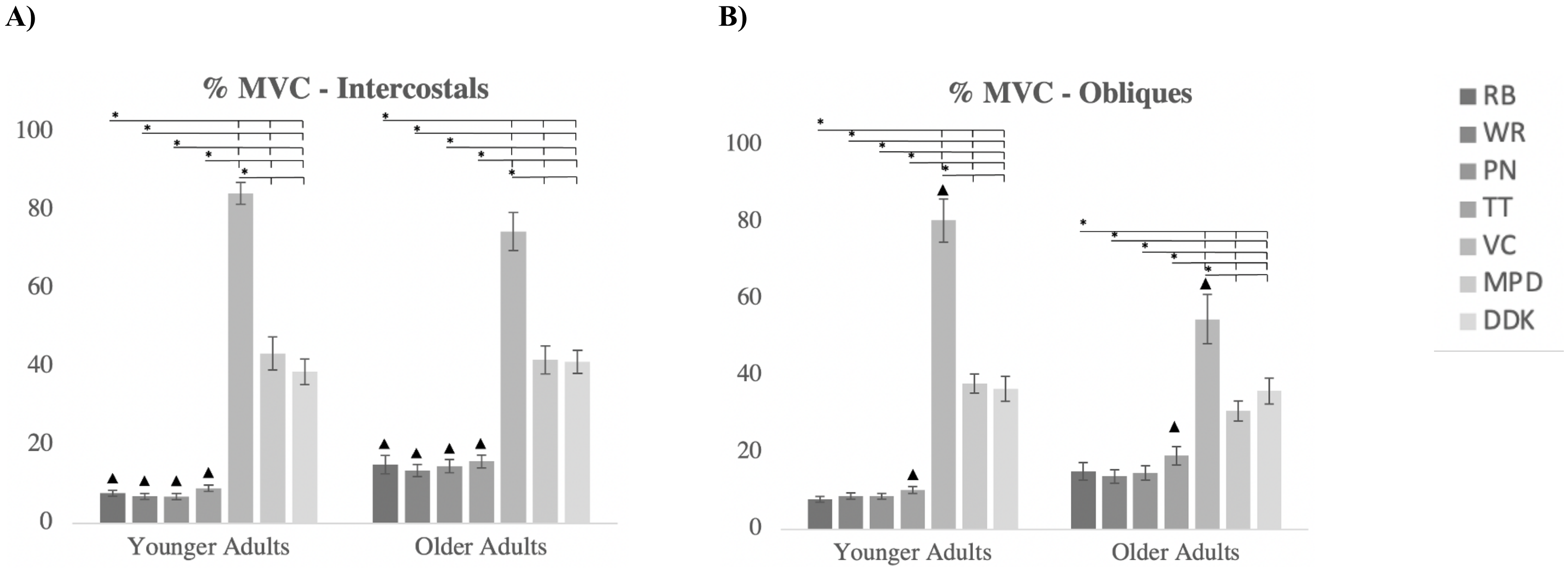
Supplemental Figure S2.1 *Lung volume excursion expressed as a percentage of vital capacity for younger and older adults. Repeated measures ANOVA conducted within younger and older adults indicated a main effect of the task (* $F_{2.11,42.21}=1175.50^{+}$ *p<0.001;* $F_{2.22,44.49}=321.59$*, p<0.001, respectively). Error bars indicate standard deviation. Task related differences meeting statistical significance (p <.05 corrected) are denoted with an asterisks. Age group differences meeting statistical significance (p <.05 corrected) are denoted with a triangle. RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*



Supplemental Figure S2.2 *Percent rib cage (%RC) contribution to total lung volume for younger and older adults. Repeated measures ANOVA revealed a main effect of task on %RC contribution in younger adults ($F_{2.81,72.93}=11.73^{+}$, $p<0.001$); no significant differences detected across tasks in older adults. Task related differences meeting statistical significance ($p<.05$ corrected) are denoted with an asterisks. Age group differences meeting statistical significance ($p<.05$ corrected) are denoted with a triangle. RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*



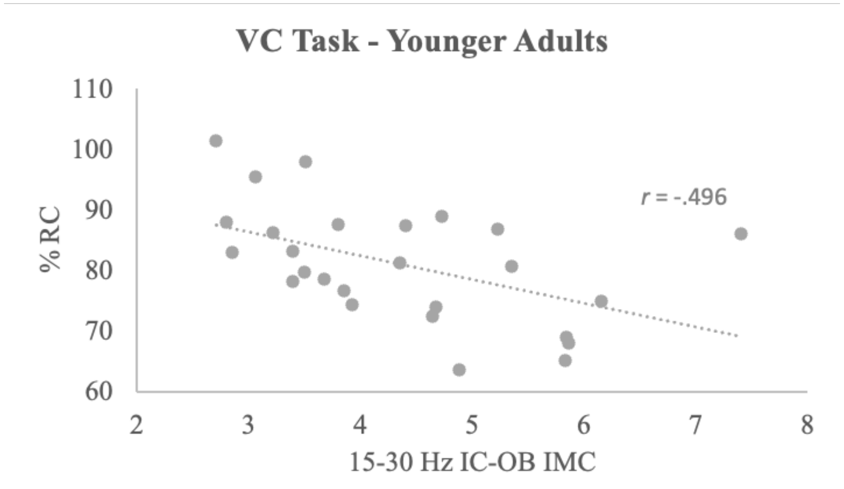
Supplemental Figure S2.3 *Percent vital capacity per syllable (%VC/SYLL) for younger and older adults. Repeated measures ANOVAs revealed a main effect of task on %VC/SYLL within both younger and older adults ($F_{2.08,47.89}$=359.39^{+}, p<0.001; $F_{1.91,45.83}$=113.02^{+}, p<0.001, respectively). Task related differences meeting statistical significance (p <.05 corrected) are denoted with an asterisks. Age group differences meeting statistical significance (p <.05 corrected) are denoted with a triangle. RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*



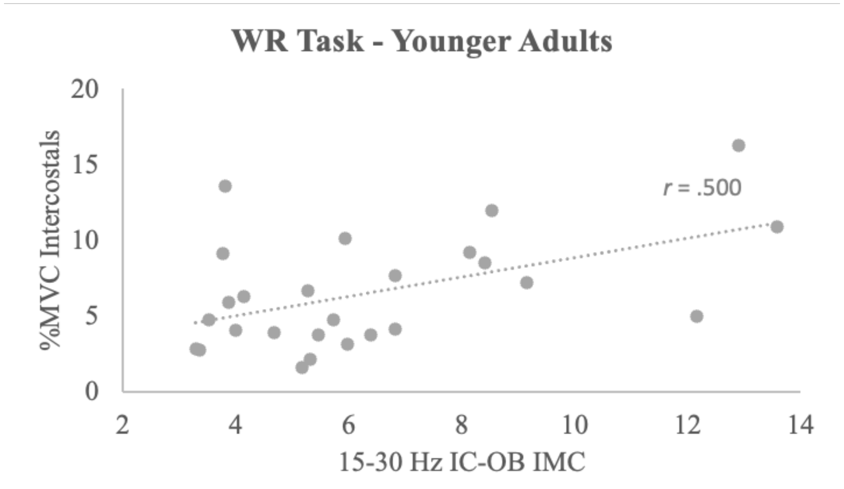
A)
% MVC - Intercostals
100
80
60
40
20
0
Younger Adults
Older Adults
B)
% MVC - Obliques
100
80
60
40
20
0
Younger Adults
Older Adults
RB
WR
PN
TT
VC
MPD
DDK

Supplemental Figure S2.4 *Muscle contraction of the Intercostals (A) and Oblique (B) muscles of the chest wall, expressed as a percent maximum voluntary contraction (%MVC) in younger and older adults. Repeated measures ANOVAs found a main effect of task for the intercostals in both younger and older adults (*$F_{2.11,44.37}=168.64^{+}$*, p< .001;* $F_{2.53,58.2}=106.22^{+}$*, p< .001, respectively). Repeated measures ANOVAs also found a main effect of task for the obliques in both younger and older adults (*$F_{1.78,39.23}=97.51^{+}$*, p< .001;* $F_{1.61,36.98}=30.84^{+}$*, p< .001, respectively). Error bars indicate standard error of the mean. Asterisks denote significant task related differences within younger and older adult age groups. Triangles above task bars indicate a significant difference between age groups. RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task*

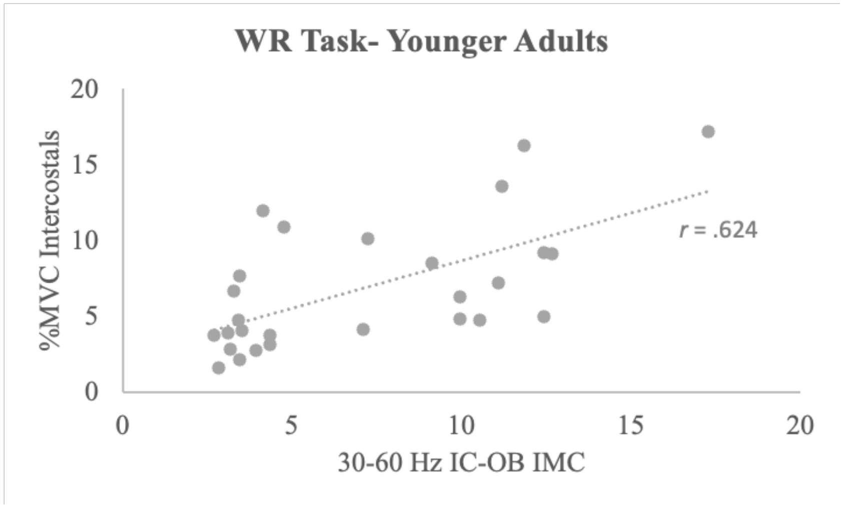
A)


VC Task - Younger Adults
110
100
90
80
70
60
% RC
r = -.496
2
3
4
5
6
7
8
15-30 Hz IC-OB IMC

B)


WR Task - Younger Adults
20
15
10
5
0
%MVC Intercostals
r = .500
2
4
6
8
10
12
14
15-30 Hz IC-OB IMC

C)


WR Task- Younger Adults
20
15
10
5
0
%MVC Intercostals
r = .624
0
5
10
15
20
30-60 Hz IC-OB IMC

Supplemental Figure S2.5 A-C. *Significant correlations between variables in younger and older adults. Transformed intermuscular coherence values are represented on the x axis. Pearson correlations were used to investigate whether intermuscular coherence is related to measures of subsystem performance, including maximum voluntary contraction and task performance. Within younger adults there was a negative correlation between percent rib cage contribution to total lung volume and ICOB coherence in the 15-30 Hz frequency bandwidth during the vital capacity task (r= -.496, p<.04; Panel A). In the WR task, significant positive correlations were detected between %MVC of the intercostal muscles and ICOB coherence in the 15-30 Hz (r= .500, p<.045; Panel B) and 31-60 Hz (r= .624 p<.005; Panel C) frequency bandwidths. These correlations were not detected in older adults. IC= Intercostals, OB=Obliques, WR= Word reading task, VC= Vital Capacity task, SEC=Seconds, %RC=percent rib cage contribution to total lung volume.*

Chapter 3: Task and Age-Related sensitivities in the Orbicularis Oris

The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Orbicularis Oris

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Author Contributions

AR was responsible for study design, data collection and analysis and wrote the manuscript, RB was involved in data analysis and development of custom Matlab scripts for analysis, and authors JC and CB supervised all stages of the project. All authors reviewed the final manuscript.

Introduction

Over the past several decades, methodological advances have led to refined models of speech production and improved assessment and treatment methods of individuals with motor speech disorders. Such advancements stem from a variety of sources including analysis of articulatory and respiratory kinematics (e.g., Hixon et al., 1973; Rowe et al., 2021), EMG activity (e.g., Hoit et al., 1988; McClean & Tasko, 2002; Mendes Balata et al., 2013; Stepp, 2012), acoustic recordings (e.g., Stathopoulos et al., 2011; Stathopoulos & Sapienza, 2005; Tang & Stathopoulos, 2005) and behavioural measurements of speech such as maximum performance duration and articulatory rate (Bóna, 2014; Jacewicz et al., 2009; Smith et al., 1987).

Studies using EMG to study the muscle activity in the articulatory subsystem during speech have demonstrated that measurements of muscle activation can contribute to our understanding of motor control across different tasks and across the lifespan. For example, surface EMG (sEMG) recordings have been used to detect changes in activation of facial musculature in relation to manipulation of vocal loudness and speech rate , as well as during speech and non-speech tasks (Boucher, 2001; Choo et al., 2010; Huang et al., 2005; McClean & Tasko, 2006; Ruark & Moore, 1997; Smith, 2006; Steeve, Moore, Green, Reilly, & Mcmurtrey, 2008). sEMG has also been used to document changes across the lifespan. For example, as the oral cavity grows and children develop the muscle synergies needed to control the articulators across a wider range of movements, sEMG has been used to document slower speech produced with more variability in the amplitude, velocity and timing of articulatory movements in children relative to adults (Green et al., 2000, 2002; Steeve, Moore, Green, Reilly, & McMurtrey, 2008; Wohlert & Smith, 2002). In older adults, studies have reported a decrease in EMG amplitude in older adults in response to perturbation of the lower lip and increased force variability in the articulators (Bronson-Lowe et al., 2013; De Miranda Marzullo et al., 2010)

Although insightful, analysis of EMG amplitude and timing does not fully characterize how muscular signaling to the effectors differs in response to task demands. Measurements such as intermuscular coherence (IMC) use EMG activity to provide information regarding the degree to which two signals receive the same input, by quantifying the similarities in the electrical activity of two sets of muscles(Grosse et al., 2002). Investigations of IMC often consider differences across tasks within specific bandwidths to provide insight into the neuromuscular coordination strategy employed by the motor control system. The beta bandwidth (15-30 Hz), for example, is thought to reflect corticomuscular drive associated with shifts between individuated versus synergistic control (Boonstra, 2013; de Vries et al., 2016; Laine & Valero-Cuevas, 2017; Mima & Hallett, 1999; Nazarpour et al., 2012; Reyes et al., 2017). The gamma bandwidth (31-60 Hz), however, is more commonly associated with differences in coordination during complex or novel movement sequences (Chang et al., 2012; De Marchis et al., 2015; Kenville et al., 2020; Mohr et al., 2015, 2018; Omlor et al., 2007; von Tscharner et al., 2018). Together, physiological measurements such as EMG recordings taken at the periphery, and derived IMC measurements, may provide a more dynamic and comprehensive understanding about task-related differences in muscular control.

Limited research using IMC exists for articulatory muscles. Early studies detected low levels of bilateral masseter IMC in frequencies below 60 Hz during a clenching task (Bruce & Ackerson, 1986). Other studies have extended these findings to include chewing, and speech tasks, reporting decreasing IMC in the masseter during clenching and speech relative to chewing (Smith & Denny, 1990). Studies conducted in the genioglossus muscle during inspiratory loading suggest that common drive becomes greater (i.e., higher IMC values) in response to increased inspiratory loading (Woods et al., 2015). Two studies of the orbicularis oris have reported similar findings, with both studies largely reporting an absence of IMC between left and right orbicularis oris during speech and non-speech tasks (Caviness et al., 2006; Goffman & Smith, 1994). More recent investigations employing higher sampling rates have reported differences in IMC between left and right segments of the orbicularis oris as a function of phase of motor control (e.g., planning vs. speech production) (Reed et al., 2021).

Although preliminary investigations of IMC in the speech mechanism have proved promising, in order to determine the utility of IMC as a tool to investigate speech motor control, researchers using IMC must investigate its sensitivity to a wider variety of task demands. Critically, future studies must include investigation of IMC sensitivity to factors known to impact articulation. For example, differences in articulatory kinematics and speech acoustics occur in response to demands placed on respiratory and phonatory systems (Dromey & Ramig, 1998b, 1998a; Watson et al., 2003). Cognitive linguistic demands have also been shown to impact articulatory movements during picture naming versus single word reading tasks (Ries et al., 2012), or when completing a divided attention task (Dromey & Bates, 2005; Dromey & Shim, 2008) . Last, investigations into IMC of the articulators should include consideration of age-related differences, due to the well-documented differences in articulation that occur across the lifespan. Sensitivity to these factors has previously been investigated in the respiratory subsystem (Reed et al., n.d.), however further investigation of the articulatory subsystem is warranted, given its importance in speech production. The orbicularis oris is ideal for these preliminary investigations due to its central role in movement of the lips and the relative ease with which it can be accessed with surface EMG electrodes. The orbicularis oris is unique in that although it is a continuous muscle, it is comprised of four distinct quadrants (Standring, 2021), with distinct patterns of innervation by the buccal, mandibular and zygomatic branches of the seventh cranial nerve (Hwang et al., 2006; Mitsukawa et al., 2014).

In summary, IMC has been proposed as a novel tool to gain further insight into the motor system's ability to coordinate movement throughout the head, neck and chest. Preliminary investigations of IMC in the articulatory subsystem provide evidence of sensitivity to articulatory demands, however, a comprehensive investigation to a wide range of speech demands is needed to understand its utility in the assessment of motor speech disorders that impact articulation as well as tracking progress during various treatment protocols specific to these disorders.

Present Study

The purpose of the present study was to further our understanding of IMC in the orbicularis oris across different speech and non-speech task demands. Thirty younger adults and thirty older adults performed a series of seven tasks designed to manipulate demands in each subsystem in order to address five key objectives; specifically the effects of (1) lung volume, (2) laryngeal engagement, (3) articulatory demands, (4) cognitive linguistic demands and (5) age on of the left versus right aspect of the orbicularis oris. We hypothesize that IMC in the orbicularis oris will be sensitive to task demands, however no directional hypotheses are made given the exploratory nature of this work. Findings will be interpreted in the context of available literature.

Materials and Methods

Participants

Sixty English speaking adults were recruited from two separate age groups, including thirty younger adults (age: 26.97 years old ± 6.04; age range: 18-43 years old; sex: 8 men, 22 women) and thirty older adults (age: 66.37 years old ± 6.83; age range: 54-77 years old; sex: 7 men, 23 women). All participants were required to have normal or corrected to normal hearing and vision, as well as a negative history of acute or chronic muscle conditions or surgeries affecting the head, neck, chest or abdomen. Individuals reporting neurological conditions (e.g., epilepsy, migraines, movement disorders) or histories of speech, language or learning delays or disorders were not permitted to participate.

Procedures

Data presented in this study were collected as part of a large data set. Data from the word reading task have previously been reported (Reed et al., 2020). Information regarding maximum performance duration, articulatory rate, respiratory kinematic data and chest wall EMG data (i.e., maximum voluntary contraction and IMC) from all tasks also has previously been reported (Reed et al., n.d.) (see Figure 3.1 for uncorrected kinematic and raw EMG signals of a representative participant). Data collection from consent to departure was approximately 2 hours. Participants received a small honorarium for participation. All study protocols received approval through the University of Alberta Research Ethics Board.

Written and informed consent were collected at the Speech Physiology Laboratory at the University of Alberta. Orbicularis oris emg electrodes were placed at four sites: the upper left, upper right, lower left and lower right. Signals were confirmed by having participants alternate between a smile and puckered lips, and the same task was repeated in order to collect the maximum voluntary contraction from each recording site. Once confirmed, data for a rest breathing (RB) task was collected by telling participants to relax while researchers checked equipment (approximately two minutes).

Two large lung volume tasks were elicited prior to the remaining small lung volume tasks. In both large lung volume tasks, participants were instructed to begin with a maximum inspiration and continue until all air was expelled. In the maximum phonation duration (MPD) task, participants produced a sustained vowel (“ah”), and in the sequential diadochokinetic (DDK) task, participants repeated three syllables (“pataka”) at their maximum articulatory rate.

Participants then completed the remaining small lung volume tasks in a randomized order, with instructions and stimuli presented by E-prime software (Psychology Software Tools, Pittsburgh, PA, USA). In all three tasks, participants were asked to complete each trial as quickly and as accurately as possible. In the word reading (WR) task, participants read aloud forty, four-letter, monosyllabic words from one of two matched lists of words, balanced for onset phoneme and word type (e.g., regular exception, nonwords, and pseudohomophones). In the picture naming (PN) task, participants were presented with a series of images depicting an object or an action and asked to name the image. Matched sets containing 40 images were used; with each set containing 20 object and 20 action stimuli each (10 low frequency and 10 high frequency items of each). Lastly, in the tongue twister (TT) task, participants were presented with one of two matched sets of 15 tongue twisters, controlled for length and lexical qualities.

As described, demands across tasks were designed to vary. Tasks are described as either small (RB,WR,PN,TT) or large (MPD, DDK) lung volume, with tracheal demands being non existent (RB), sustained (MPD) or alternating (WR,PN,TT,DDK). Tasks also differed by articulatory demands, including tasks with no demands (RB), low demands (MPD), habitual speech demands (WR,PN) or high demands (TT,DDK). Last, we described the cognitive linguistic demands across tasks, assigning labels of no demands (RB), novel non-speech (MPD, DDK), reading (WR, TT), and naming (PN). For these descriptions in table format, please see Table 3.1 (Reproduced with permission from Reed et al., nd)

Table 3.1. *Description of the lung volume requirements, laryngeal engagement, articulatory demands and cognitive-linguistic considerations of each task.*

Task	Lung Volume Requirements (respiratory subsystem)	Tracheal Pressure Requirements (laryngeal subsystem)	Articulatory demands (Articulation Subsystem)	Cognitive- linguistic considerations
Maximum Phonation Duration (MPD)	Range of Large Lung Volumes	Sustained	Low demand	Novel non speech
Sequential Diadochokinetic (DDK)	Range of Large Lung Volumes	Alternating	High demand	Novel non speech
Rest Breathing (RB)	Range of Small Lung Volumes	None	None	None
Word Reading (WR)	Range of Small Lung Volumes	Alternating	Habitual Speech	Reading
Picture Naming (PN)	Range of Small Lung Volumes	Alternating	Habitual Speech	Naming
Tongue Twister Repetition (TT)	Range of Small Lung Volumes	Alternating	High Demand	Reading

Data Acquisition and Signal Analysis

Measures of Task Performance. Throughout all tasks, a small omni-directional condenser microphone (Audio-Technica, Model AT 803b) was affixed ten centimeters above participants mouths. Audio signals were amplified (M-Audiobuddy Pre-Amplifier) and recorded using TF32, a Windows based form of CSpeech Software (Milenkovic, 2001). Recordings were analyzed using PRATT software (Boersma & Weenink, 2013), and four measures of task performance were calculated. For the MPD and DDK tasks, maximum performance duration was defined as the difference between voice onset and offset for each trial. For the DDK and TT tasks, rate (syllables per second) was calculated for each trial by dividing task duration (i.e., voice onset-offset) by the number of syllables. TT trials in which participants produced phoneme substitutions or repetitions were excluded from rate measurements.

EMG Recordings. EMG data was collected using previously published protocols (Boliek et al., 2019; Reed et al., 2021; Tomczak et al., 2013). EMG recordings were made using paired, disposable Ag/AgCl disc electrodes (Model DE-48, Grass Technologies) placed on four sites of the orbicularis oris: the upper left (UL), the lower left (LL), the upper right (UR) and the lower right (LR). Skin was prepared using a mild exfoliant and electrodes were filled with gel (Spectra 360, Parker Spectra). A ground electrode (Kendal Soft-E H69P, Tyco Healthcare Group) was placed on the clavicle. Electrode placement along the oribularis oris was confirmed by having participants alternate between pursed lips and a smile. Recordings were made using a multichannel acquisition system (PowerLab 16SP ML795; ADInstruments, Colorado Springs, CO) and saved digitally using LabChart software (version 5.5.6; ADInstruments). EMG signals were amplified and filtered using a Grass Isolation System (Grass P511; Astro-Med, Inc., Quincy, MA). Sampling rate across all recording sites was 10 kHz, with a band-pass filter set to

3-3000 Hz and a notch filter at 60 Hz. To support off-line analysis of signals, EMG and acoustic recordings were time-locked with respiratory kinematics recordings. Respiratory kinematics were recorded using variable inductance plethysmography calibrated using standard protocols (see Reed et al., n.d. for further details). Respiratory kinematic findings and specific protocols used are reported in Reed et al., nd.

EMG recordings yielded two measures of interest: signal amplitude and IMC. Using the respiratory kinematic signal, a period of ~10 sequential breaths was segmented for the rest breathing task (i.e., inspiration and expiration). For the remaining tasks, the expiratory limb for each trial (i.e., peak inspiration to end expiration) was segmented and saved for further analysis using custom Matlab scripts (See Boliek et al., 2019 and Tomczak et al., 2013 for further details). EMG signal amplitude, expressed as a percentage of each muscle's maximal voluntary contraction (%MVC), was calculated using reference values from resting EMG and the muscle's maximum contraction recorded during the alternating lip puckering and smiling task. Data were filtered (high pass filter cutoff frequency of 30 Hz), rectified and smoothed prior to analysis. For each trial, separate values were calculated for all four orbicularis oris recording sites. Values were averaged across trials prior to statistical analysis; any individual trial values resulting in %MVC values over 200% were removed.

Separate custom Matlab scripts using open-access programs were used to calculate IMC (See Boliek et al., 2019 and Tomczak et al., 2013 for further details). Data processing included filtering using a 30 Hz high-pass Butterworth filter and a 300 Hz low-pass filter and rectification of signals. IMC calculations used a frequency resolution of 2.44 Hz and segment length of 2,048 points (equation 1). In order to mitigate the effects of varying task durations, IMC values were normalized for the number of segments prior to statistical analysis (equation 2). Within tasks, IMC was calculated by concatenating data across the upper and lower recording sites to yield a singular coherence value for the articulatory subsystem (i.e., left (upper and lower) vs right (upper and lower)). IMC was calculated in both the beta (15-30 Hz) and gamma (31-60 Hz) frequency bandwidths.

$$Coh_{XY}(f) = \left|C_{xy}(w)\right|^2 = \frac{\left|\overline{G_{xy}(w)}\right|^2}{\overline{G_{xx}(w)}\cdot\overline{G_{yy}(w)}}$$

Equation 1. Intermuscular coherence calculation, where Coh=magnitude square coherence of the x and y muscles of interest; Gxx(w) and Gyy(w)= averaged power spectra for a given frequency (w); Gxy=averaged cross-power spectrum of x and y signals at frequency w (Norton & Gorassini, 2006; Rosenberg et al., 1989).

$$Z\,(f) = \operatorname{atanh}\left(\sqrt{Coh\,(f)}\,\right) / \sqrt{1/(2 * L)}$$

Equation 2. Standardized Z score transformation of intermuscular coherence at frequency (f), given L segments ((Rosenberg et al., 1989, as used by Baker et al., 2003)*)*

Statistics

All statistical analyses were conducted using the open source statistical software JASP (version 0.16.3; JASP Team, 2022). For all variables, values more than 1.5 SDs from the age group's mean were excluded from further analysis (<1% of data). Shapiro-Wilk test of normality indicated that normality assumptions had not been met across variables, therefore task related effects were analyzed within each age group using separate repeated measures ANOVAs. When Mauchly's test of sphericity indicated a violation of sphericity, Greenhouse-Geisser corrected values are reported (denoted using +). All post hoc analyses are reported using a Holm correction for multiple comparisons. Age related differences were investigated using independent samples t-tests or Mann-Whitney U tests; Holm corrected values are reported. The same statistical routine was followed for descriptive variables including EMG amplitude (%MVC for UL, UR, LL, LR) and performance measures (maximum performance duration and rate). Individual %MVC values above 200 were removed prior to averaging within tasks for each participant. Relationships between IMC and descriptive variables were explored using Bonferroni corrected Pearson correlations.

Results

Unfiltered kinematic and raw EMG signals of a representative participant are shown in Figure 3.1. IMC findings are presented below (see Figure 3.2 for IMC in a representative participant during the maximum phonation duration task) and EMG amplitude variables and exploratory correlations are presented in the Supplementary materials by task and by age.

EMG amplitude variables include degree of contraction relative to the muscle's maximum voluntary contraction (%MVC) for UL, UR, LL, and LR segments of the orbicularis oris are presented in Supplemental Materials Figures S3.1A-D. Exploratory Pearson correlations between IMC and %MVC and behavioural measures can be found in Supplemental Materials, Figures S3.2A-C. Statistical significance of task and age related differences are denoted within figures and reported in figure captions.

These findings will be referenced throughout the discussion to provide context to IMC values. Although some differences between sites were observed, in general, orbicularis oris EMG amplitude findings aligned with manipulation of articulatory demands: No/low demand tasks (RB and MPD) had the lowest %MVC followed by tasks with habitual speech demands (PN, WR), with high demand tasks having the highest %MVC overall (TT, DDK).

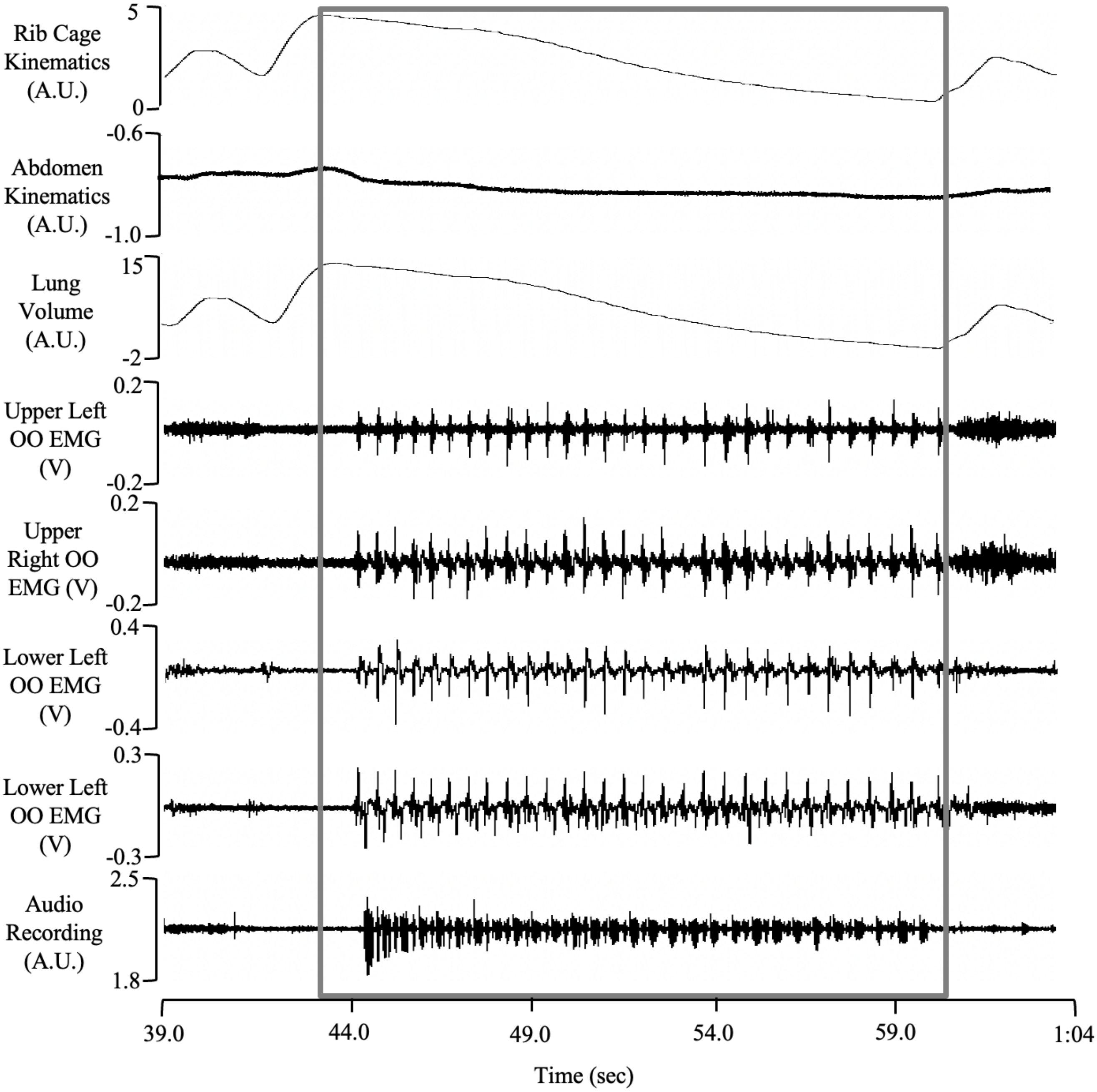

Figure 3.1 *Unfiltered data from a representative subject.*

Panel A depicts simultaneously recorded rib cage (RC) and abdominal (AB) kinematic signals, uncalibrated lung volume (LV) signal used for file segmentation in LabChart (corrected for RC and AB contributions), upper left, lower left, upper right and lower right orbicularis oris (OO) EMG activity, and the acoustic recording during the diadochokinetic task. Expiratory window denoted using box overlay (as measured by the LV signal). A.U = arbitrary units, V = volts OO = oribicularis oris

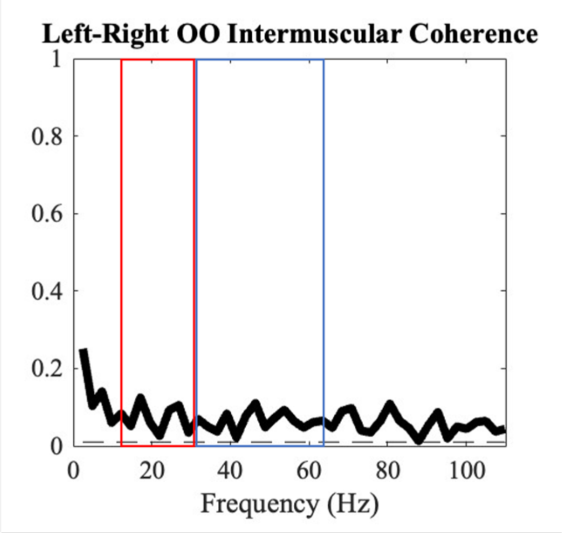

Figure 3.2 Left versus Right Orbicularis Oris (OO) Intermuscular coherence for a representative subject for the maximum phonation duration (MPD) task. The y and x axes represent intermuscular coherence strength and frequency (Hz), respectively. The red and blue rectangles indicate the 15-30 Hz and 31-60 Hz frequency bandwidths, respectively. The dotted line represents the 95% confidence interval.

Measures of task performance

Maximum performance duration and rate measurements are reported in Table 3.2 (Reproduced with permission from Reed et al., n.d). In summary, both groups demonstrated a significantly longer task duration in the MPD task relative to DDK, as well as a significantly faster rate in the DDK task relative to MPD. Between group comparisons revealed that younger adults had a significantly faster rate in TT relative to older adults.

Table 3.2. *Mean duration (in seconds) and rate (syllables per second) for maximum phonation duration (MPD) task, diadochokinetic task (DDK) and tongue twisters (TT) task.*

	MPD Duration (sec)	DDK Duration (sec)	DDK Rate (syll/sec)	TT Rate (syll/sec)
Younger adults	20.42 (5.09)	16.87 (5.77)	5.83 (0.74)	3.49 (0.53)
Older adults	19.67 (6.77)	16.17 (3.52)	5.54 (0.91)	2.96 (0.34)

Intermuscular Coherence

Beta Frequency Bandwidth (15-30 Hz). In the younger adults, repeated measures ANOVA found a main effect of task ($F_{3.51,63.22}$=20.61, $p < .001$; see Figure 3.3A). Post hoc testing revealed significantly lower coherence in the MPD task relative to the PN, WR, TT and DDK tasks (all $p<0.05$). The RB task also had significantly lower coherence than the PN, WR, TT, and DDK tasks (all $p<0.05$). Last, the PN task had significantly higher coherence than the TT task ($p < .002$).

Similarly, a repeated measures ANOVA found a main effect of task within older adults ($F_{2.87,54.53}$=13.81^{+}, $p < .001$), with post hoc testing revealing significantly lower coherence in the

RB task relative to the PN, WR, TT, MPD and DDK tasks (all $p<0.05$). The PN task had significantly higher coherence relative to the WR, TT, MPD and DDK tasks (all $p<0.05$).

Independent samples t-tests and Mann Whitney-U tests did not detect significant differences between age groups in any task.

Gamma Frequency Bandwidth (31-60 Hz). In younger adults, repeated measures ANOVA did not reveal a main effect of task ($F_{2.51,40.09}=1.383^{+}$, $p< .263$). In older adults, there was a main effect of task ($F_{2.26,45.01}=7.956^{+}$, $p< .001$; Figure 3.3B). Post hoc testing found significantly higher coherence in the MPD task relative to the PN, WR , TT and DDK tasks (all $p<0.05$). The RB task also had significantly higher coherence than the TT task ($p < .015$) within this age group.

Independent samples t-tests and Mann Whitney-U tests did not detect significant differences between age groups in any task.

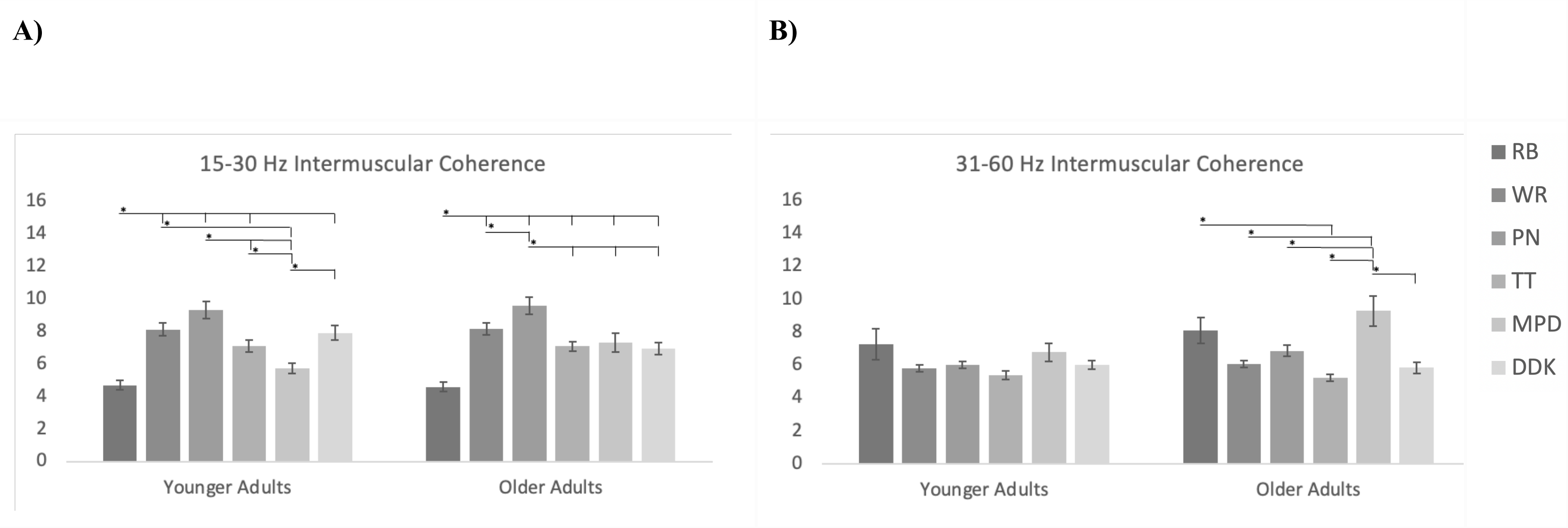

Figure 3.3 *Orbicularis Oris Intermuscular coherence (IMC) in Younger and Older Adults. Transformed intermuscular coherence values are represented on the y axis; values are graphed separately by frequency bandwidth. Panels A and B depict left vs right orbicularis oris IMC in the 15-30 Hz and 31-60 Hz frequency bands, respectively. Error bars indicate standard deviation of the mean. Asterisks denote significant task related differences within younger and older adult age groups. OO= Orbicularis oris, RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*

Discussion

The purpose of the present study was to examine the effects of varying task demands on intermuscular coherence (IMC) of the articulatory subsystem in healthy younger and older adults. Six speech and non-speech tasks of varying lung volume excursions, tracheal pressures, articulatory demands, and cognitive requirements were used. IMC of left vs right orbicularis oris in both beta and gamma bandwidths were sensitive to task manipulation with patterns of sensitivity differing for IMC bandwidth, and age. IMC in the beta bandwidth demonstrated sensitivity to articulatory demands, with decreased levels of beta band IMC detected between tasks with no or low articulatory demands (RB and MPD) relative to the tasks with habitual or high demands (PN and WR; TT and DDK, respectively). Within gamma bandwidth IMC, we report evidence of multiple task related differences among older adults that were not observed in younger participants. Together, these findings represent an important, novel addition to our understanding of speech motor control in younger and older healthy adults.

Effects of Lung Volume and Laryngeal Demands

Overall, no systematic effects of lung volume or laryngeal demands were observed in orbicularis oris IMC for either frequency bandwidth. This novel finding is consistent with existing knowledge of speech production. Although the integration and association between the respiratory and laryngeal systems is well documented (Davis et al., 1992; Dromey & Ramig, 1998a; Peters & Boves, 1988; Stathopoulos & Sapienza, 1993, 2005), the impact of changes in the respiratory and laryngeal system on articulatory measures is less clear. Of the few studies that have investigated these relationships, lung volume initiation has had inconsistent effects on displacement and velocity of lip movement (Dromey & Ramig, 1998b). The lack of interaction between these subsystems may be due to the differences in the neural control mechanisms of the respiratory, laryngeal and articulatory systems (Davis et al., 1996). Whereas the respiratory and laryngeal systems are managed by both the central pattern generators controlling metabolic breathing and cortical control centers coordinating speech production (Guyenet & Bayliss, 2016; Levitzky, 2017; Loucks et al., 2007), the articulators are innervated by cranial nerves with no apparent connection to the control of respiration. Neurophysiologists suggest that although articulatory activity is coordinated with and shares overlap in control via cortical centers, it is likely separate from laryngorespiratory activity (Davis et al., 1996).

Interpreted within this literature, compensatory action in the articulators would only be expected if downstream systems have failed to produce adequate pressures. As all participants in the present study were healthy adults asked to produce speech at a typical conversational loudness levels loudness (i.e., with consistent average tracheal pressure), consistent articulatory IMC across tasks of varying lung volumes and laryngeal demands is in line with our current understanding of speech motor control mechanisms.

Articulatory Demand Sensitivity in the Beta Bandwidth (15-30 Hz)

Both younger and older adults demonstrated significant differences in IMC values across tasks of varying articulatory demands in the beta bandwidth. In younger adults, tasks with no or low articulatory demands (RB and MPD) had lower beta bandwidth IMC relative to the tasks with habitual or high demands (PN and WR; TT and DDK, respectively). A similar pattern was observed in older adults, however RB was also found to be significantly lower than tasks with low demands (i.e., MPD).

Previous studies investigating IMC in the orbicularis oris have reported that, across a range of tasks, left versus right IMC was only detected in controls during a sustained pucker task

(Caviness et al., 2006; Goffman & Smith, 1994). Our data represent a novel contribution to this growing body of research as we report statistically significant levels of IMC across a wide variety of speech and non-speech related tasks and provide evidence of significant differences between tasks requiring varying degrees of articulatory demands. The discrepancy between the present work and previous studies may be due to differences in data acquisition protocols, namely sampling rate and recording sites used. In the current study, a sampling rate of 10 kHz was used to collect data across four recording sites, in contrast to the sampling rate of 0.5 or 1 kHz employed to collect data from two recording sites (Caviness et al., 2006; Goffman & Smith, 1994).

Other studies of IMC in the speech mechanism are also in contrast to the pattern observed here (i.e., low articulatory demand tasks having decreased IMC relative to habitual or high demand tasks). Investigations of laryngeal IMC have reported decreases in IMC in the beta bandwidth during "hyperfunctional speech" (i.e., speaking as though it were difficult to produce voicing) (Stepp et al., 2011). The extent to which the differential pattern observed in the present study is accounted for by differences in location of IMC measured (i.e., orbicularis vs. laryngeal) or in how tasks were elicited remains to be seen. With respect to the latter, Stepp et al.,'s study used a task in which participants were asked to consciously change their performance to achieve an atypical speech pattern, whereas in the present study participants were not asked to alter their performance during the task (Stepp et al., 2011). With respect to the former, studies that record simultaneous IMC from various sub-systems associated with speech will be necessary to fully reconcile these disparate findings. Overall, the results here add to the growing body of literature that describes the contribution of various muscles to speech motor control.

Recent developments in our understanding of the role of synergistic versus individuated movements provide further context to the seemingly disparate patterns observed between the present study and previously published research. The beta bandwidth IMC is thought to reflect differences between synergistic and individuated control of movement (de Vries et al., 2016; Laine & Valero-Cuevas, 2017; Nazarpour et al., 2012; Reyes et al., 2017). Some studies have reported a decrease in this bandwidth during dynamic versus static movements, when the dynamic movement may require the two muscles to shift to individuated movements (Kilner et al., 1999; Reyes et al., 2017). The decrease in IMC is hypothesized to reflect the "unbinding" of muscle control in response to task demands. In line with this finding, more recent investigations have reported increases in this bandwidth in dynamic versus static tasks when the dynamic task requires more synergistic control of muscles (Kenville et al., 2020). That is, while decreases in the beta bandwidth may reflect an "unbinding" of muscle control, increases may reflect increased coupling of control. Within this context, one interpretation of the present finding is that the motor control for tasks involving habitual or high articulatory demands relies on increased synergistic, not individuated, control of orbicularis oris segments during speech production. Although the orbicularis oris is often viewed as a single muscle, it is comprised of four distinct quadrants (Standring, 2021), with distinct patterns of innervation by the buccal, mandibular and zygomatic branches of the seventh cranial nerve (Hwang et al., 2006; Mitsukawa et al., 2014). The present findings extend our understanding of orbicularis oris control by providing evidence of varying patterns of coordination between the right and left subsections in response to increasing task demands.

Cognitive Linguistic Demand Sensitivity in the Beta Bandwidth (15-30 Hz)

Beyond the difference of IMC across tasks of varying articulatory demands, some differences were observed between tasks requiring varying cognitive linguistic demands. In older adults, the PN task had significantly higher beta bandwidth IMC relative to the RB, WR, TT, MPD and DDK tasks. In younger adults, a similar pattern was detected although the only statistically significant differences were found between the PN task and the RB, TT and MPD tasks.

This finding differs from previous studies of laryngeal IMC, which have reported decreases in beta bandwidth IMC with increased cognitive load; with IMC during a divided attention task (i.e., counting backwards by an integer) demonstrating significantly lower IMC than a reference task (Stepp et al., 2011). Studies conducted in the limbs have also demonstrated decreased beta bandwidth IMC during increased cognitive load in healthy older adults (Nojima et al., 2018). For example, when presented with a choice to step using the left or right leg, participants demonstrated decreased IMC when compared to directed trials (i.e., when instructed to use left or right leg) (Nojima et al., 2018). The decrease in IMC is hypothesized to reflect increased involvement of inhibitory mechanisms, as the study also reported a positive correlation between IMC and the number of step errors by participants. In the speech mechanism, previous studies have demonstrated that increased cognitive load results in increased variability in stability and timing of speech production (Abur et al., 2023; Bailey & Dromey, 2015; Dromey & Bates, 2005; Dromey & Shim, 2008; MacPherson, 2019;Shen & Janse, 2020). While the relationship between increased IMC in the PN task and task performance is unclear, the present findings add to a growing body of research demonstrating the effects of cognitive load on motor performance.

Interestingly, in the present study there were no significant correlations between beta bandwidth IMC and the speaking rate and maximum performance duration measures (Supplemental materials: Figures S3.2), however measures of task accuracy were not included. Further exploration of this relationship may provide insight into the observed pattern of findings. One hypothesis is that the reported increased beta bandwidth IMC may be a result of the inherent differences in the processes underlying speech versus gross motor control, or anatomical differences in the orbicularis oris' vs. laryngeal muscle fiber and innervation (Perkell, 2013) . While measurements of response time and accuracy across a wider variety of tasks and speech musculature are ultimately needed to fully explore these hypotheses, our findings provide some novel avenues for future inquiry.

Age- related Sensitivities in the Gamma bandwidth (31-60 Hz)

In the gamma bandwidth, younger adults had no task-related differences in orbicularis oris IMC. Interestingly, older adults demonstrated several significant differences across tasks across tasks of varying articulatory demands. The RB task (no demand) had significantly higher IMC than TT (high demand), and the MPD task (low demand) had higher IMC than WR and PN (habitual demand) as well as TT and DDK (high demand) tasks. Increases in gamma bandwidth IMC have been reported during novel and/or higher complexity tasks, thought to be mediated by the increased information integration that occurs in order to effectively execute these tasks (De Marchis et al., 2015; Mohr et al., 2015, 2018; Nishimura et al., 2009; von Tscharner et al., 2018). Despite the articulatory complexity of TT and DDK tasks used here, we did not find significantly higher IMC in either younger or older adults. Thus, although previous reports of gamma bandwidth IMC sensitivity to complexity cannot be generalized to the orbicularis oris, future work is needed to test the robustness of the findings here and to assess more nuanced and subtle differences of task demands to disentangle the role of gamma bandwidth IMC in speech motor control.

Interestingly, although only significant in older adults, younger adults displayed a similar pattern of IMC across tasks. Thus, it is possible that age related changes underlie the difference in observed patterns. Differences in behavioural and physiological measures of speech are well documented between younger and older adults. For example, older adults experience a decline in articulator endurance, sensitivity, strength and mobility (Amerman & Parnell, 1992; Bilodeau-Mercure & Tremblay, 2016; Bronson-Lowe et al., 2013; Dietsch et al., 2015; Etter et al., 2018; Peladeau-Pigeon & Steele, 2017; Sonies et al., 1984; Vanderwegen et al., 2013). These changes contribute to older adults displaying increased variability in articulator movement and slower rate of speech (i.e., longer duration of pauses, individual phonemes and syllables) (Bilodeau-Mercure & Tremblay, 2016; Bóna, 2014; Huber et al., 2012; Liss et al., 1990; Liu et al., 2011; Stathopoulos et al., 2011; Wohlert & Smith, 1998). Consistent with the literature, we report faster articulation rates in younger adults in the TT and DDK tasks. Muscle activation data also indicated that older adults had higher %MVC in the lower left and lower right segments of the orbicularis oris during the RB, WR, PN and TT tasks compared with younger adults (Supplemental Materials: Figures S3.1C and S3.1D). Taken together, it is possible that the differences in IMC between tasks observed in the gamma bandwidth are connected to the age-related changes in speech motor control as documented in the literature.

Age related differences in gamma bandwidth activity is further supported by previous work showing differences in younger and older adults' modulation of lower orbicularis oris EMG power spectra in gamma bandwidth (De Miranda Marzullo et al., 2010). Using a lower lip perturbation paradigm in younger and older adults, researchers proposed that younger adults' decreased response to perturbation was mediated by gamma bandwidth activity in the orbicularis oris. Younger adults demonstrated more power in this bandwidth in the perturbed lower lip (versus the upper lip) as well as a significant negative correlation between increased power and decreased lip displacement. Thus, our data provide additional evidence for differences in older adults' gamma bandwidth oscillatory activity.

In order to further investigate the potential contribution of age-related factors to the patterns observed in younger and older adults, studies should include an age range expansion. If age is a contributing factor to patterns of IMC in the orbicularis oris, it would be hypothesized that children would show no evidence of this effect, whereas older adults should demonstrate an enhanced effect.

Conclusion

The present findings build on existing work in the field of speech motor control and IMC. We have reported novel findings of the orbicularis oris' sensitivity to task demands in the beta bandwidth, with tasks involving habitual or high articulatory demands demonstrating significantly higher coherence than tasks with no or low demands. In line with previous work reporting differences in gamma bandwidth modulation between age groups, our work also established differences between the patterns of IMC in the gamma bandwidth between younger and older adults. These findings support the continued investigation of IMC as a tool to study speech motor control. Future studies are needed to test the robustness of the findings and to establish its connection to measures of performance.

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References

Abur, D., MacPherson, M. K., Shembel, A. C., & Stepp, C. E. (2023). Acoustic Measures of Voice and Physiologic Measures of Autonomic Arousal During Speech as a Function of Cognitive Load in Older Adults. *Journal of Voice*, *37*(2), 194–202. https://doi.org/10.1016/j.jvoice.2020.12.027

Amerman, J. D., & Parnell, M. M. (1992). Speech Timing Strategies in Elderly Adults. *Journal of Phonetics*, *20*(1), 65–76.

Bailey, D. J., & Dromey, C. (2015). Bidirectional Interference Between Speech and Nonspeech Tasks in Younger, Middle-Aged, and Older Adults. *Journal of Speech, Language, and Hearing Research : JSLHR*, *58*(6), 1637–1653. https://doi.org/10.1044/2015_JSLHR-S-14-0083

Baker, S. N., Pinches, E. M., & Lemon, R. N. (2003). Synchronization in monkey motor cortex during a precision grip task. II. Effect of Oscillatory Activity on Corticospinal Output. *Journal of Neurophysiology*, *89*, 1941–1953. https://doi.org/10.1152/jn.00832.2002

Bilodeau-Mercure, M., & Tremblay, P. (2016). Age Differences in Sequential Speech Production: Articulatory and Physiological Factors. *Journal of the American Geriatrics Society*, *64*(11), e177–e182. https://doi.org/10.1111/jgs.14491

Boliek, C. A., Bakhtiari, R., Pedersen, L., Esch, J., & Cummine, J. (2019). Differential cortical control of chest wall muscles during pressure- and volume-related expiratory tasks and the effects of acute expiratory threshold loading. *Motor Control*, *23*(1), 13–33. https://www.ncbi.nlm.nih.gov/pubmed/29902955

Bóna, J. (2014). Temporal characteristics of speech: The effect of age and speech style. *The Journal of the Acoustical Society of America*, *136*(2), EL116–EL121. https://doi.org/10.1121/1.4885482

Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. *Frontiers in Human Neuroscience*, *7*(DEC), 1–2. https://doi.org/10.3389/FNHUM.2013.00855

Boucher, V. J. (2001). A stumbling block in the development of motor theories of speech: Relating EMG to force-related changes in articulation. *Clinical Linguistics and Phonetics*, *15*(1–2), 123–127. https://doi.org/10.1080/026992001461433

Bronson-Lowe, C. R., Loucks, T., Ofori, E., & Sosnoff, J. J. (2013). Aging Effects on Sensorimotor Integration: A Comparison of Effector Systems and Feedback Modalities. *Article in Journal of Motor Behavior*. https://doi.org/10.1080/00222895.2013.784239

Bruce, E. N., & Ackerson, L. M. (1986). High-frequency oscillations in human electromyograms during voluntary contractions. *Journal of Neurophysiology*, *56*(2), 542–553. http://www.ncbi.nlm.nih.gov/pubmed/3760934

Caviness, J. N., Liss, J. M., Evidente, C., & Adler, V. (2006). *Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson's Disease*. *49*(April), 424–439.

Chang, Y. J., Chou, C. C., Chan, H. L., Hsu, M. J., Yeh, M. Y., Fang, C. Y., Chuang, Y. F., Wei, S. H., & Lien, H. Y. (2012). Increases of Quadriceps Inter-Muscular Cross-Correlation and Coherence during Exhausting Stepping Exercise. *Sensors 2012, Vol. 12, Pages 16353-16367*, *12*(12), 16353–16367. https://doi.org/10.3390/S121216353

Choo, A. L., Robb, M. P., Dalrymple-Alford, J. C., Huckabee, M. L., & O'Beirne, G. A. (2010). Different lip asymmetry in adults who stutter: Electromyographic evidence during speech and non-speech. *Folia Phoniatrica et Logopaedica*, *62*(3), 143–147. https://doi.org/10.1159/000287213

Davis, P. J., Bartlett, D., & Luschei, E. S. (1992). Coordination of the Respiratory and Laryngeal Systems in Breathing and Vocalization. *NCVC Status and Progress Report*, 59–81.

Davis, P. J., Zhang, S. P., Winkworth, A., & Bandler, R. (1996). Neural control of vocalization: respiratory and emotional influences. *Journal of Voice : Official Journal of the Voice Foundation*, *10*(1), 23–38. https://doi.org/10.1016/S0892-1997(96)80016-6

De Marchis, C., Severini, G., Castronovo, A. M., Schmid, M., & Conforto, S. (2015). Intermuscular coherence contributions in synergistic muscles during pedaling. *Experimental Brain Research*, *233*(6), 1907–1919. https://doi.org/10.1007/S00221-015-4262-4/METRICS

De Miranda Marzullo, A. C., Neto, O. P., Ballard, K. J., Robin, D. A., Chaitow, L., & Christou, E. A. (2010). Neural control of the lips differs for young and older adults following a perturbation. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *206*(3), 319. https://doi.org/10.1007/S00221-010-2411-3

de Vries, I. E. J., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, *116*(6), 2576–2585. https://doi.org/10.1152/jn.00460.2016

Dietsch, A. M., Clark, H. M., Steiner, J. N., & Solomon, N. P. (2015). Effects of Age, Sex, and Body Position on Orofacial Muscle Tone in Healthy Adults. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1145–1150. https://doi.org/10.1044/2015_JSLHR-S-14-0325

Dromey, C., & Bates, E. (2005). Speech Interactions With Linguistic, Cognitive, and Visuomotor Tasks. *Journal of Speech, Language, and Hearing Research*, *48*(2), 295–305. https://doi.org/10.1044/1092-4388(2005/020)

Dromey, C., & Ramig, L. O. (1998a). Intentional Changes in Sound Pressure Level and Rate: Their Impact on Measures of Respiration, Phonation, and Articulation. In *Journal of Speech Language and Hearing Research* (Vol. 41, Issue October, pp. 1003–1018). https://doi.org/10.1044/jslhr.4105.1003

Dromey, C., & Ramig, L. O. (1998b). The Effect of Lung Volume on Selected Phonatory and Articulatory Variables. *Journal of Speech, Language, and Hearing Research*, *41*(3), 491–502. https://doi.org/10.1044/jslhr.4103.491

Dromey, C., & Shim, E. (2008). The Effects of Divided Attention on Speech Motor, Verbal Fluency, and Manual Task Performance. *Journal of Speech, Language, and Hearing Research*, *51*(5), 1171–1182. https://doi.org/10.1044/1092-4388(2008/06-0221)

Etter, N. M., McKeon, P. O., Dressler, E. V., & Andreatta, R. D. (2018). Effects of ageing on orofacial fine force control and its relationship with parallel change in sensory perception. *International Journal of Speech-Language Pathology*, *20*(5), 502–515. https://doi.org/10.1080/17549507.2017.1318303

Goffman, L., & Smith, A. (1994). Motor Unit Territories in the Human Perioral Musculature. *Journal of Speech and Hearing Research*, *37*(5), 975–984. https://doi.org/10.1044/JSHR.3705.975

Green, J. R., Moore, C. A., Higashikawa, M., & Steeve, R. W. (2000). The Physiologic Development of Speech Motor Control: Lip and Jaw Coordination. *Journal of Speech Language and Hearing Research*, *43*, 239–255. https://doi.org/10.1037//1082-989X.5.2

Green, J. R., Moore, C. A., & Reilly, K. J. (2002). The Sequential Development of Jaw and Lip Control for Speech. *Journal of Speech, Language and Hearing Research*, *45*, 66–79.

Grosse, P., Cassidy, M. J., & Brown, P. (2002). EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: Physiological principles and clinical applications. *Clinical Neurophysiology*, *113*, 1523–1531. https://doi.org/10.1016/S1388-2457(02)00223-7

Guyenet, P. G., & Bayliss, D. A. (2016). Neural control of breathing and CO2 homeostasis. 25(3), 289–313. https://doi.org/10.1007/s11065-015-9294-9.Functional

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the Chest Wall during Speech Production: Volume Displacements of the Rib Cage, Abdomen, and Lung. *Journal of Speech and Hearing Research*, *16*(1), 78–115. https://doi.org/10.1044/jshr.1601.78

Hoit, J. D., Plassman, B. L., Lansing, R. W., & Hixon, T. J. (1988). Abdominal muscle activity during speech production. *Journal of Applied Physiology*, *65*(6), 2656–2664. https://doi.org/10.1152/jappl.1988.65.6.2656

Huang, C. N., Chen, C. H., & Chung, H. Y. (2005). The review of applications and measurements in facial electromyography. *Journal of Medical and Biological Engineering*, *25*(1), 15–20.

Huber, J. E., Darling, M., Francis, E. J., & Zhang, D. (2012). Impact of typical aging and Parkinson’s disease on the relationship among breath pausing, syntax, and punctuation. *American Journal of Speech-Language Pathology*, *21*(4), 368–379. https://doi.org/10.1044/1058-0360(2012/11-0059)

Hwang, K., Jin, S., Hwang, S. H., & Chung, I. H. (2006). Innervation of upper orbicularis oris muscle. *The Journal of Craniofacial Surgery*, *17*(6), 1116–1117. https://doi.org/10.1097/01.SCS.0000235107.70118.06

Jacewicz, E., Fox, R. A., O'Neill, C., & Salmons, J. (2009). Articulation rate across dialect, age, and gender. *Language Variation and Change*, *21*(2), 233–256. https://doi.org/10.1017/S0954394509990093

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020). Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, *124*(4), 1045–1055. https://doi.org/10.1152/JN.00231.2020

Kilner, J. M., Baker, S. N., Salenius, S., Jousmäki, V., Hari, R., & Lemon, R. N. (1999). Task-dependent modulation of 15-30 Hz coherence between rectified EMGs from human hand and forearm muscles. *The Journal of Physiology*, *516.2*, 559–570. http://www.ncbi.nlm.nih.gov/pubmed/10087353

Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, *118*(3), 1775–1783. https://doi.org/10.1152/jn.00204.2017

Levitzky M.G.(Ed.), (2017). *Pulmonary Physiology, 9e*. McGraw Hill. https://accessmedicine-mhmedical-com.login.ezproxy.library.ualberta.ca/content.aspx?bookid=2288&sectionid=178857560

Liss, J. M., Weismer, G., & Rosenbek, J. C. (1990). Selected Acoustic Characteristics of Speech Production in Very Old Males. *Journal of Gerontology*, *45*(2), P35–P45. https://doi.org/10.1093/geronj/45.2.P35

Liu, P., Chen, Z., Jones, J. A., Huang, D., & Liu, H. (2011). Auditory feedback control of vocal pitch during sustained vocalization: A Cross-Sectional study of adult aging. *PLoS ONE*, *6*(7), 0–7. https://doi.org/10.1371/journal.pone.0022791

Loucks, T. M. J., Poletto, C. J., Simonyan, K., Reynolds, C. L., & Ludlow, C. L. (2007). Human brain activation during phonation and exhalation : Common volitional control for two upper airway functions. Human Brain Mapping Journal, 36, 131–143. https://doi.org/10.1016/j.neuroimage.2007.01.049

MacPherson, M. K. (2019). Cognitive load affects speech motor performance differently in older and younger adults. *Journal of Speech, Language, and Hearing Research*, *62*(5), 1258–1277. https://doi.org/10.1044/2018_JSLHR-S-17-0222

McClean, M. D., & Tasko, S. M. (2002). Association of orofacial with laryngeal and respiratory motor output during speech. *Experimental Brain Research*, *146*(4), 481–489. https://doi.org/10.1007/s00221-002-1187-5

McClean, M. D., & Tasko, S. M. (2006). Association of Orofacial Muscle Activity and Movement During Changes in Speech Rate and Intensity. *Journal of Speech, Language, and Hearing Research*, *46*(6), 1387–1400. https://doi.org/10.1044/1092-4388(2003/108)

Mendes Balata, P. M., Da Silva, H. J., Rocha De Moraes, K. J., De Araújo Pernambuco, L., & Arruda De Moraes, S. R. A. (2013). Use of surface electromyography in phonation studies: An integrative review. *International Archives of Otorhinolaryngology*, *17*(3), 329–339. https://doi.org/10.7162/S1809-97772013000300014

Mima, T., & Hallett, M. (1999). Corticomuscular coherence: a review. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *16*(6), 501–511. https://doi.org/10.1097/00004691-199911000-00002

Mitsukawa, N., Moriyama, H., Shiozawa, K., & Satoh, K. (2014). Study on distribution of terminal branches of the facial nerve in mimetic muscles (orbicularis oculi muscle and orbicularis oris muscle). *Annals of Plastic Surgery*, *72*(1), 71–74. https://doi.org/10.1097/SAP.0B013E318284ECA0

Mohr, M., Nann, M., Von Tscharner, V., Eskofier, B., & Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *PLOS ONE*, *10*(11), e0142048. https://doi.org/10.1371/JOURNAL.PONE.0142048

Mohr, M., Schön, T., von Tscharner, V., & Nigg, B. M. (2018). Intermuscular coherence between surface EMG signals is higher for monopolar compared to bipolar electrode configurations. *Frontiers in Physiology*, *9*(MAY), 566. https://doi.org/10.3389/FPHYS.2018.00566/BIBTEX

Nazarpour, K., Barnard, A., & Jackson, A. (2012). Flexible cortical control of task-specific muscle synergies. *Journal of Neuroscience*, *32*(36), 12349–12360. https://doi.org/10.1523/JNEUROSCI.5481-11.2012

Nishimura, Y., Morichika, Y., & Isa, T. (2009). A subcortical oscillatory network contributes to recovery of hand dexterity after spinal cord injury. *Brain*, *132*(3), 709. https://doi.org/10.1093/BRAIN/AWN338

Nojima, I., Watanabe, T., Saito, K., & Tanabe, S. (2018). Modulation of EMG-EMG Coherence in a Choice Stepping Task. *Frontiers in Human Neuroscience*, *12*, 1–11. https://doi.org/10.3389/fnhum.2018.00050

Norton, J. A., & Gorassini, M. (2006). Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *Journal of Neurophysiology*, *95*, 2580–2589. https://doi.org/10.1152/jn.01289.2005

Omlor, W., Patino, L., Hepp-Reymond, M. C., & Kristeva, R. (2007). Gamma-range corticomuscular coherence during dynamic force output. *NeuroImage*, *34*(3), 1191–1198. https://doi.org/10.1016/J.NEUROIMAGE.2006.10.018

Peladeau-Pigeon, M., & Steele, C. M. (2017). Age-Related Variability in Tongue Pressure Patterns for Maximum Isometric and Saliva Swallowing Tasks. *Journal of Speech, Language, and Hearing Research*, *60*(11), 3177–3184. https://doi.org/10.1044/2017_jslhr-s-16-0356

Perkell, J. S. (2013). Five decades of research in speech motor control: What have we learned, and where should we go from here? *Journal of Speech, Language, and Hearing Research*, *56*(6), 1857-1874–1874. https://doi-org.login.ezproxy.library.ualberta.ca/10.1044/1092-4388(2013/12-0382)

Peters, H. F. M., & Boves, L. (1988). Coordination of Aerodynamic and Phonatory Processes in Fluent Speech Utterances of Stutterers. *Journal of Speech and Hearing Research*, *31*(3), 352–361. https://doi.org/10.1044/JSHR.3103.352

Reed, A., Cummine, J., Bakhtiari, R., & Boliek, C. (n.d.). *The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Chest Wall* .

Reed, A., Cummine, J., Bhat, N., Jhala, S., Bakhtiari, R., & Boliek, C. A. (2021). Changes in Intermuscular Coherence as a Function of Age and Phase of Speech Production During an

Overt Reading Task. *Motor Control*, *25*(2), 295–314. https://doi.org/10.1123/MC.2020-0003

Reyes, A., Laine, C. M., Kutch, J. J., & Valero-Cuevas, F. J. (2017). Beta Band Corticomuscular Drive Reflects Muscle Coordination Strategies. *Frontiers in Computational Neuroscience*, *11*(April), 1–10. https://doi.org/10.3389/fncom.2017.00017

Rosenberg, J. R., Amjad, A. M., Breeze, P., Brillinger, D. R., & Halliday, D. M. (1989). The Fourier approach to the identification of functional coupling between neuronal spike trains. *Progress in Biophysics and Molecular Biology*, *53*(1), 1–31. https://doi.org/10.1016/0079-6107(89)90004-7

Rowe, H. P., Stipancic, K. L., Lammert, A. C., & Green, J. R. (2021). Validation of an Acoustic-Based Framework of Speech Motor Control: Assessing Criterion and Construct Validity Using Kinematic and Perceptual Measures. *Journal of Speech, Language, and Hearing Research*, *64*(12), 4736–4753. https://doi.org/10.1044/2021_JSLHR-21-00201

Ruark, J. L., & Moore, C. A. (1997). Coordination of Lip Muscle Activity by 2-Year-Old Children During Speech and Nonspeech Tasks. *Journal of Speech, Language, and Hearing Research : JSLHR*, *40*(6), 1373. https://doi.org/10.1044/JSLHR.4006.1373

Shen, C., & Janse, E. (2020). Maximum speech performance and executive control in young adult speakers. *Journal of Speech, Language, and Hearing Research*, *63*(11), 3611-3627.

Smith, A. (2006). Speech motor development: Integrating muscles, movements, and linguistic units. *Journal of Communication Disorders*, *39*(5), 331–349. https://doi.org/10.1016/j.jcomdis.2006.06.017

Smith, A., & Denny, M. (1990). High-frequency oscillations as indicators of neural control mechanisms in human respiration, mastication, and speech. *Journal of Neurophysiology*, *63*(4), 745–758.

Smith, Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech and Hearing Research*, *30*(4), 522–529. http://www.ncbi.nlm.nih.gov/pubmed/3695445

Sonies, B. C., Baum, B. J., & Shawker, T. H. (1984). Tongue Motion in Elderly Adults: Initial in Situ Observations. *Journal of Gerontology*, *39*(3), 279–283. https://doi.org/10.1093/geronj/39.3.279

Standring, S. (Ed.). (2021). *Gray's anatomy : the anatomical basis of clinical practice* (Forty-second edition). Elsevier.

Stathopoulos, E. T., Huber, J. E., Sussman, J. E., & Lafayette, W. (2011). *Changes in Acoustic Characteristics of the Voice Across Life Span*. *54*(August), 1011–1021. https://doi.org/10.1044/1092-4388(2010/10-0036)b

Stathopoulos, E. T., & Sapienza, C. (1993). Respiratory and laryngeal function of women and men during vocal intensity variation. *Journal of Speech and Hearing Research*, *36*(1), 64–75. https://doi.org/10.1044/JSHR.3601.64

Stathopoulos, E. T., & Sapienza, C. (2005). Respiratory and laryngeal measures of children during vocal intensity variation. *The Journal of the Acoustical Society of America*, *94*(5), 2531–2543. https://doi.org/10.1121/1.407365

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & Mcmurtrey, J. R. (2008). Babbling, Chewing, and Sucking: Oromandibular Coordination at 9 Months. *Journal of Speech Language and Hearing Research*, *51*(December), 1390–1405.

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & McMurtrey, J. R. (2008). Babbling, chewing, and sucking: oromandibular coordination at 9 months. *Journal of Speech, Language, and Hearing Research : JSLHR*, *51*(6), 1390–1404. https://doi.org/10.1044/1092-4388(2008/07-0046)

Stepp, C. E. (2012). Surface Electromyography for Speech and Swallowing Systems: Measurement, Analysis, and Interpretation. *Journal of Speech, Language and Hearing*, *55*, 1232–1247. https://doi.org/10.1044/1092-4388(2011/11-0214)a

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2011). Modulation of neck intermuscular Beta coherence during voice and speech production. *Journal of Speech, Language, and Hearing Research*, *54*, 836–844. https://doi.org/10.1044/1092-4388(2010/10-0139)

Tang, J., & Stathopoulos, E. T. (2005). Vocal efficiency as a function of vocal intensity: A study of children, women, and men. *The Journal of the Acoustical Society of America*, *97*(3), 1885–1892. https://doi.org/10.1121/1.412062

Tomczak, C. R., Greidanus, K. R., & Boliek, C. A. (2013). Modulation of chest wall intermuscular coherence: effects of lung volume excursion and transcranial direct current stimulation. *Journal of Neurophysiology*, *110*, 680–687. https://doi.org/10.1152/jn.00723.2012

Vanderwegen, J., Guns, C., Van Nuffelen, G., Elen, R., & De Bodt, M. (2013). The influence of age, sex, bulb position, visual feedback, and the order of testing on maximum anterior and posterior tongue strength and endurance in healthy Belgian adults. *Dysphagia*, *28*(2), 159–166. https://doi.org/10.1007/s00455-012-9425-x

von Tscharner, V., Ullrich, M., Mohr, M., Comaduran Marquez, D., & Nigg, B. M. (2018). Beta, gamma band, and high-frequency coherence of EMGs of vasti muscles caused by clustering of motor units. *Experimental Brain Research*, *236*(11), 3065–3075. https://doi.org/10.1007/S00221-018-5356-6/METRICS

Watson, P. J., Ciccia, A. H., Weismer, G., & Soc, J. A. (2003). The relation of lung volume initiation to selected acoustic properties of speech. *The Journal of the Acoustical Society of America*, *113*(5), 2812–2819. https://doi.org/10.1121/1.1567279

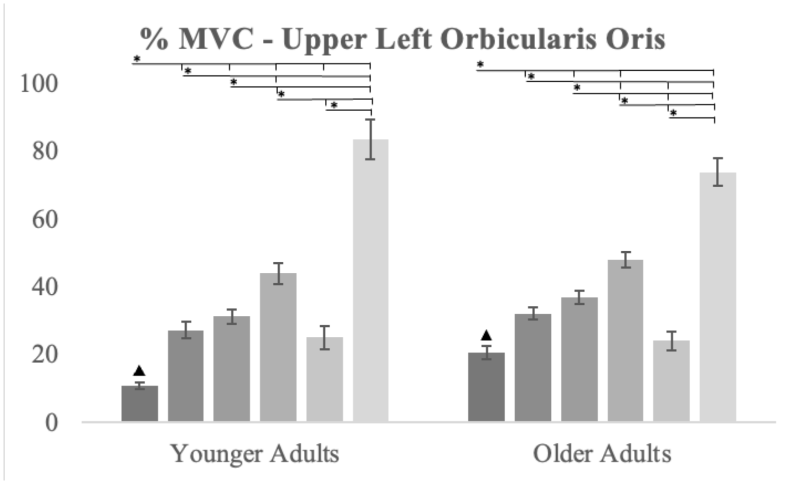
Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *Journal of Speech, Language, and Hearing Research : JSLHR*, *41*(1), 41–50. http://www.ncbi.nlm.nih.gov/pubmed/9493732

Wohlert, A. B., & Smith, A. (2002). Developmental Change in Variability of Lip Muscle Activity During Speech. *Journal of Speech, Language, and Hearing Research*, *45*(6), 1077–1087. https://doi.org/10.1044/1092-4388(2002/086)

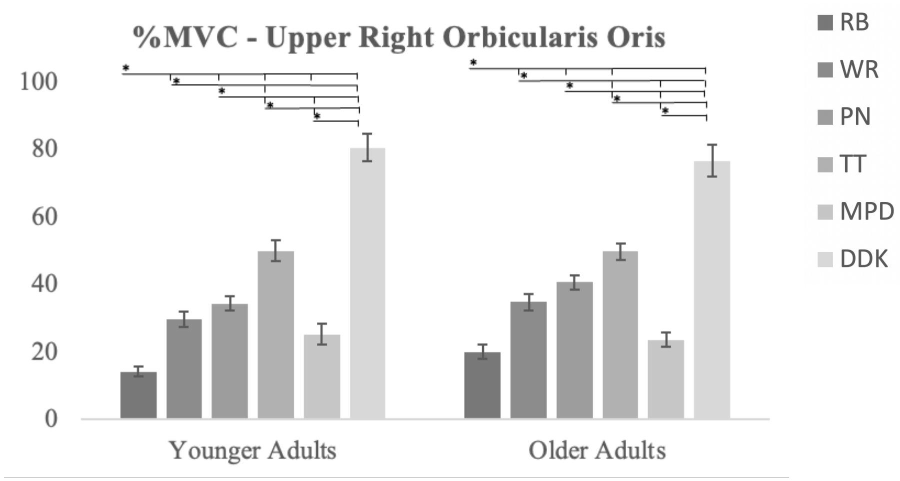
Woods, M. J., Nicholas, C. L., Semmler, J. G., Chan, J. K. M., Jordan, A. S., & Trinder, J. (2015). Common drive to the upper airway muscle genioglossus during inspiratory loading. *Journal of Neurophysiology*, *114*(5), 2883–2892. https://doi.org/10.1152/jn.00738.2014

Supplemental Materials

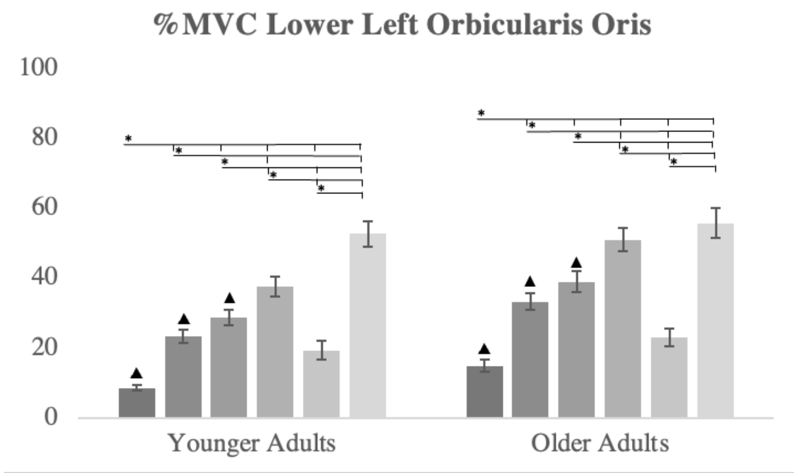
A)



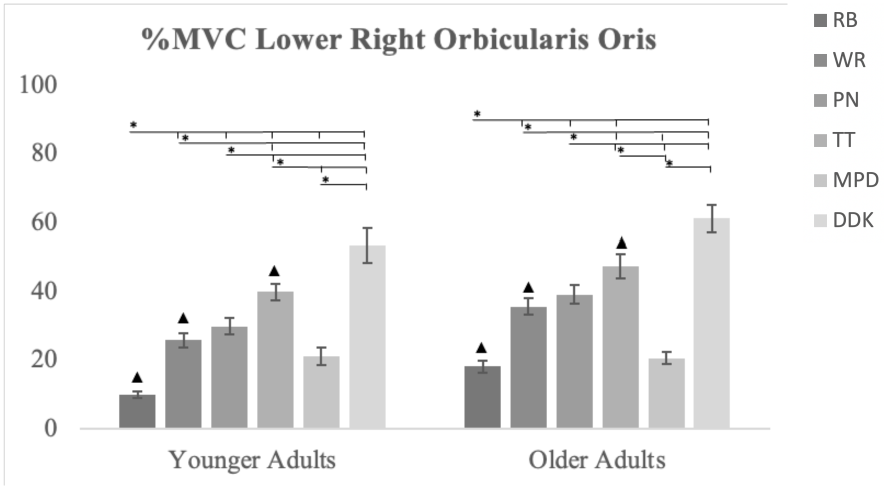
B)



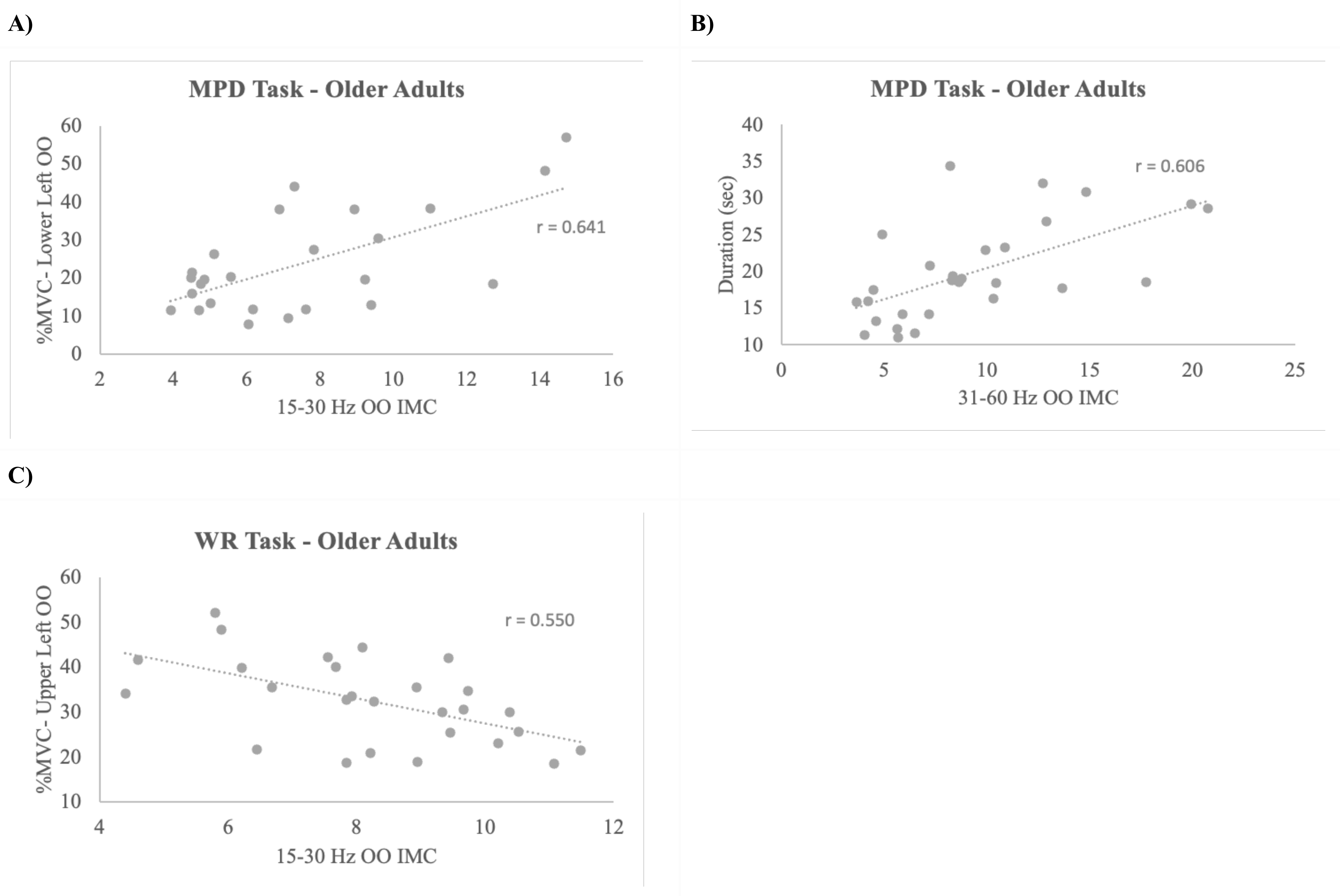
C)



D)



Supplemental Figure S3.1 A-D *Muscle contraction expressed as a percent maximum voluntary contraction (%MVC) of the upper left (A), upper right (B), lower left (C) and lower right (D) orbicularis oris in younger and older adults. Repeated measures ANOVAs were conducted in each segment for both age groups. There was a main effect of task for younger and older adults in the upper left segment (Younger:* $F_{2.28,59.19}=97.37^{+}$*, p< .001; Older:* $F_{2.50,55.04}=84.39^{+}$*, p < .001), upper right (Younger:* $F_{2.75,65.94}=115.2^{+}$*, p< .001 ; Older:* $F_{2.39,50.10}=58.46^{+}$*, p < .001), lower left (Younger:* $F_{2.91,66.85}=66.06^{+}$*, p< .001; Older:* $F_{2.47,56.78}=51.21^{+}$*, p < .001), and lower right (Younger:* $F_{1.97,47.22}=50.45^{+}$*, p< .001; Older:* $F_{2.80,55.95}=61.12^{+}$*, p < .001). Error bars indicate standard error of the mean. Asterisks denote significant task related differences within younger and older adult age groups. Triangles above task bars indicate a significant difference between age groups. RB= Rest breathing task, WR= Word reading task, PN=Picture naming task, TT=Tongue twisters task, MPD= Maximum phonation duration task, DDK= Diadochokinetic task.*


A)
MPD Task - Older Adults
%MVC- Lower Left OO
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
15-30 Hz OO IMC
r = 0.641
B)
MPD Task - Older Adults
Duration (sec)
40
35
30
25
20
15
10
0
5
10
15
20
25
31-60 Hz OO IMC
r = 0.606
C)
WR Task - Older Adults
%MVC- Upper Left OO
60
50
40
30
20
10
4
6
8
10
12
15-30 Hz OO IMC
r = 0.550

Supplemental Figure S3.2 A-C *Significant correlations between variables in younger and older adults. Transformed intermuscular coherence values are represented on the x axis. Pearson correlations were used to investigate whether intermuscular coherence is related to measures of subsystem performance, including maximum voluntary contraction and task performance. In the MPD task, older adults had a positive correlation between OO coherence in the 15-30 Hz frequency bandwidth and %MVC of the lower left orbicularis oris recording site (r= .641, p<.005; Panel A), and between OO coherence in the 31-60 hz frequency bandwidth and phonation duration (r= .606, p<.005; Panel B). There was also a negative correlation between OO coherence in the 15-30 Hz frequency bandwidth and activation of the upper left orbicularis oris during the WR task (r= - .550, p<0.012; Panel C). These correlations were not detected in younger adults. OO= Orbicularis oris, WR= Word reading task, MPD= Maximum phonation duration task, SEC=Seconds, %MVC=muscle activation expressed as a percentage of maximal voluntary contraction.*

Chapter 4: Lifespan Differences in Chest Wall Intermuscular Coherence

Neuromuscular Control of the Chest Wall for Speech and Non-speech Tasks in Children, Adolescents, and Adults: A Developmental Examination of Intermuscular Coherence

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Author Contributions

AR was responsible for study design, data collection and analysis and wrote the manuscript, RB was involved in data analysis and development of custom Matlab scripts for analysis, and authors JC and CB supervised all stages of the project. All authors reviewed the final manuscript.

Introduction

Changes in speech breathing have been well documented across the lifespan (e.g., Boliek et al., 2009; Connaghan et al., 2014; Hoit et al., 1989, 1990; Hoit & Hixon, 1987; Huber, 2008; Huber & Spruill, 2008; Sperry & Klich, 1992; Wang et al., 2010). Kinematic changes in respiratory patterns are the most well documented, and have primarily been studied through the use of variable inductance plethysmography and magnetometry, which involves the recording and calibration of chest wall movements to infer lung volume changes during speech and non-speech tasks(Hixon et al., 1973, 1976). Other measures, such as electromyographic recordings, can be used to further describe speech breathing behaviours including degree of muscular activation, its timing, as well as the frequency content (i.e., intermuscular coherence, IMC). In the current work, we systematically explore multiple measures of muscle activity (i.e., EMG, IMC) across varying age groups and tasks, to advance our understanding of speech breathing across the lifespan.

Over the past five decades, researchers have used observations of surface motions of the chest wall to document maturational changes in speech breathing. For example, when speaking, typical adults will initiate breath groups within the mid-range of their vital capacity (VC: maximum amount of air expired after a maximum inhalation) (Binazzi et al., 2006; Hixon et al., 1973, 1976; Hoit et al., 1989; Hoit & Hixon, 1987; Wang et al., 2010). Adults maximize efficiency of moving lung volume within their respiratory system by relying on the large surface area of the rib cage with the lungs, rather than displacing air using abdominal wall contraction. When the ratio of rib cage to abdominal wall movement is quantified using respiratory kinematics, adults typically demonstrate 80% contribution of the rib cage movement to lung volume displacement (Hixon et al., 1973, 1976). These efficiencies begin to emerge by age 10 years. Prior to age 10, children demonstrate variability in lung volume expenditure and also variability in rib cage and abdominal contributions during speech breathing (Boliek et al., 1997, 2009; Connaghan et al., 2014; Hoit et al., 1990; Moore et al., 2001; Stathopoulos & Sapienza, 1997). Children also demonstrate fewer syllables per breath group and use more air per syllable. Breathing patterns associated with speech remain stable until approximately the seventh and eighth decade of life, when changes are observed as an increase in lung volume excursion during speech and higher rib cage initiations (Hoit & Hixon, 1987; Huber, 2008; Sperry & Klich, 1992). Older adults exhibit a decrease in the number of syllables per breath group and more air expended (relative to VC) per syllable.

Investigations of the muscle activity underlying chest wall movements has provided additional context to our understanding of the respiratory subsystem. For example, in healthy young adults, large lung volume events a facilitated by expiratory braking (i.e., muscle activity controlling the flow of air to maintain tracheal pressure) primarily driven by abdominal wall activity and internal intercostal muscles (Hixon et al., 1976; Hoit et al., 1988; McFarland & Smith, 1989). For lung volume events that span the entire vital capacity, expiratory braking above resting level is accomplished by inspiratory muscle activity (i.e., diaphragm and external intercostals). When conversational speech continues below resting level, increasing expiratory muscle activity (i.e., internal intercostals) supports continued pressure generation. Muscles of the abdominal wall are active throughout the entire utterance.

The muscle activity underlying these movements remains poorly understood in the developmental context, as many of the studies have been conducted in healthy young adults. Some age-related differences have been reported in investigations using measures such as EMG activity of individual muscles or inferred muscle activity via changes in intra-abdominal pressure. For example, children and young adults show differences in task-specific abdominal wall and rib cage activation patterns (Clair-Auger et al., 2015). Whereas muscle activation of the chest wall varies as a function of the tracheal pressure needed during speech production in young adults (Clair-Auger et al., 2015; Hixon et al., 1976; Hoit et al., 1988; McFarland & Smith, 1989), children do not show a systematic change in EMG amplitude, and demonstrate higher levels of activation relative to adults (Clair-Auger et al., 2015). Although the preliminary studies suggest maturational changes in muscle activation, no studies have investigated chest wall muscle activity associated with speech in older adults.

In pursuit of a deeper understanding of underlying muscle activation patterns, researchers have started to employ the use of a variety of measurements derived from the EMG signal. For example, while the amplitude of a signal is, at least in part, related to the muscular force employed by a muscle (Merletti & Muceli, 2019), measurements such as intermuscular coherence (IMC) use EMG activity to provide information regarding the degree to which two signals receive the same neuromuscular input. IMC considers the frequency content of the EMG signal from two distinct muscle groups (Grosse et al., 2002). A cross-correlation between signals is performed, yielding a value between 0 and 1. Quantifying the two signal's similarity in this way is thought to provide insight into the afferent control used to execute muscular contraction (Conway et al., 1995; Grosse et al., 2002; Nishimura et al., 2009; Norton & Gorassini, 2006). By considering IMC within different frequency bandwidths, we can better characterize motor control that may arise from varying neural sources. In the beta bandwidth (15-30 Hz), for example, high degrees of IMC thought to arise from increased synergistic control, whereas decreased IMC may reflect an individuated control strategy (Boonstra, 2013; Boonstra & Breakspear, 2012; de Vries et al., 2016; Laine & Valero-Cuevas, 2017; Nazarpour et al., 2012;

Reyes et al., 2017). The gamma bandwidth (30-60 Hz) is often monitored to provide insight into the changes in sensory integration, which is associated with novel, complex or dynamic movements sequences and reflected in an increase in IMC values (Chang et al., 2012; De Marchis et al., 2015; Mohr et al., 2015, 2018; Omlor et al., 2007; von Tscharner et al., 2018).

IMC in the chest wall has previously been investigated across a variety of frequency bandwidths. Early research focused on high frequency (60-110 Hz) IMC in the diaphragm and intercostal muscles, and its connection to reflexive breathing control via the brainstem (Ackerson & Bruce, 1983; Bruce & Ackerson, 1986; Bruce & Goldman, 1983). More recent research began to expand our knowledge of the IMC sensitivity to changing task demands. Smith and Denny (1990) were the first to demonstrate a decrease in 60-110 Hz IMC during mid-range lung volume tasks compared to large lung volume tasks, additionally reporting that this difference occurred in the absence of any differences in beta or gamma bandwidth IMC (Smith & Denny, 1990). Whereas this initial work focused on evaluating IMC across inspiratory and expiratory phases of breathing, nearly a decade later, research has shifted to investigating muscles of the chest wall during expiratory phases of speech production. For example, expiratory muscles of the chest wall (intercostals and obliques) show sensitivity in beta bandwidth IMC in response to changes in lung volume (Boliek et al., 2019), generation of tracheal pressures (Tomczak et al., 2013) and in modulation relative to phase of speech production (Reed et al., 2021).

To date, investigations on the effects of aging on IMC in the chest wall remain sparse, despite the changes in respiratory kinematics documented in children and older adults. Studies investigating lifespan differences in IMC in the limbs have yielded mixed results, with some studies showing an increase (Castronovo et al., 2018; Farmer et al., 2007; Semmler, Kornatz, & Enoka, 2006) or no change (Jaiser, Baker, & Baker, 2016) with age. Preliminary work in the speech mechanism has failed to detect systematic differences in IMC between older (54-77 year olds) and younger adults (18-45 year olds) (Reed et al., n.d.-a, n.d.-b, 2021), although some differences in the pattern of IMC across tasks have been described.

In summary, although respiratory kinematics have provided valuable insight into age-related changes in speech breathing, the muscular control associated with age-related changes has yet to be fully explored. IMC has been proposed as a novel tool to further our understanding of speech motor control by providing insight into the coordination strategy employed by two disparate muscles. Together, physiological measurements taken at the periphery (i.e., EMG recordings), and derived IMC measurements, provide unique information regarding muscle firing patterns. Pairing traditional measures of speech motor control (e.g., acoustics, kinematics) to these unique peripheral measures of muscle activity can provide a more thorough understanding of speech motor control.

Present Study

The present study employed a cross-sectional design to evaluate IMC across the lifespan using four tasks designed to manipulate lung volume and tracheal pressure requirements. It includes a secondary analysis of the data from 120 typically developing children and adults in three separate studies. Each study used identical data acquisition protocols to collect chest wall kinematics and EMG recordings from the intercostals and external obliques. Given the lifespan changes in kinematic patterns observed in children over the age of 10, and in adults over the age of 50, we hypothesized that there would be significant differences in chest wall IMC for children, relative to all other age groups, and for older adults, relative to all other age groups.

Materials and Methods

Experimental overview

This study represents a secondary analysis of data collected during three separate studies in the Speech Physiology laboratory at the University of Alberta. All studies followed the same protocols for the acquisition of respiratory kinematics, EMG recordings from the intercostals and obliques and acoustic recordings (all study protocols approved through the University of Alberta Research Ethics Board). A subset of these data have previously been prepared for publication (Reed et al., n.d.-a, n.d.-b, 2021). After obtaining written and informed consent, participants were asked to sit upright in a chair as respiratory inductance plethysmography bands and EMG electrodes were placed on the chest. After confirming placement, an omni-directional microphone was placed on the forehead and data collection began. See Figure 4.1 for uncorrected kinematic and raw EMG signals of a representative participant.

Participants

Participants across all studies included thirty children (age: 7.70 years old ± 1.29; age range: 6-10 years old; sex: 14 male, 16 female), fifteen adolescents (age: 14.33 years old ±1.05; age range: 13-16 years old; sex: 4 male, 11 female), forty-five younger adults (age: 26.97 years old ± 6.04; age range: 18-43 years old; sex: 11 male, 34 female) and thirty older adults (age: 66.37 years old ± 6.83; age range: 54-77 years old; sex: 7 male, 23 female). All participants were native English speakers, free of neurological and muscular conditions. Participants were required to have a negative history of speech, language or learning delays or disorders. Participants with corrected vision or hearing impairments were permitted to participate.

Tasks

Four tasks designed to manipulate lung volume requirements and laryngeal function (i.e., generating pressure to produce sound) were included in this study (see Table 4.1). Two were non-speech tasks requiring no maintenance of subglottal pressure: a vital capacity (VC) maneuver (high lung volume) and rest breathing (RB) (small lung volume). The VC task consisted of a maximum inspiration followed by a maximum expiration, and was performed three times (e.g., *take a deep breath in and blow it all out*). The RB task was recorded while participants relaxed (2 minutes of recording, approximately 20 rest breaths).

Two tasks involving generation of tracheal pressure for sound production were included. A maximum phonation duration (PHON) task is a large lung volume task involving a maximum inspiration followed by the production of a neutral vowel ("ah") until all air is expended (e.g., *take a big breath in and then say ah for as long and as steady as you can*). A small lung volume task requiring maintenance of subglottal pressure also was included (i.e., speech task (SP)). In two of the three studies included in the present analysis, data from a sentence repetition task was used (e.g., *Buy bobby a puppy*, *The blue spot is on the key*, and *The potato stew is in the pot*). In the third study, a single word overt reading task served as the small lung volume task involving speech. During this task, two lists of forty words containing monosyllabic four-letter words were used. These lists were balanced for onset phoneme and word type (e.g., regular words such as hint, exception words such as pint, nonwords such as bint and pseudohomophones, such as pynt). Stimuli were presented using E-prime software.

T*able 4.1. Description of the lung volume requirements, laryngeal engagement, articulatory demands and cognitive-linguistic considerations of each task.*

Task	Lung volume requirements (respiratory subsystem)	Laryngeal engagement (laryngeal subsystem)	Articulatory demands (Articulation Subsystem)	Cognitive- linguistic considerations
Vital Capacity Maneuver (VC)	Range of Large Lung Volumes	None	None	Novel non speech
Maximum Phonation Duration (MPD)	Range of Large Lung Volumes	Sustained	Low demand	Novel non speech
Rest Breathing (RB)	Range of Small Lung Volumes	None	None	None
Speech (SP)	Range of Small Lung Volumes	Alternating	Habitual Speech	Sentence Repetition & Naming

Analysis

All EMG and kinematic signals were sampled at 10 kHz and collected simultaneously using a multichannel acquisition system (PowerLab 16SP ML795; ADInstruments, Colorado Springs, CO); time locked digital recordings were saved using LabChart software (version 5.5.6; ADInstruments). Data were collected according to previously published protocols (Boliek et al., 2019; Reed et al., 2021; Tomczak et al., 2013).

Kinematics. Chest wall kinematics were recorded using variable inductance plethysmography (Respitrace, Ambulatory Monitoring Company, NY). This technique measures the change in diameters of the rib cage and abdomen using separate transduction bands (i.e., one band placed over the rib cage, with the upper edge below the axillae, and another over the abdomen, with its upper edge just below the costal margin). These measurements were calibrated and analyzed offline using custom Matlab programs. Calibrations were calculated using an isovolume maneuver (during a breath hold, pulling their stomach in and letting it relax) and a rest breathing task where participants breathe through a mouthpiece attached to a calibrated pneumotachometer and differential pressure transducer (nares occluded with soft nose clips) (Validyne model DP45-14; Validyne Model CD15). Together, these measurements allow for the conversion of the summed movement of the rib cage and abdomen into displacement of the lung in volume (Hixon et al., 1973). Calibrated estimates of vital capacity were compared to predictions based on age, sex and height to confirm accuracy of calibration (Quanjer et al., 2012).

Calibrated signals were segmented from onset to offset of expiration for each trial, for each participant. Analysis yielded two variables for all tasks: lung volume excursion expressed in percent vital capacity (%VC) and percent rib cage contribution to total lung volume excursion (%RC). %VC was individually calculated by trial by dividing the lung volume displacement by the person's vital capacity. The value used for vital capacity was, for most participants, the largest lung volume excursion observed across vital capacity trials. When the observed values were below a participant's predicted value based on age, height, and sex, the predicted value was used in calculations of %VC. %RC was calculated by dividing the lung volume displacement of the rib cage by the total lung volume displacement. Additionally, in the SP task, lung volume excursion per syllable in percent vital capacity/syllable (%VC/SYLL) was calculated.

EMG data. EMG data were collected using paired surface electrodes placed over the right intercostals (between the 6-7th intercostal space) and right obliques (10 cm left of umbilicus). Correct placement was confirmed using tasks designed to elicit maximum voluntary contractions from each muscle (a vital capacity maneuver with a breath-hold at the top of the inspiratory capacity for the intercostals, a trunk rotation against resistance for the obliques). A reference electrode was placed on the midline of the right clavicle. Signals were sampled at a rate of 10 kHz, amplified and band-pass filtered (3-3000 Hz) (Grass P511; Astro-Med, Inc., Quincy, MA). An additional notch filter at 60 Hz was used to minimize power line interference.

EMG signals were used to calculate two dependent variables: muscle contraction as a percentage of the muscle's maximum voluntary contraction amplitude (%MVC) and IMC. Signal amplitude provides insight into the degree of muscle contraction during a task. It is calculated as a percentage of maximal voluntary contraction using reference values from resting EMG and tasks designed to elicit MVC (e.g., tasks used to confirm electrode placement, see above). Reference values were extracted and used to calculate degree of muscle contraction using custom matlab scripts (See Boliek et al., 2019 and Tomczak et al., 2013 for further details). Data were high-pass filtered using a cut off frequency of 60 Hz, prior to rectification and smoothing. Values were generated for each trial and averaged within each task. Individual values over 200 percent MVC were dropped from analysis. Individual trials were segmented using the respiratory kinematic signal: for the SP, VC and MPD tasks, the expiratory limb was isolated. For the rest breathing task, a period of ~10 sequential breaths was segmented (i.e., inspiration and expiration). These segments were used for both %MVC and IMC calculations.

IMC values were also calculated using custom Matlab scripts and open-access programs (see Reed et al., 2021). Data processing involved multiple steps including filtering using a 30 Hz high-pass butterworth filter and a 300 Hz low-pass filter and rectification of signals. IMC (Equation 1) was calculated using a frequency resolution of 2.44 Hz and segment length of 2,048 points. IMC values were normalized for the number of segments (Equation 2) prior to statistical analysis.

$$Coh_{XY}(f) = \left|C_{xy}(w)\right|^2 = \frac{\left|\overline{G_{xy}(w)}\right|^2}{\overline{G_{xx}(w)}\cdot\overline{G_{yy}(w)}}$$

Equation 1 . Intermuscular coherence calculation where Coh=magnitude square coherence; Gxx(w) and Gyy(w)= averaged power spectra of the x and y muscles of interest, for a given frequency (w); Gxy=averaged cross-power spectrum of x and y signals at frequency w (Norton & Gorassini, 2006; Rosenberg et al., 1989).

$$Z\,(f) = \operatorname{atanh}\left(\sqrt{Coh\,(f)}\,\right) / \sqrt{1/(2 * L)}$$

Equation 2. Standardized Z score transformation of intermuscular coherence at frequency (f), given L segments (Rosenberg et al., 1989, as used by Baker, Pinches, & Lemon, 2003)

Measures of Task performance. Acoustic recordings were made from an omni-directional microphone (Audio-Technica, Model AT 803b) placed 10 cm above participant's mouth. Signals were sampled at 48 kHz, amplified (M-Audiobuddy Pre-Amplifier) and recorded using TF32, a Windows based form of CSpeech Software (Milenkovic, 2001). Offline analysis of maximum performance duration for the MPD task was calculated by isolating voice onset and offset using TF32 and PRATT software (Boersma & Weenink, 2013).

Statistics

Statistical analyses were performed using JASP statistical software (version 0.16.3; JASP Team, 2022). Values more than 1.5 *SD*s from the mean of each age group were excluded from the analysis (<1% of data). Between group differences were investigated using one way ANOVAs for each individual variable. Task related differences were calculated within each age group using repeated measures ANOVAs. All post hoc analyses are reported using a Holm correction. Normality was confirmed using the Shapiro-Wilk test of normality. When necessary, Mann-Whitney U tests were used to conduct post hoc analyses. In the event of a violation of sphericity (as per Mauchly's test of sphericity), Greenhouse-Geisser corrected values are reported (denoted using +). Chest wall kinematic variables (%VC, %RC, %VC/SYLL) and muscle activation variables (%MVC for intercostals and obliques) were subjected to the same statistical routine. Prior to analysis, individual %MVC values above 200 were removed. In addition to one-way ANOVAs, the relationship between age and IMC was investigated using Bonferroni corrected Pearson correlations.

Results

IMC findings are presented below, with representative, unfiltered kinematic and raw EMG signals depicted in Figure 4.1 and representative IMC in Figure 4.2. Exploratory variables including respiratory kinematics and EMG amplitude, as well as correlations between these variables and IMC are presented in Supplementary Materials by task and by age.

For each variable, statistical significance of task- and age-related differences are denoted within figures and reported in figure captions. Supplemental Materials Figures S4.1A-B, S4.2A-B and S4.3A-B, depict lung volume excursion in percent vital capacity (%VC), percent rib cage contribution to total lung volume excursion (%RC) and lung volume excursion (in percent vital capacity, %VC) per syllable (%VC/SYLL), respectively. Degree of muscle contraction, expressed relative to the muscle's maximum voluntary contraction, is reported for both the intercostal and oblique muscles in Supplemental Materials Figures S4.4A-B and S4.5A-B, respectively. The findings confirmed successful manipulation of lung volume excursion, with small lung volume tasks demonstrating significantly lower %VC relative to large lung volume tasks. Data presented in supplemental materials will be used to provide context to IMC findings in the discussion.

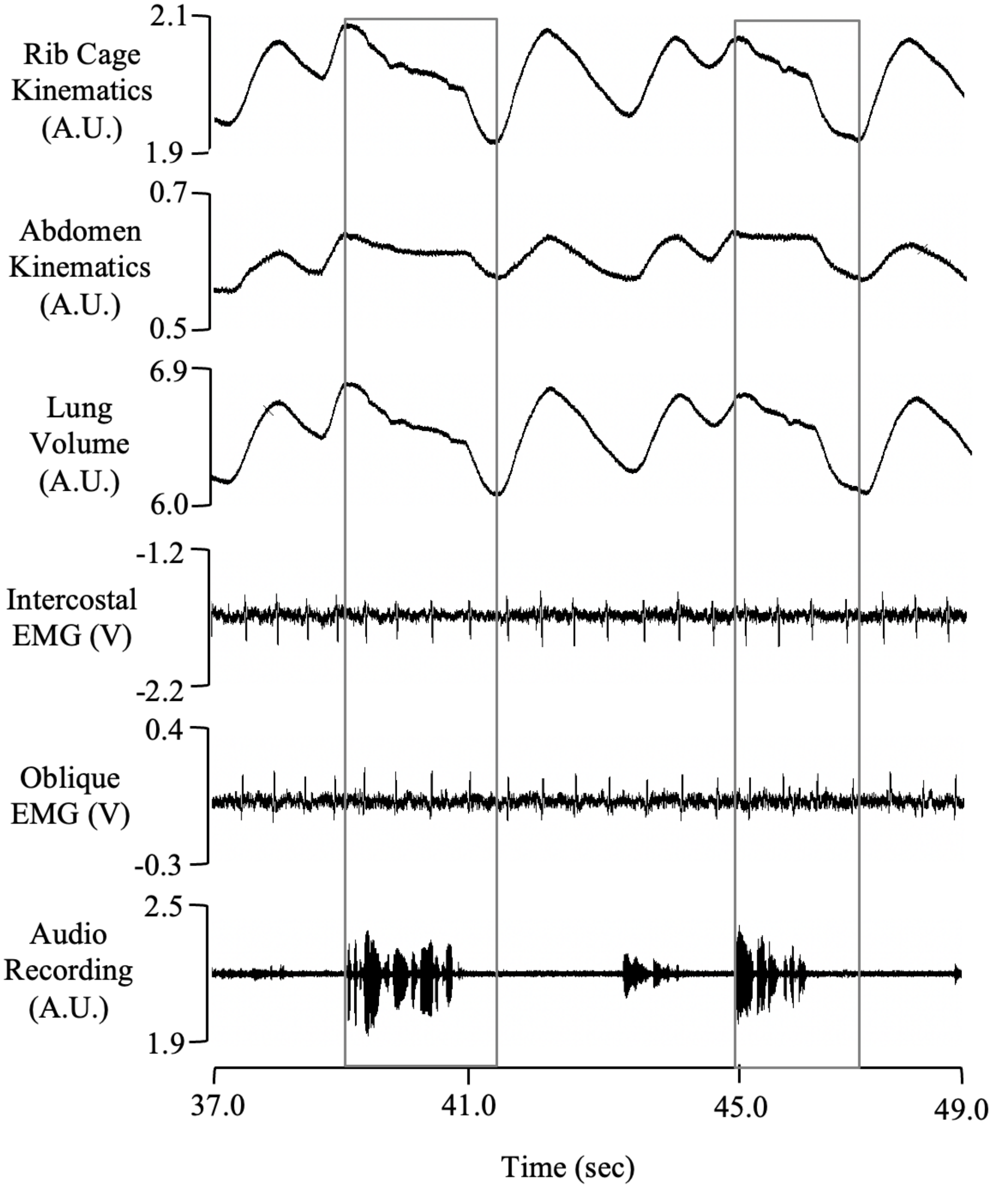


Figure 4.1 *Unfiltered data from a representative subject. Rib cage (RC) and abdominal (AB) kinematic signals, uncalibrated lung volume signal used for file segmentation in LabChart (corrected for RC and AB contributions), intercostal and oblique EMG activity, and the acoustic signal (AC) during a Maximum Phonation (MPD) and Speech (SP) task. Expiratory window denoted using dotted lines (as measured by the LV signal). au = arbitrary units, V = volts.*

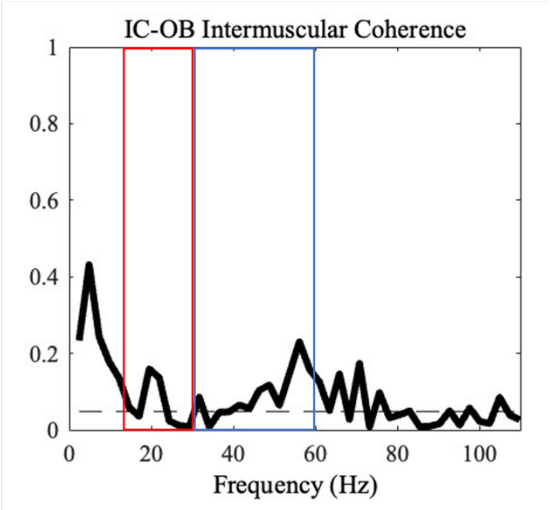


Figure 4.2 Intercostal (IC)- Oblique (OB) Intermuscular coherence for a representative subject for the rest breathing task. The y and x axes represent intermuscular coherence strength and frequency (Hz), respectively. The red and blue rectangles indicate the 15-30 Hz and 31-60 Hz frequency bandwidths, respectively. The dotted line represents the 95% confidence interval.

Measures of Task Performance

MPD task duration across age groups is reported in Table 4.2. One Way ANOVA indicated significant differences between groups ($F_{3,111}$=13.544, *p*< .001). Post hoc independent samples t-tests indicated that children had significantly shorter maximum phonation times relative to all other age groups (all *p*<0.001). No other age related differences were detected.

Table 4.2 *Mean Duration (in seconds) and rate (syllables per second) for maximum phonation duration (MPD) task, diadochokinetic task (DDK) and tongue twisters (TT) task.*

Age	MPD Duration (sec)
Children	13.33 (3.58)
Adolescents	22.40 (6.41)
Younger Adults	20.32 (4.68)
Older Adults	19.67 (6.77)

Intermuscular Coherence

Age related differences in IMC were investigated using a series of statistical tests. First, one way ANOVAs were used to investigate differences between age groups within each task (Figure 4.3 B,D). Second, repeated measures ANOVAs were executed within each age group in order to detect whether each group demonstrated different patterns of IMC across tasks (Figure 4.3 B,D). Last, Pearson correlations were used to investigate whether age correlates with IMC.

Age Related Differences Within Tasks

In the 15-30 Hz bandwidth, one way ANOVAs did not detect between group differences in the small lung volume tasks (RB: $F_{3, 113} = 0.823$ $p<0.484$; SP: $F_{3,60.18} = 1.854^{+}$ $p<0.147$), however significant differences were detected in both the VC ($F_{3,63.03} = 4.86^{+}$ $p<0.004$) and MPD ($F_{3, 29.55} = 10.28^{+}$ $p<0.001$) tasks. In the VC task, post hoc testing indicated that children had significantly lower IMC relative to adolescents and younger and older adults (all $p<0.05$). In the MPD task, children had significantly lower IMC relative to adolescents and younger adults (both $p<0.05$). Adolescents had higher IMC relative to younger and older adults (both $p<0.05$).

A similar pattern was found in the 31-60Hz bandwidth. No differences were detected between groups in either the RB ($F_{3,112} = 1.418$ $p<0.241$) or SP ($F_{3,70.33} = 1.513^{+}$ $p<0.219$) tasks, however lower IMC was detected in children for the MPD ($F_{3,53.46} = 4.68^{+}$ $p<0.006$) and VC ($F_{3,85.39} = 2.988^{+}$ $p<0.036$) tasks. In the MPD task, children had lower IMC relative to adolescents and older adults (both $p<0.05$). In the VC task, children had lower IMC compared to older adults ($p<0.05$).

Task differences within age groups

As previously stated, repeated measures ANOVAs were conducted within each age group in order to further investigate task related differences in IMC. ANOVAs indicated no main effect of task in the 15-30 Hz frequency bandwidth for older adults ($F_{2.01,38.22}=3.08^{+}$, $p< .057$). A main effect of task was detected in all remaining age groups for the 15-30 Hz (Children: $F_{6.55,128.89}=19.67^{+}$, $p< .001$;Adolescents: $F_{1.94,25.15}=3.58^{+}$, $p< .044$; Younger Adults: $F_{3,105}=6.10$, $p< .001$;) bandwidth, and across all ages in the 31-60 Hz (Children: $F_{3.12,138.31}=29.68^{+}$, $p< .001$; Adolescents: $F_{3,27}=3.21$, $p< .039$; Younger Adults:$F_{3,111}=7.77$, $p< .001$; Older Adults: $F_{3,66}=3.68$, $p< .016$) frequency bandwidth. The following sections outline the task related differences in IMC for each age group.

Children. The same pattern of IMC across tasks was detected in both the 15-30 Hz and 31-60 Hz frequency bandwidths. In this age group, the MPD and VC tasks had the lowest IMC overall, followed by the SP task, with RB having the highest IMC overall (all $p<0.05$).

Adolescents. Few task related differences were detected in the adolescent age group. In the 15-30 Hz frequency bandwidth, the MPD task was found to have significantly higher IMC relative to the VC task ($p<0.05$). In the 31-60 Hz frequency bandwidth, the RB task was found to have significantly higher IMC compared to the VC task ($p<0.05$).

Younger Adults. A pattern of low IMC for the VC task also was found in both frequency bandwidths in younger adults. In both bandwidths, the RB and SP tasks had significantly higher IMC relative to VC (both $p<0.05$). In the 31-60 Hz frequency bandwidth, the MPD task also was found to have higher IMC relative to VC ($p<0.05$).

Older adults. The RB task was found to have significantly higher IMC relative to the VC task in the 31-60 Hz frequency bandwidth of older adults ($p<0.05$).

Correlations with age

Pearson correlations detected no significant relationship between age and IMC in either frequency bandwidth, in any task (all $p > 0.05$).

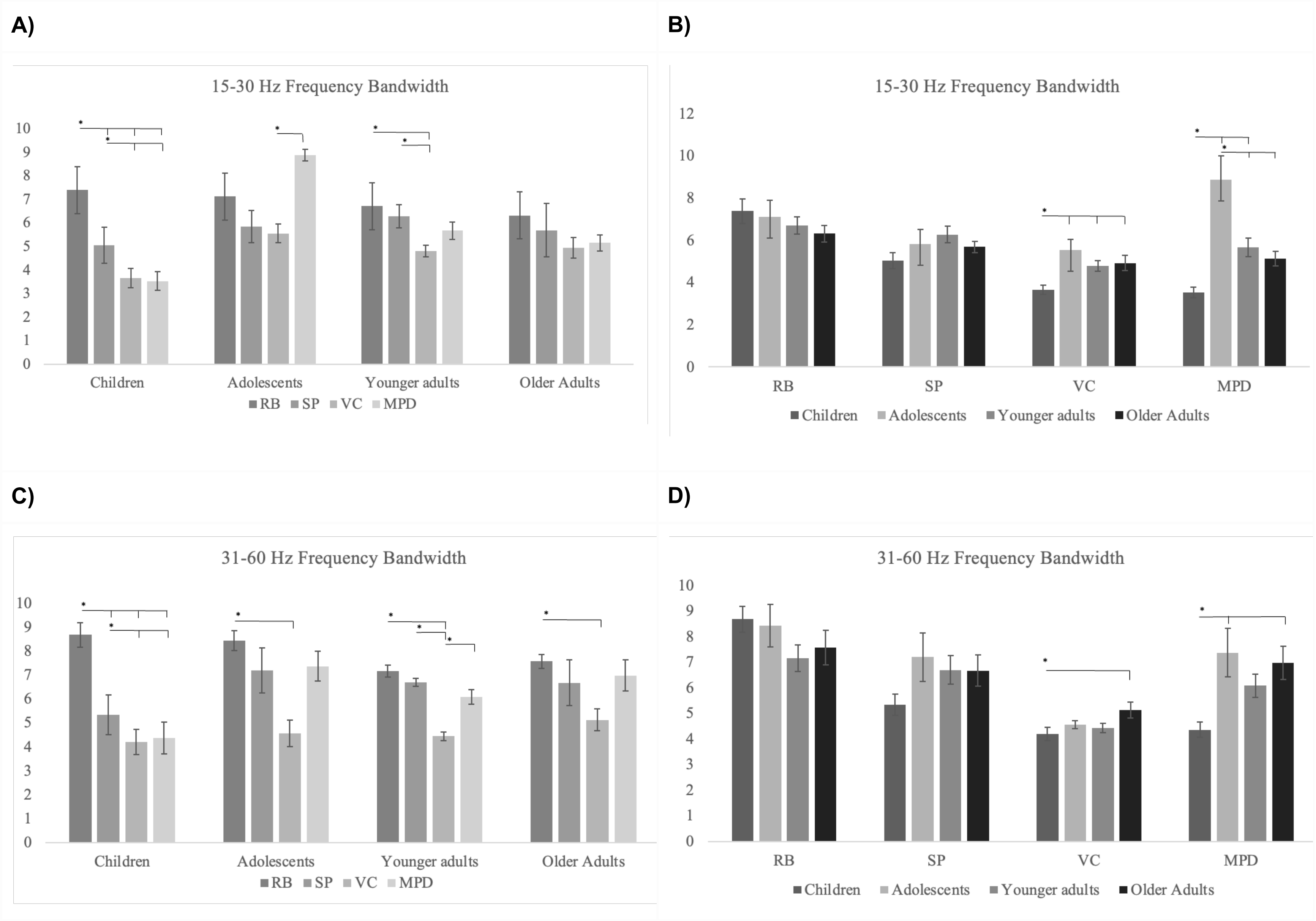

A)
15-30 Hz Frequency Bandwidth
0
1
2
3
4
5
6
7
8
9
10
*
*
Children
Adolescents
Younger adults
Older Adults
RB
SP
VC
MPD
B)
15-30 Hz Frequency Bandwidth
0
2
4
6
8
10
12
*
RB
SP
VC
MPD
Children
Adolescents
Younger adults
Older Adults
C)
31-60 Hz Frequency Bandwidth
0
1
2
3
4
5
6
7
8
9
10
*
Children
Adolescents
Younger adults
Older Adults
RB
SP
VC
MPD
D)
31-60 Hz Frequency Bandwidth
0
1
2
3
4
5
6
7
8
9
10
*
RB
SP
VC
MPD
Children
Adolescents
Younger adults
Older Adults

Figure 4.3 *Intercostal-Oblique Intermuscular coherence (IMC) in Children, Adolescents, Younger Adults and Older Adults. Transformed IMC values are represented on the y axis; values are graphed separately by age and by task for both frequency bandwidths to highlight task differences within age groups (Panels A and C), and between group differences within tasks (Panels B and D). Panels A and C depict task differences, within each age group, for the 15-30 Hz and 31-60 Hz frequency bands, respectively. Panels B and D depict age related differences, within each task, for the 15-30 Hz and 31-60 Hz frequency bands, respectively. Error bars indicate standard deviation of the mean. Asterisks denote significant task related differences within younger and older adult age groups. RB= Rest breathing task, SP= Speech task, VC= Vital Capacity task, MPD= Maximum phonation duration task.*

Discussion

The purpose of the present study was to examine IMC between intercostal and oblique muscles during speech breathing from childhood to older adulthood. Four tasks were performed by participants across four age groups: children, adolescents, younger adults and older adults. There were three key age related findings. First, in both the beta (15-30 Hz) and gamma (31-60 Hz) bandwidths, age related differences were prominent in maximum performance tasks. In the beta bandwidth, children demonstrated significantly lower IMC relative to other age groups in both the VC and MPD tasks, suggesting a shift from individuated towards synergistic control of the chest wall as we age. In the gamma bandwidth, this pattern was also observed in the MPD task, with children demonstrating significantly lower IMC relative to adolescents and older adults. Second, the highest number of task related differences in IMC was found in younger children. This is consistent with previous reports of variability in chest wall contribution as a defining characteristic of development. Third, despite differences in older adult's level of muscle activation relative to younger age groups, older adults did not demonstrate significantly different IMC. In addition to age related findings, the present data extend previous reports of decreased IMC in large lung volume tasks relative to small lung volume tasks. Although this effect has previously been reported in adults, lung volume effects were present across all age groups, with most age groups demonstrating significantly lower beta and gamma bandwidth IMC in the VC task relative to the RB task. This pattern was absent in the beta bandwidth of adolescents. These findings will be contextualized within respiratory kinematic and muscle activation data presented in Supplementary Materials (Figures S4.1-S4.3 and S4.4-S4.5, respectively), and interpreted within existing IMC research.

Age related differences in High Performance tasks

Between-group age-related differences in IMC were restricted to high performance tasks in both the beta and gamma frequency bandwidths for VC and MPD tasks (Figure 4.3B and 4.3D). These age-related differences represent a novel contribution to the growing body of IMC research in the speech mechanism. The findings within each frequency bandwidth will be interpreted below within the context of existing research.

Beta Bandwidth

In both the VC and MPD tasks, children in general demonstrated significantly lower IMC relative to adolescents, younger adults and older adults. This finding is consistent with preliminary studies reporting age related increases in IMC in gross and fine motor control of the limbs (Castronovo et al., 2015; Farmer et al., 2007; Semmler et al., 2006). IMC in this bandwidth has previously been linked to differences in neuromuscular control strategy, with higher IMC values indicating synergistic control of disparate muscles, and lower IMC suggesting individuated control (Kenville et al., 2020; Laine & Valero-Cuevas, 2017). Interpreted within this context, the pattern of IMC reported in the present study may suggest that children employ an individuated control strategy of chest wall musculature for speech breathing, whereas adolescents and adults employ synergistic control.

This interpretation aligns with our current understanding of the variability that underlies speech breathing in children. Speech breathing becomes adult-like by age 10, with children at this age beginning to demonstrate more refined breathing patterns that capitalize on biomechanical efficiencies of the chest wall (Hoit et al., 1990). Respiratory kinematic findings reported in supplemental materials also support this finding. Children showed higher %RC contribution relative to younger and older adults in the MPD task (see Supplemental Materials S4.2). In the MPD task, children also demonstrated higher %MVC in the obliques relative to younger and older adults, and higher %MVC in the intercostals relative to younger adults (see Supplemental Materials S4.4). Although these differences in %RC and %MVC align with the interpretation of children utilizing a different neuromuscular control strategy in the MPD task, the same pattern was not observed in the VC task. That is, although the between group differences in the MPD task were accompanied by differences in chest wall mechanics, the VC task was accomplished using similar amounts of rib cage contribution and muscle activation across age groups. Taken together, this finding suggests that chest wall mechanics is likely not the sole mechanism underlying the difference in neuromuscular control strategy observed in VC and MPD tasks. Instead, the lower IMC observed in children may be due to additional factors such as the high performance nature of the task and the sensitivity of chest wall IMC to the effects of lung volume. It is possible that in order to successfully accomplish this task, children are more dependent on a synergistic control strategy, and as the speech mechanism matures, individuated control drives performance.

Beyond the reported differences between groups in large lung volume tasks, a novel finding was the presence of significant task related differences in children's IMC values in the beta bandwidth. All age groups demonstrated similar task related differences of respiratory kinematics and muscle activation, however children showed more task related differences in IMC. Younger children displayed the highest levels of IMC in the RB task followed by the SP task, with VC and MPD tasks having the lowest IMC overall. Whereas the differences between small and large lung volume tasks can be accounted for by lung volume effects (explored in subsequent sections), the difference in IMC between the RB and SP task warrants further consideration. Interestingly, there are no differences between these two tasks in %RC, %VC or %MVC. Thus, the individuated control present for the SP task may be due to the increased task demands involved in speech breathing versus rest breathing. In other words, the addition of laryngeal and articulatory demands required to produce speech may differentially impact the neuromuscular control strategy of children versus the other age groups. Together, these findings suggest that these control strategies are continuing to mature in this period of development.

Interestingly, although older adults demonstrated several differences in respiratory kinematics and muscle activation relative to other age groups, few differences were detected between chest wall IMC of this age group relative to the others. For example, older adults demonstrated significant differences in % MVC of the IC and OB in small lung volume tasks. In the RB task, older adults had significantly higher %MVC in both muscle groups relative to children and younger adults. In the SP task, both children and older adults had higher %MVC for both muscles relative to younger adults. Older adults also had significantly higher %VC/SYLL values relative to all other age groups. Despite these differences in small lung volume tasks, no differences in IMC during these tasks were observed. This finding was also present in large lung volume tasks. In line with previous findings, older adults demonstrated decreased respiratory efficiencies in chest wall kinematics, with lower %RC contribution being reported in this age group in the VC and MPD tasks relative to all other age groups (Hoit & Hixon, 1987; Huber, 2008; Sperry & Klich, 1992). Similar to the patterns observed in small lung volume tasks, older adults did not demonstrate significant differences in IMC relative to adolescents or younger adults. Taken together, it is unclear to what extent age-related differences in speech motor control efficiencies, especially in older adults, are linked with differences in neuromuscular drive. In the present study, no differences in IMC were detected in older adults despite differences in chest wall efficiencies. Although not measured in the present study, previous research has also established that with increasing age, changes are observed in signal transmission, characterized by a decrease in the number of motor units (Campbell et al., 1973), changes in neuronal size (Haug & Eggers, 1991), and glutamate uptake capacity (Segovia et al., 2001), as well as decreased elasticity of tissues and increased rigidity of chest wall structures (Scott-Warren & Maguire, 2017).

While IMC as measured in the current study was not sensitive to such changes, further research is needed to establish how speech motor control networks compensate for these changes. Moreover, given the central role of acoustic and somatosensory information in monitoring and adjusting motor control in speech production, the impact of senescent changes warrants further investigation (Behroozmand et al., 2015; Bronson-Lowe et al., 2013; De Miranda Marzullo et al., 2010; Etter et al., 2018; Tourville et al., 2008; Tourville & Guenther, 2011; Tremblay et al., 2003; Villacorta et al., 2007).

Gamma Bandwidth

Fewer age-related differences were detected in the gamma bandwidth, however the differences observed support the conclusion that the maturational changes in speech breathing that occur after the first decade of life may also be accompanied by differences in neuromuscular control strategies. In the gamma bandwidth, children demonstrated significantly lower IMC relative to older adults in the VC task and significantly lower IMC relative to adolescents and older adults in the MPD task.

Differences in this bandwidth are most commonly reported to reflect a shift in the integration needed to execute a novel or complex task, with increases in IMC reported to occur during these tasks relative to baseline (De Marchis et al., 2015; Mohr et al., 2015; von Tscharner et al., 2018). Interpreted within this context, the gamma bandwidth findings may suggest differences in how sensory information impacts neuromuscular control as the system develops and matures. The role of sensory feedback in outgoing adjustments in speech motor control has been well documented across the lifespan (Behroozmand et al., 2015; Bronson-Lowe et al., 2013; De Miranda Marzullo et al., 2010; Tourville et al., 2008; Tourville & Guenther, 2011; Tremblay et al., 2003; Villacorta et al., 2007). More recently, differences in sensorimotor adaptation between children and adults have also been reported (Ohashi & Ostry, 2021). The present findings may provide additional support to a growing body of literature suggesting continued growth in the sensory system in children of this age group.

Further evidence of developmental differences was observed when considering task-related differences in each age group. Similar to the beta bandwidth findings, younger children displayed the highest levels of IMC in the RB task followed by the SP task, with VC and MPD tasks having the lowest IMC overall. Differences between RB and SP tasks were not observed in other age groups, suggesting developmental differences in neuromuscular control. The decrease in SP relative to RB observed in the gamma bandwidth is difficult to interpret within existing IMC literature. When considering the demands between the RB and SP tasks, the tracheal pressure requirements of the SP task suggest that this task would be considered more complex. Thus, increases in this bandwidth would not be expected for the RB task, given the relatively simplistic nature of the task. Perhaps this unexpected difference is due to developmental differences in the sensory system, which may be impacting the extent to which children are able to integrate sensory information during speech production. This finding further highlights the need for more extensive research to continue to elucidate the mechanisms underlying changes in IMC within the speech mechanism.

In older adults, consistent with the beta bandwidth, differences in IMC relative to other age groups were also notably absent in the gamma bandwidth, despite differences in chest wall kinematics and muscular activation. This finding was unexpected, given the growing body of research establishing differences in sensorimotor integration in older adults (Bronson-Lowe et al., 2013; De Miranda Marzullo; Etter et al., 2018). The absence of a significant difference in IMC despite documented differences in how older adults detect and integrate sensory information may be due to the speech subsystem measured in the present study. Although sensory system changes are well documented, differences have primarily been investigated in the articulatory subsystem. It is possible that these changes may not impact sensorimotor control of the respiratory system. Indeed, previous work published on IMC in the orbicularis oris derived from a subset of participants as the present study, reported several task-related differences in gamma bandwidth IMC in older adults that were not present in younger adults (Reed et al., n.d.-b).

Lung volume effects across lifespan

Interestingly, all age groups demonstrated significantly lower IMC in the VC relative to the RB task in both beta and gamma frequency bandwidths, with the exception of beta bandwidth IMC in adolescents and older adults. The mechanism underlying this effect will be explored within existing research and current understanding of beta and gamma frequency bandwidth changes.

Beta Bandwidth

Lung volume effects on IMC in the beta bandwidth have previously been reported in younger and older adults (Boliek et al., 2019; Reed et al., n.d.-a; Tomczak et al., 2013). The present study extends these findings to include the presence of such effects in children. Interestingly, although the effects of lung volume were only observed between RB and VC tasks in younger and older adults, children demonstrated significantly lower IMC in both large lung volume tasks relative to both small lung volume tasks.

This shift from synergistic to individuated control has previously been proposed to arise from the chest wall mechanics employed during lung volume events spanning the entire vital capacity (Reed et al., n.d.-a). That is, during large lung volume events, the activity of the rib cage and abdomen is coordinated to expel air, however the timing of activation between muscles differs greatly (Clair-Auger et al., 2015; Hixon et al., 1976; Hoit et al., 1988). Interestingly, although similar patterns of activation are theoretically used in both VC and MPD tasks, a shift to individuated control was only statistically significant between RB and VC tasks in younger and older adults. Respiratory kinematics may provide additional context to these findings. When comparing %VC between the two tasks, younger and older adults expended significantly less air during the MPD task relative to the VC task, whereas children and adolescents had similar lung volume expenditure. It is possible then, that younger and older adults did not demonstrate significantly lower IMC in the MPD task as the task did not involve the same degree of lung volume expenditure as the VC task.

Alternatively, it may be hypothesized that the added laryngeal demands of the MPD task played a role in the results of older and younger adults. This explanation is unlikely, however, as previous studies have in fact reported a significant decrease in beta bandwidth IMC in VC and MPD tasks in healthy young adults (Tomczak et al., 2013). Critically, although statistical analysis of between task differences in %VC is not reported, visual inspection of figures from this work suggests that the VC and MPD tasks were completed using similar lung volume expenditure (see Fig. 5, Tomczak et al., 2013), which may account for the discrepancy with present findings. In order to test this hypothesis, future investigations should include tasks of varying demands (e.g., with phonation requirements) produced at similar lung volumes, to determine whether the effect remains present.

Gamma Bandwidth

The mechanism underlying the decrease in IMC with increased lung volume in the gamma bandwidth is not well understood. Studies of IMC in the limbs have not found force related changes in this frequency bandwidth (Castronovo et al., 2015; Poston et al., 2010), and few studies have investigated the relationship between force and IMC in the speech mechanism. Studies of chest wall IMC in the 30-60 hz frequency range have reported similar values across tasks with the same muscular contraction levels produced across a range of lung volumes, providing further evidence that force is an unlikely explanation for the decrease in IMC observed (Boliek et al., 2019). Further work with more systematic control of task variables is needed to understand the mechanism underlying this finding.

Gamma IMC is thought to represent sensory integration, with increases in this bandwidth observed in highly complex and/or novel tasks (Chang et al., 2012; De Marchis et al., 2015; Kenville et al., 2020; Mohr et al., 2015; Omlor et al., 2007). This interpretation is difficult to reconcile with our knowledge of the differences underlying the small and large lung volume tasks included in this study. Performance of VC and MPD tasks are commonly viewed in the field of speech motor control as maximum performance tasks, as they require the system to coordinate chest wall musculature to overcome the peak expiratory and inspiratory recoil pressures that occur at the top and bottom of the vital capacity, respectively. In the case of the MPD task, the systems must also ensure consistent tracheal pressure. Although not measured in this study, it may be hypothesized that these tasks would result in increased sensory information relative to small lung volume tasks. It would therefore be expected (according to findings from limb literature) that these large lung volume tasks would result in increased gamma band IMC. It is possible that the differences in sensory information being utilized in both tasks has differing impacts on IMC in the gamma bandwidth. For example, in speech production, the target is auditory, with both auditory and somatosensory reference targets providing online adjustments to outgoing commands (Tourville & Guenther, 2011; Tourville, Reilly & Guenther, 2008; Villacorta, Perkell & Guenther, 2007). The basis of our interpretation of gamma bandwidth IMC however, is built upon studies investigating tasks wherein the target is visual or force related (e.g., completing fine motor task or executing motor movements such as squatting or contracting to target MVC level). Ultimately, it is possible that the discrepancy in targets results in differences in how changing somatosensory information may be reflected in gamma bandwidth IMC.

Conclusion

Taken together, the similarities and differences in IMC across the lifespan add to a growing body of research investigating the effects of age on neuromuscular control in the speech mechanism. Our work established several significant differences in IMC across the lifespan, providing further context to our existing understanding of the development of chest wall efficiencies for speech breathing. We demonstrated that the effect of lung volume on chest wall IMC in the beta and gamma frequency bandwidths is a robust effect observable across the lifespan.

References

Ackerson, L. M., & Bruce, E. N. (1983). Bilaterally synchronized oscillations in human diaphragm and intercostal EMGs during spontaneous breathing. *Brain Research*, *271*(2), 346–348. https://doi.org/10.1016/0006-8993(83)90299-8

Behroozmand, R., Shebek, R., Hansen, D. R., Oya, H., Robin, D. A., Howard, M. A., & Greenlee, J. D. W. (2015). Sensory-motor networks involved in speech production and motor control: An fMRI study. *NeuroImage*, *109*, 418–428. https://doi.org/10.1016/j.neuroimage.2015.01.040

Binazzi, B., Lanini, B., Bianchi, R., Romagnoli, I., Nerini, M., Gigliotti, F., Duranti, R., Milic-Emili, J., & Scano, G. (2006). Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiologica*, *186*(3), 233–246. https://doi.org/10.1111/j.1748-1716.2006.01529.x

Boliek, C. A., Bakhtiari, R., Pedersen, L., Esch, J., & Cummine, J. (2019). Differential cortical control of chest wall muscles during pressure- and volume-related expiratory tasks and the effects of acute expiratory threshold loading. *Motor Control*, *23*(1), 13–33. https://www.ncbi.nlm.nih.gov/pubmed/29902955

Boliek, C. A., Hixon, T. J., Watson, P. J., & Jones, P. B. (2009). Refinement of speech breathing in healthy young children ages 4 to 6 years of life. *Journal of Speech, Language and Hearing Research*, *52*(August), 990–1008.

Boliek, C. A., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1997). Vocalization and breathing during the second and third years of life. *Journal of Voice*, *11*(4), 373–390. https://doi.org/10.1016/S0892-1997(97)80033-1

Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. *Frontiers in Human Neuroscience*, *7*(DEC), 1–2. https://doi.org/10.3389/FNHUM.2013.00855

Boonstra, T. W., & Breakspear, M. (2012). Neural mechanisms of intermuscular coherence: implications for the rectification of surface electromyography. *Journal of Neurophysiology*, *107*(3), 796–807. https://doi.org/10.1152/jn.00066.2011

Bronson-Lowe, C. R., Loucks, T., Ofori, E., & Sosnoff, J. J. (2013). Aging Effects on Sensorimotor Integration: A Comparison of Effector Systems and Feedback Modalities. *Article in Journal of Motor Behavior*. https://doi.org/10.1080/00222895.2013.784239

Bruce, E. N., & Ackerson, L. M. (1986). High-frequency oscillations in human electromyograms during voluntary contractions. *Journal of Neurophysiology*, *56*(2), 542–553. http://www.ncbi.nlm.nih.gov/pubmed/3760934

Bruce, E. N., & Goldman, M. D. (1983). High-frequency oscillations in human respiratory electromyograms during voluntary breathing. *Brain Research*, *269*(2), 259–265. https://doi.org/10.1016/0006-8993(83)90135-X

Campbell, M. J., McComas, A. J., & Petito, F. (1973). Physiological changes in ageing muscles. *Journal of Neurology, Neurosurgery, and Psychiatry*, *36*(2), 174–182. https://doi.org/10.1136/JNNP.36.2.174

Castronovo, A. M., Negro, F., Conforto, S., & Farina, D. (2015). The proportion of common synaptic input to motor neurons increases with an increase in net excitatory input. *Journal of Applied Physiology*, *119*(11), 1337–1346. https://doi.org/10.1152/japplphysiol.00255.2015

Chang, Y. J., Chou, C. C., Chan, H. L., Hsu, M. J., Yeh, M. Y., Fang, C. Y., Chuang, Y. F., Wei, S. H., & Lien, H. Y. (2012). Increases of Quadriceps Inter-Muscular Cross-Correlation and Coherence during Exhausting Stepping Exercise. *Sensors 2012, Vol. 12, Pages 16353-16367*, *12*(12), 16353–16367. https://doi.org/10.3390/S121216353

Clair-Auger, J. M., Gan, L. S., Norton, J. A., & Boliek, C. A. (2015). Simultaneous Measurement of Breathing Kinematics and Surface Electromyography of Chest Wall Muscles during Maximum Performance and Speech Tasks in Children: Methodological Considerations. *Folia Phoniatrica et Logopaedica*, *67*(4), 202–211. https://doi.org/10.1159/000441326

Connaghan, K. P., Moor, C. A. M., & Higashakawa, M. (2014). Respiratory Kinematics During Vocalization and Nonspeech Respiration in Children From 9 to 48 Months. *Journal of Speech Language and Hearing Research*, *41*(1), 70–84. https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE

Conway, B. A., Halliday, D. M., Farmer, S. F., Shahani, U., Maas, P., Weir, A. I., & Rosenberg, J. R. (1995). Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. *The Journal of Physiology*, *489*(3), 917–924. https://doi.org/10.1113/JPHYSIOL.1995.SP021104

De Marchis, C., Severini, G., Castronovo, A. M., Schmid, M., & Conforto, S. (2015). Intermuscular coherence contributions in synergistic muscles during pedaling. *Experimental Brain Research*, *233*(6), 1907–1919. https://doi.org/10.1007/S00221-015-4262-4/METRICS

De Miranda Marzullo, A. C., Neto, O. P., Ballard, K. J., Robin, D. A., Chaitow, L., & Christou, E. A. (2010). Neural control of the lips differs for young and older adults following a perturbation. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *206*(3), 319. https://doi.org/10.1007/S00221-010-2411-3

de Vries, I. E. J., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, *116*(6), 2576–2585. https://doi.org/10.1152/jn.00460.2016

Etter, N. M., McKeon, P. O., Dressler, E. V., & Andreatta, R. D. (2018). Effects of ageing on orofacial fine force control and its relationship with parallel change in sensory perception. *International Journal of Speech-Language Pathology*, *20*(5), 502–515. https://doi.org/10.1080/17549507.2017.1318303

Farmer, S. F., Gibbs, J., Halliday, D. M., Harrison, L. M., James, L. M., Mayston, M. J., & Stephens, J. A. (2007). Changes in EMG coherence between long and short thumb abductor muscles during human development. *Journal of Physiology*, *579*(2), 389–402. https://doi.org/10.1113/jphysiol.2006.123174

Grosse, P., Cassidy, M. J., & Brown, P. (2002). EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: Physiological principles and clinical applications. *Clinical Neurophysiology*, *113*, 1523–1531. https://doi.org/10.1016/S1388-2457(02)00223-7

Haug, H., & Eggers, R. (1991). Morphometry of the human cortex cerebri and corpus striatum during aging. *Neurobiology of Aging*, *12*(4), 336–338. http://www.ncbi.nlm.nih.gov/pubmed/1961364

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the Chest Wall during Speech Production: Volume Displacements of the Rib Cage, Abdomen, and Lung. *Journal of Speech and Hearing Research*, *16*(1), 78–115. https://doi.org/10.1044/jshr.1601.78

Hixon, T. J., Mead, J., & Goldman, M. D. (1976). Dynamics of the chest wall during speech production: function of the thorax, rib cage, diaphragm, and abdomen. *Journal of Speech and Hearing Research*, *19*(2), 297–356. https://doi.org/10.1044/jshr.1902.297

Hoit, J. D., & Hixon, T. J. (1987). Age and Speech Breathing. *Journal of Speech and Hearing Research*, *30*, 351–366.

Hoit, J. D., Hixon, T. J., Altman, M. E., & Morgan, W. J. (1989). Speech breathing in women. *Journal of Speech and Hearing Research*, *32*(2), 353–365. https://doi.org/10.1044/JSHR.3202.353

Hoit, J. D., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1990). Speech Breathing in Children and Adolescents. *Journal of Speech and Hearing Research*, *33*, 51–69.

Hoit, J. D., Plassman, B. L., Lansing, R. W., & Hixon, T. J. (1988). Abdominal muscle activity during speech production. *Journal of Applied Physiology*, *65*(6), 2656–2664. https://doi.org/10.1152/jappl.1988.65.6.2656

Huber, J. E. (2008). Effects of Utterance Length and Vocal Loudness on Speech Breathing in Older Adults. *Respiratory, Physiology and Neurobiology*, *164*(3), 323–330. https://doi.org/10.1016/j.resp.2008.08.007.Effects

Huber, J. E., & Spruill, J. (2008). Age-Related Changes to Speech Breathing With Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047)

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020). Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, *124*(4), 1045–1055. https://doi.org/10.1152/JN.00231.2020

Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, *118*(3), 1775–1783. https://doi.org/10.1152/jn.00204.2017

McFarland, D. H., & Smith, A. (1989). Surface recordings of respiratory muscle activity during speech: some preliminary findings. *Journal of Speech and Hearing Research*, *32*(3), 657–667. http://www.ncbi.nlm.nih.gov/pubmed/2779209

Merletti, R., & Muceli, S. (2019). Tutorial. Surface EMG detection in space and time: Best practices. *Journal of Electromyography and Kinesiology*, *49*(August), 102363. https://doi.org/10.1016/j.jelekin.2019.102363

Mohr, M., Nann, M., Von Tscharner, V., Eskofier, B., & Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *PLOS ONE*, *10*(11), e0142048. https://doi.org/10.1371/JOURNAL.PONE.0142048

Mohr, M., Schön, T., von Tscharner, V., & Nigg, B. M. (2018). Intermuscular coherence between surface EMG signals is higher for monopolar compared to bipolar electrode configurations. *Frontiers in Physiology*, *9*(MAY), 566. https://doi.org/10.3389/FPHYS.2018.00566/BIBTEX

Moore, C. A., Caulfield, T. J., & Green, J. R. (2001). Relative Kinematics of the Rib Cage and Abdomen During Speech and Nonspeech Behaviors of 15-Month-Old Children. *Journal of Speech, Language, and Hearing Research*, *44*(1), 80–94. https://doi.org/10.1044/1092-4388(2001/008)

Nazarpour, K., Barnard, A., & Jackson, A. (2012). Flexible cortical control of task-specific muscle synergies. *Journal of Neuroscience*, *32*(36), 12349–12360. https://doi.org/10.1523/JNEUROSCI.5481-11.2012

Nishimura, Y., Morichika, Y., & Isa, T. (2009). A subcortical oscillatory network contributes to recovery of hand dexterity after spinal cord injury. *Brain*, *132*(3), 709. https://doi.org/10.1093/BRAIN/AWN338

Norton, J. A., & Gorassini, M. (2006). Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *Journal of Neurophysiology*, *95*, 2580–2589. https://doi.org/10.1152/jn.01289.2005

Ohashi, H., & Ostry, D. J. (2021). Neural Development of Speech Sensorimotor Learning. *Journal of Neuroscience*, *41*(18), 4023–4035. https://doi.org/10.1523/JNEUROSCI.2884-20.2021

Omlor, W., Patino, L., Hepp-Reymond, M. C., & Kristeva, R. (2007). Gamma-range corticomuscular coherence during dynamic force output. *NeuroImage*, *34*(3), 1191–1198. https://doi.org/10.1016/J.NEUROIMAGE.2006.10.018

Poston, B., Santos, A. D. Dos, Jesunathadas, M., Hamm, T. M., & Santello, M. (2010). Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping. *Journal of Neurophysiology*, *104*(2), 1141–1154. https://doi.org/10.1152/JN.00185.2010/ASSET/IMAGES/LARGE/Z9K0081002390008.JPEG

Reed, A., Cummine, J., Bakhtiari, R., & Boliek, C. (n.d.-a). *The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Chest Wall .*

Reed, A., Cummine, J., Bakhtiari, R., & Boliek, C. (n.d.-b). *The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Orbicularis Oris*.

Reed, A., Cummine, J., Bhat, N., Jhala, S., Bakhtiari, R., & Boliek, C. A. (2021). Changes in Intermuscular Coherence as a Function of Age and Phase of Speech Production During an Overt Reading Task. *Motor Control*, *25*(2), 295–314. https://doi.org/10.1123/MC.2020-0003

Reyes, A., Laine, C. M., Kutch, J. J., & Valero-Cuevas, F. J. (2017). Beta Band Corticomuscular Drive Reflects Muscle Coordination Strategies. *Frontiers in Computational Neuroscience*, *11*(April), 1–10. https://doi.org/10.3389/fncom.2017.00017

Scott-Warren, V., & Maguire, S. (2017). Physiology of ageing. *Anaesthesia & Intensive Care Medicine*, *18*(1), 52-54.

Segovia, G., Porras, A., Del Arco, A., & Mora, F. (2001). Glutamatergic neurotransmission in aging: A critical perspective. *Mechanisms of Ageing and Development*, *122*, 1–29. https://doi.org/10.1016/S0047-6374(00)00225-6

Semmler, J. G., Kornatz, K. W., & Enoka, R. M. (2006). Motor-Unit Coherence During Isometric Contractions Is Greater in a Hand Muscle of Older Adults. *Journal of Neurophysiology*, *90*(2), 1346–1349. https://doi.org/10.1152/jn.00941.2002

Smith, A., & Denny, M. (1990). High-frequency oscillations as indicators of neural control mechanisms in human respiration, mastication, and speech. *Journal of Neurophysiology*, *63*(4), 745–758.

Sperry, E. E., & Klich, R. J. (1992). Speech breathing in senescent and younger women during oral reading. *Journal of Speech and Hearing Research*, *35*(6), 1246–1255. https://doi.org/10.1044/JSHR.3506.1246

Stathopoulos, E. T., & Sapienza, C. M. (1997). Developmental Changes in Laryngeal and Respiratory Function With Variations in Sound Pressure Level. *Journal of Speech, Language, and Hearing Research*, *40*(3), 595–614. https://doi.org/10.1044/JSLHR.4003.595

Tomczak, C. R., Greidanus, K. R., & Boliek, C. A. (2013). Modulation of chest wall intermuscular coherence: effects of lung volume excursion and transcranial direct current stimulation. *Journal of Neurophysiology*, *110*, 680–687. https://doi.org/10.1152/jn.00723.2012

Tourville, J. A., & Guenther, F. H. (2011). The DIVA model: A neural theory of speech acquisition and production. *Language and Cognitive Processes*, *26*(7), 952–981. https://doi.org/10.1080/01690960903498424

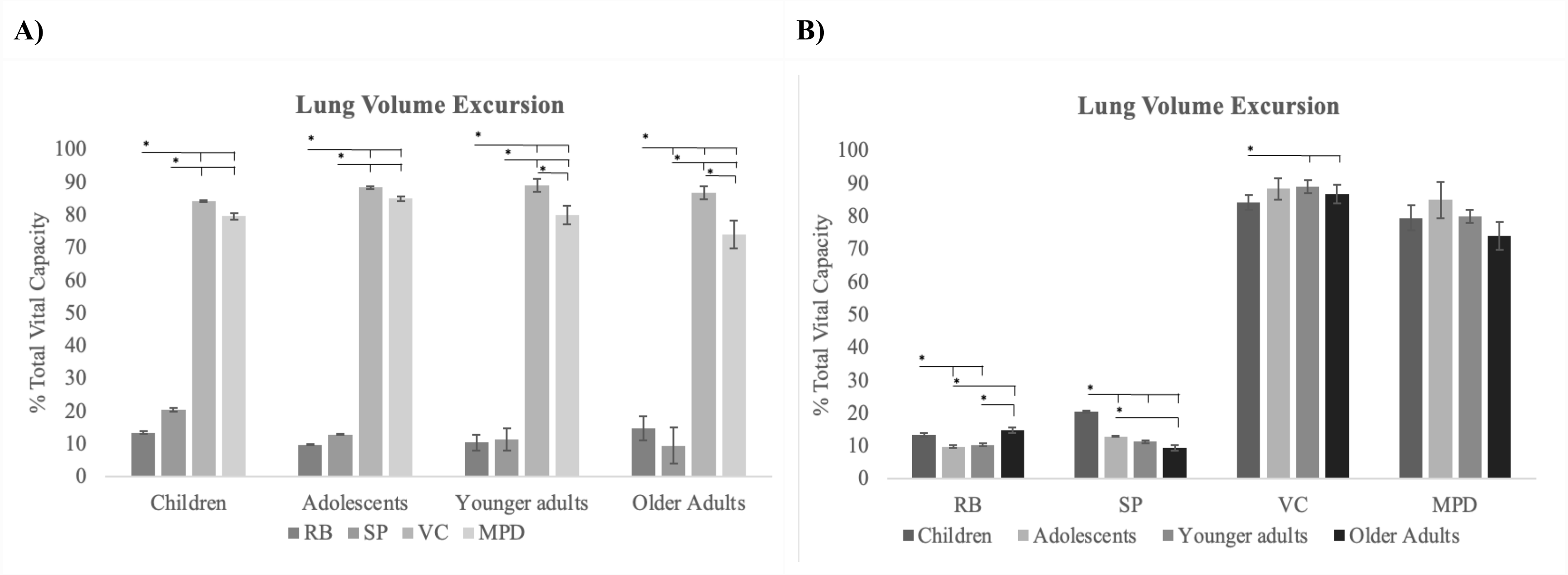
Tourville, J. A., Reilly, K. J., & Guenther, F. H. (2008). Neural mechanisms underlying auditory feedback control of speech. *NeuroImage*, *39*(3), 1429–1443. https://doi.org/10.1016/j.neuroimage.2007.09.054

Tremblay, S., Shiller, D. M., & Ostry, D. J. (2003). Somatosensory basis of speech production. *Nature*, *423*(6942), 866–869. https://doi.org/10.1038/nature01710

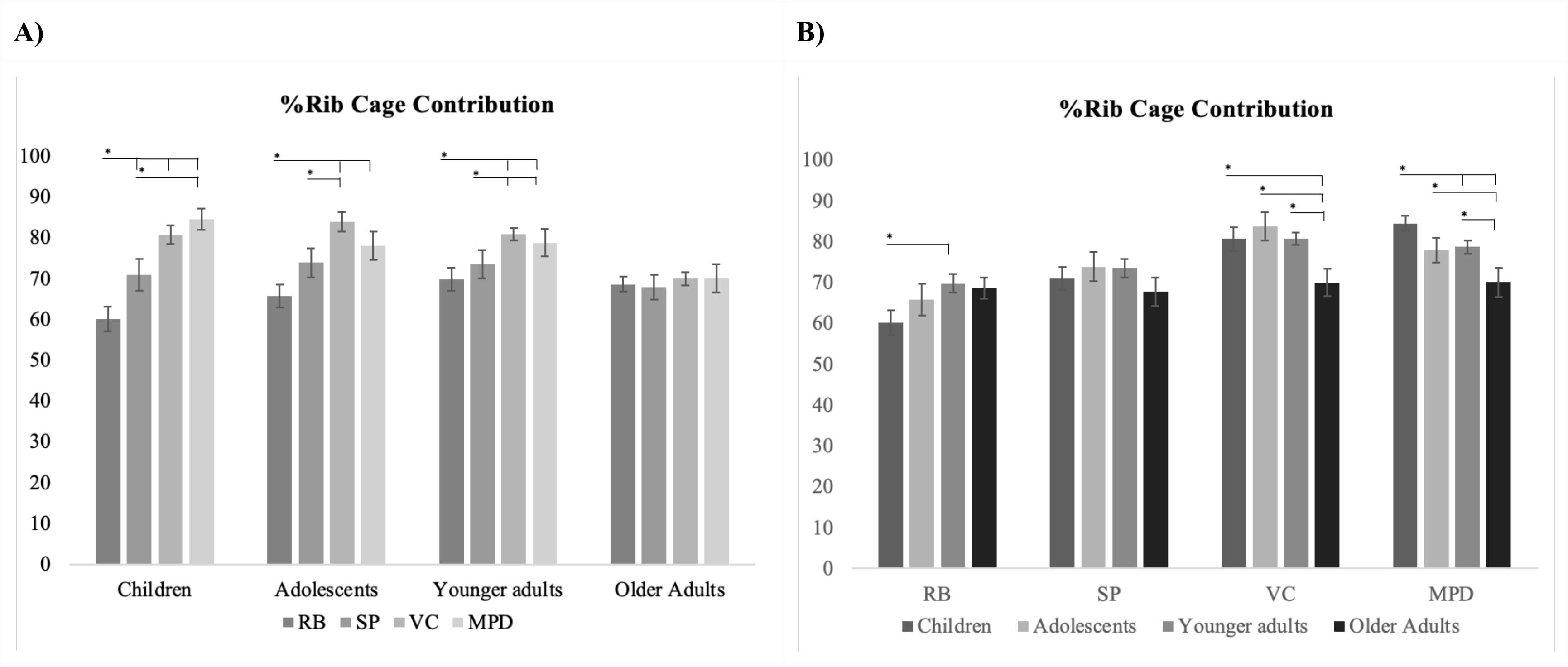
Villacorta, V. M., Perkell, J. S., & Guenther, F. H. (2007). Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception. *The Journal of the Acoustical Society of America*, *122*(4), 2306–2319. https://doi.org/10.1121/1.2773966 von Tscharner, V., Ullrich, M., Mohr, M., Comaduran Marquez, D., & Nigg, B. M. (2018). Beta, gamma band, and high-frequency coherence of EMGs of vasti muscles caused by clustering of motor units. *Experimental Brain Research*, *236*(11), 3065–3075. https://doi.org/10.1007/S00221-018-5356-6/METRICS

Wang, Y. T., Green, J. R., Nip, I. S. B., Kent, R. D., & Kent, J. F. (2010). Breath Group Analysis for Reading and Spontaneous Speech in Healthy Adults. *Folia Phoniatrica et Logopaedica*, *62*(6), 297–302. https://doi.org/10.1159/000316976

Supplemental Materials



Supplemental Figure S4.1A-B *Lung volume expressed as a percentage of vital capacity (%VC) in Children, Adolescents, Younger Adults and Older Adults. %VC values are represented on the y axis; values are graphed separately by age and by task to highlight task differences within age groups (Panel A), and between group differences within tasks (Panel B). Repeated measures ANOVA conducted within each age group revealed a main effect of task on %RC contribution in children ($F_{1.64, 44.27} = 309.66^{+}$ $p<0.001$), adolescents ($F_{1.56, 21.87} = 250.31^{+}$ $p<0.001$), younger adults ($F_{1.51, 48.21} = 1555.15^{+}$ $p<0.001$) and older adults ($F_{1.33, 26.57} = 375.99^{+}$ $p<0.001$). Task related differences meeting statistical significance ($p <.05$ corrected) are denoted with an asterisk (Panel A). One way ANOVAs conducted within each task revealed a main effect of age in the RB ($F_{3, 69.5} = 17.70^{+}$ $p<0.001$), SP ($F_{3, 85.08} = 36.15^{+}$ $p<0.001$) and VC ($F_{3,48.27} = 5.936^{+}$ $p<0.002$) tasks. No significant differences detected across groups in the MPD task ($F_{3,66.88} = 0.675^{+}$ $p<0.57$). Age group differences meeting statistical significance ($p <.05$ corrected) are denoted with an asterisk (Panel B). RB= Rest breathing task, SP= Speech task, VC= Vital Capacity task, MPD= Maximum phonation duration task.*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VC
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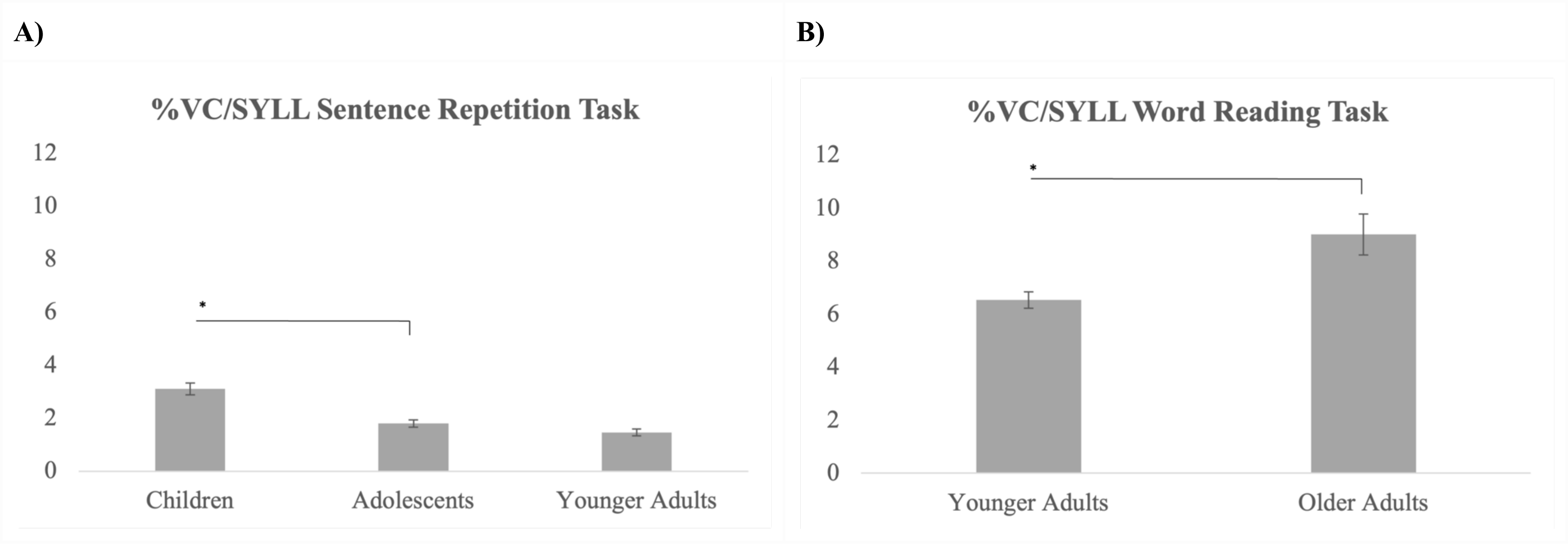
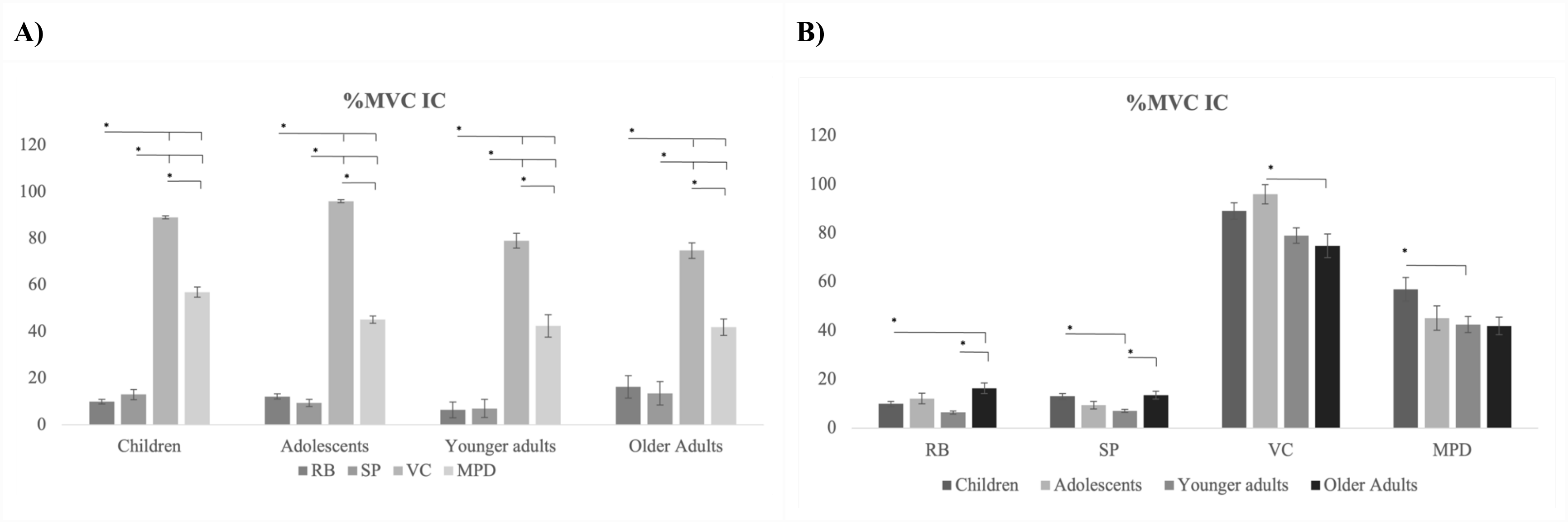
Older Adults

Supplemental Figure S4.2A-B *Percent rib cage contribution (%RC) to total lung volume in Children, Adolescents, Younger Adults and Older Adults. %RC values are represented on the y axis; values are graphed separately by age and by task to highlight task differences within age groups (Panel A), and between group differences within tasks (Panel B). Repeated measures ANOVA conducted within each age group revealed a main effect of task on %RC contribution in children (*$F_{3,\ 72} = 26.36$ $p<0.001$*), adolescents (*$F_{3,\ 36} = 12.22$ $p<0.001$*) and younger adults (*$F_{2.13,\ 87.25} = 11.27^{+}$ $p<0.001$*). No significant differences detected across tasks in older adults (*$F_{1.97,\ 43.23} = .13^{+}$ $p<0.94$*). Task related differences meeting statistical significance (*$p <.05$* corrected) are denoted with an asterisk (Panel A). One way ANOVAs conducted within each task revealed a main effect of age in the RB (*$F_{3,113} = 3.266$ $p<0.024$*), VC (*$F_{3,82.44} = 4.34^{+}$ $p<0.007$*) and MPD (*$F_{3,101.99} = 17.74^{+}$ $p<0.001$*) tasks. No significant differences detected across groups in the SP task (*$F_{3,109} = 0.62$ $p<0.602$*). Age group differences meeting statistical significance (*$p <.05$* corrected) are denoted with an asterisk (Panel B). RB= Rest breathing task, SP= Speech task, VC= Vital Capacity task, MPD= Maximum phonation duration task.*



Supplemental Figure S4.3A-B *Lung volume expenditure per syllable expressed as a function of vital capacity (%VC/SYLL) for Children, Adolescents, Younger Adults and Older Adults. %VC/SYLL was calculated for the SP task and is presented according to the nature of the task included in this secondary analysis. Panel A depicts %VC/SYLL data for the SP task collected using a sentence repetition task (e.g., Buy bobby a puppy, The blue spot is on the key, and The potato stew is in the pot). A one way revealed a main effect of age (*$F_{2,52} = 9.55$ $p<0.001$*). Age group differences meeting statistical significance (*$p < .05$* corrected) are denoted with an asterisk. Panel B depicts %VC/SYLL data for the SP task collected using a single word overt reading task (see Appendix 1). A paired t-test revealed that older adults expended significantly more %VC per syllable than younger adults (*$p<0.008$*).*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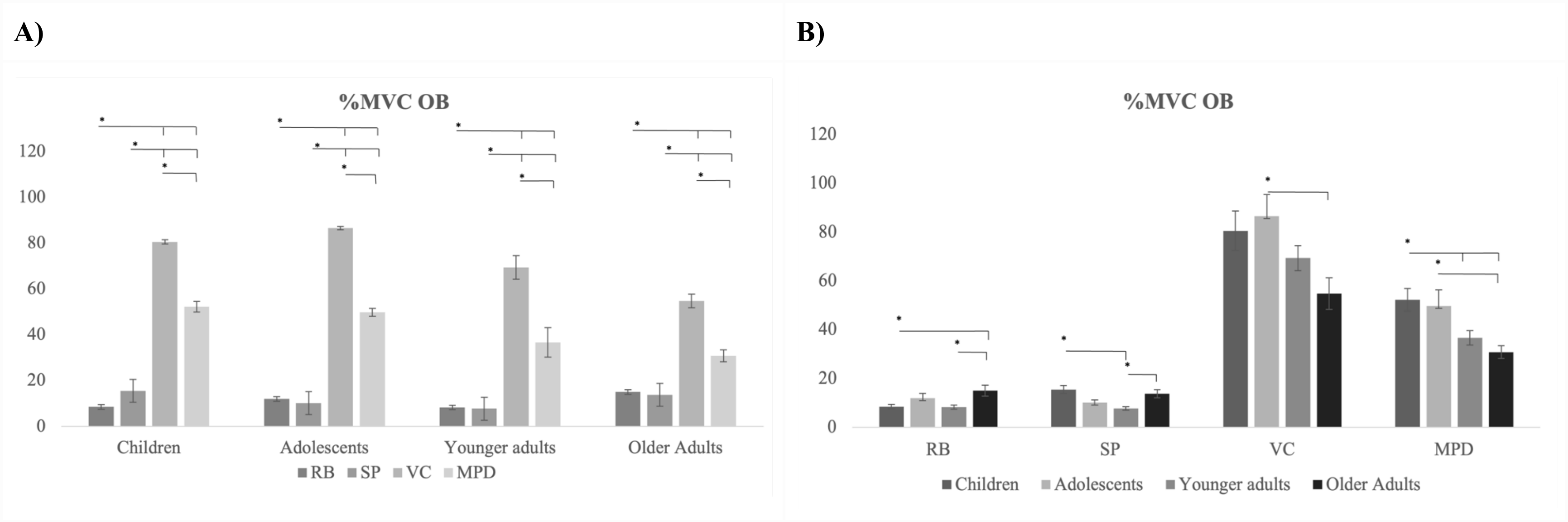
■Children ■Adolescents ■Younger adults ■Older Adults

Supplemental Figure S4.4A-B *Muscle contraction of the intercostals expressed as a percent maximum voluntary contraction (%MVC) in Children, Adolescents, Younger Adults and Older Adults. %MVC values are represented on the y axis; values are graphed separately by age and by task to highlight task differences within age groups (Panel A), and between group differences within tasks (Panel B). Repeated measures ANOVA conducted within each age group revealed a main effect of task on %MVC in children (*$F_{1.82,34.95}=132.84^{+}$*, *$p<0.001$*), adolescents (*$F_{1.80,19.78}=105.63^{+}$*, *$p<0.001$*), younger adults (*$F_{1.87,67.23}=219.80^{+}$*, *$p<0.001$*) and older adults (*$F_{1.85,46.17}=114.40^{+}$*, *$p<0.001$*). Task related differences meeting statistical significance (*$p<.05$* corrected) are denoted with an asterisk (Panel A). One way ANOVAs conducted within each task revealed a main effect of age in the RB (*$F_{3,104}=10.25$*, *$p<0.001$*), SP task (*$F_{3,106}=8.73$*, *$p<0.001$*), VC (*$F_{3,108}=4.34$*, *$p<0.006$*) and MPD (*$F_{3,108}=3.08$*, *$p<0.031$*) tasks. Age group differences meeting statistical significance (*$p<.05$* corrected) are denoted with an asterisk (Panel B). RB= Rest breathing task, SP= Speech task, VC= Vital Capacity task, MPD= Maximum phonation duration task.*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Supplemental Figure S4.5 A-B *Muscle contraction of the obliques expressed as a percent maximum voluntary contraction (%MVC) in Children, Adolescents, Younger Adults and Older Adults. %MVC values are represented on the y axis; values are graphed separately by age and by task to highlight task differences within age groups (Panel A), and between group differences within tasks (Panel B). Repeated measures ANOVA conducted within each age group revealed a main effect of task on %MVC in children* ($F_{1.41,29.54}=52.54^{+}$, $p<0.001$)*, adolescents* ($F_{1.75,21.03}=39.15^{+}$, $p<0.001$)*, younger adults* ($F_{1.39,54.10}=107.96^{+}$, $p<0.001$) *and older adults* ($F_{1.23,29.51}=34.05^{+}$, $p<0.001$)*. Task related differences meeting statistical significance* ($p <.05$ *corrected) are denoted with an asterisk (Panel A). One way ANOVAs conducted within each task revealed a main effect of age in the RB* ($F_{3,100} =5.06$, $p<0.003$)*, SP task* ($F_{3,106} =8.34$, $p<0.001$)*, VC* ($F_{3,111}=3.36$, $p<0.021$) *and MPD* ($F_{3,109}=6.44$, $p<0.001$) *tasks. Age group differences meeting statistical significance* ($p <.05$ *corrected) are denoted with an asterisk (Panel B). RB= Rest breathing task, SP= Speech task, VC= Vital Capacity task, MPD= Maximum phonation duration task.*

Chapter 5: Conclusions

Summary of Contributions

The aim of my doctoral dissertation was to characterize intermuscular coherence (IMC) in selected muscles of the speech mechanism in an effort to further establish its utility as a tool to study speech motor control. I addressed these aims through a series of three studies. The main contributions are as follows:

1. Across the lifespan, consistent patterns of neuromuscular control of select chest wall muscles were observed in response to changing lung volume demand. In the beta bandwidth, we report a shift to individuated control (i.e., decreased IMC) during the vital capacity task relative to rest breathing. In the gamma bandwidth, we report a decrease in IMC during the vital capacity task, which may be associated with decreased sensory information integration during this task relative to rest breathing.
2. In healthy young adults, the respiratory subsystem was primarily sensitive to manipulation of lung volume, whereas the articulatory subsystem was primarily sensitive to manipulation of articulatory complexity. In the respiratory subsystem, chest wall IMC generally indicated a shift towards individuated control (i.e., decreased beta bandwidth IMC) and a shift in sensory information integration (i.e., decreased gamma bandwidth IMC) in large versus small lung volume tasks. In the articulatory subsystem, beta bandwidth left versus right orbicularis oris IMC indicated a shift towards synergistic control (i.e., increased IMC) in tasks with habitual or high demands (picture naming and word reading; tongue twister and diadochokinetic tasks, respectively), relative to tasks with no or low articulatory demands (rest breathing and maximum phonation duration).

3. Differences in patterns of IMC across tasks emerged in older adults.
    a. Unlike younger adults, beta bandwidth IMC in the chest wall was sensitive to articulatory demands, with older adults shifting towards synergistic control (i.e., higher IMC) in picture naming (habitual articulatory demands) relative to tongue twister and diadochokinetic tasks (high demand tasks). The same pattern was observed in the rest breathing (no articulatory demands) compared to diadochokinetic task.
    b. In the articulatory subsystem, only older adults had significant differences between tasks of varying articulatory demands in the gamma frequency bandwidth. Although the same pattern was observed in younger adults, the differences were only significant in older adults, and no differences between groups were observed in any task. Taken together, this suggests age related differences in how the speech motor control system modulates sensorimotor integration across tasks.
    c. Although older adults demonstrated several differences in respiratory kinematics and chest wall muscle activation relative to other age groups, these differences were not accompanied by different neuromuscular control strategies.
4. Two key developmental differences emerged in the chest wall IMC of children.
    a. First, in the beta bandwidth, children demonstrated a shift towards individuated control (i.e., lower IMC) relative to other age groups in both the VC and MPD tasks. In the gamma bandwidth, differences in sensory integration during the MPD task was also observed in children relative to adolescents and older adults.

b. Second, children demonstrated more task related differences in IMC than other age groups, consistent with the notion that speech motor control strategies continue to mature in this period of development.

Impact

The present findings support the potential utility of IMC in advancing existing models of motor control. As outlined in Chapter 1, existing models of speech motor control such as the Directions Into Velocities of Articulators (DIVA) model of speech production (Guenther, 2014; Guenther & Vladusich, 2012; Tourville & Guenther, 2011), lack consideration of integration with the respiratory system and of neural signaling to the periphery. The findings presented above indicate that IMC within the respiratory and articulatory subsystems changes in response to a variety of factors relevant to speech motor control, including lung volume demands, articulatory complexity and cognitive-linguistic demands. This, along with the reported developmental changes, support that IMC may be a sensitive measure to detect whether changes in central control systems (e.g., feedback versus feedforward control mechanism) result in peripherally detected differences in neural signalling to the effectors. Investigations into the differences in peripheral measures such as IMC resulting from somatosensory and auditory perturbations have the potential to advance our understanding of speech motor control.

The present findings also support the potential utility of IMC as a tool to support clinical investigations. Indeed, existing work has documented its use as a tool to monitor a return to post-injury function (Norton & Gorassini, 2006), habilitation of function (i.e., in the case of developmental neurogenic communication disorders), and perhaps serve as a biomarker for disease (Velázquez-Pérez et al., 2017). Although researchers have begun to investigate the utility of IMC in the assessment and treatment of motor speech disorders (Stepp et al., 2010, 2012; Rong & Pattee, 2021), my doctoral work highlights the need to increase our understanding of IMC in typically developing populations. Because of our somewhat limited understanding of speech motor control in general, it seems reasonable to first study these dynamics in healthy speakers before tackling the diverse symptoms observed in populations with motor speech disorders.

Limitations

There are several important considerations to make when interpreting the current findings. Across all studies, a key limitation was the use of surface electromyography. Due to the overlapping, layered sets of muscles at the recording sites used in the present study, the use of surface electromyography limits the ability to make inferences regarding specific muscles of interest. For example, the intercostal electrode sites have EMG contributions from both internal and external intercostals, whereas the oblique recording site may have additional contributions from deeper muscle tissues such as the internal obliques. Study specific limitations are discussed below:

Study 1 & Study 2

The clarity of findings of these studies were limited by the design of the original study's data collection procedures. In the original study, the rest breathing and vital capacity maneuver were included to serve as calibration tasks for respiratory kinematics and EMG signals only, which had two important implications for their use in these retrospective studies. First, orbicularis oris electrodes were not placed until after the vital capacity maneuver had been completed. As a result, this task was not included in Study 2, limiting our ability to make comparisons between the respiratory and articulatory subsystems. Given that lung volume effects were exclusively reported between the rest breathing and vital capacity task in the respiratory system, the inability to make the same comparison in the articulatory subsystem is a significant limitation of the current study. Second, the randomization of tasks was limited in the original study. In addition to the rest breathing and vital capacity tasks being excluded from randomization due to their use as calibration tools, the study did not randomize the order of small and large lung volume tasks. Although the remaining small lung volume tasks (word reading, picture naming and tongue twisters) were randomized, the procedures did not control for the order of large lung volume tasks. Given the high performance nature of these tasks, it is possible that the order of tasks impacted findings.

Last, although we demonstrated several patterns IMC sensitivity to lung volume, future studies would need to explore why there was not a systematic difference between small versus large lung volumes (i.e., differences between all small lung volume tasks and all large lung volume tasks). It is possible that differences between other small and large lung volume tasks were mitigated by engagement of one or more of the other subsystems (i.e., laryngeal or articulatory demands). Future work would need to isolate lung volume requirements by having participants perform the same task (i.e., DDK or sustained phonation) as both a high performance (i.e., spanning the entire vital capacity) and habitual speech task (i.e., performed for a shorter duration within the midrange of vital capacity).

Study 3

The third study had two key limitations resulting from the use of a retrospective, secondary analysis design. First, although outliers were removed, differences in variance were observed across age groups. Although non-parametrics were used where necessary to account for these differences, it is possible that this resulted in fewer age-related differences being observed across tasks. Second, in order to compare maximize task comparisons across participants, two different tasks were used as the “speech” task: a phrase repetition task (e.g., *Buy bobby a puppy*, *The blue spot is on the key*, and *The potato stew is in the pot*) and a word reading task (see Appendix 1). Although tasks were similar, they ultimately differed in the cognitive (e.g., reading versus copying) and respiratory system (e.g., six to nine syllables per breath group versus one syllable) demands needed to execute the task.

Future work

The current findings build on a growing body of literature supporting the utility of IMC in the study of speech motor control. While the potential utility of this measure has been outlined above, there are several gaps in our understanding of IMC that need to be investigated prior to expanding our use of IMC.

Critically, the relationship between IMC and behavioural measures needs to be explored to deepen our understanding of the utility of IMC in speech production. Whereas the existing work has established differences in IMC as a function of task demands, exploratory correlations between IMC and other measures (e.g., biomechanical efficiency, task performance etc.) did not yield any notable findings. Second, in order to determine the usefulness of IMC in the identification and remediation of speech disorders, reliability, over time and as a function of task, must be established. To date, no research has been conducted to measure the reliability of IMC in the speech mechanism; however, studies published in other motor systems suggest higher than expected levels of intersession variance (Jaiser et al., 2016; Van Asseldonk, Campfens, Verwer, Van Putten, & Stegeman, 2014).

References

Caviness, J. N., Liss, J. M., Evidente, C., & Adler, V. (2006). *Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson's Disease*. *49*(April), 424–439.

Jaiser, S. R., Baker, M. R., & Baker, S. N. (2016). Intermuscular coherence in normal adults: Variability and changes with age. *PLoS ONE*, *11*(2), 1–16. https://doi.org/10.1371/journal.pone.0149029

Rong, P., & Pattee, G. L. (2021). A potential upper motor neuron measure of bulbar involvement in amyotrophic lateral sclerosis using jaw muscle coherence. Amyotrophic lateral sclerosis & frontotemporal degeneration, 22(5-6), 368–379. https://doi.org/10.1080/21678421.2021.1874993

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2010). Use of Neck Strap Muscle Intermuscular Coherence as an Indicator of Vocal Hyperfunction. *IEEE Trans Neural Syst Rehabil Eng.EEE Trans Neural Syst Rehabil Eng.*, *18*(3), 329–335. https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2011). Modulation of neck intermuscular Beta coherence during voice and speech production. *Journal of Speech, Language, and Hearing Research*, *54*, 836–844. https://doi.org/10.1044/1092-4388(2010/10-0139)

Van Asseldonk, E. H. F., Campfens, S. F., Verwer, S. J. F., Van Putten, M. J. A. M., & Stegeman, D. F. (2014). Reliability and agreement of intramuscular coherence in tibialis anterior muscle. *PLoS ONE*, *9*(2), 1–10. https://doi.org/10.1371/journal.pone.0088428

Bibliography

Abur, D., MacPherson, M. K., Shembel, A. C., & Stepp, C. E. (2023). Acoustic Measures of Voice and Physiologic Measures of Autonomic Arousal During Speech as a Function of Cognitive Load in Older Adults. *Journal of Voice*, *37*(2), 194–202. https://doi.org/10.1016/j.jvoice.2020.12.027

Ackerson, L. M., & Bruce, E. N. (1983). Bilaterally synchronized oscillations in human diaphragm and intercostal EMGs during spontaneous breathing. *Brain Research*, *271*(2), 346–348. https://doi.org/10.1016/0006-8993(83)90299-8

Amerman, J. D., & Parnell, M. M. (1992). Speech Timing Strategies in Elderly Adults. *Journal of Phonetics*, *20*(1), 65–76.

Bailey, D. J., & Dromey, C. (2015). Bidirectional Interference Between Speech and Nonspeech Tasks in Younger, Middle-Aged, and Older Adults. *Journal of Speech, Language, and Hearing Research : JSLHR*, *58*(6), 1637–1653. https://doi.org/10.1044/2015_JSLHR-S-14-0083

Baker, S. N., Pinches, E. M., & Lemon, R. N. (2003). Synchronization in monkey motor cortex during a precision grip task. II. Effect of Oscillatory Activity on Corticospinal Output. *Journal of Neurophysiology*, *89*, 1941–1953. https://doi.org/10.1152/jn.00832.2002

Behroozmand, R., Shebek, R., Hansen, D. R., Oya, H., Robin, D. A., Howard, M. A., & Greenlee, J. D. W. (2015). Sensory-motor networks involved in speech production and motor control: An fMRI study. *NeuroImage*, *109*, 418–428. https://doi.org/10.1016/j.neuroimage.2015.01.040

Berry, J. K., Vitalo, C. A., Larson, J. L., Patel, M., & Kim, M. J. (1996). Respiratory muscle strength in older adults. *Nursing Research*, *45*(3), 154–159. https://doi.org/10.1097/00006199-199605000-00006

Bilodeau-Mercure, M., & Tremblay, P. (2016). Age Differences in Sequential Speech Production: Articulatory and Physiological Factors. *Journal of the American Geriatrics Society*, *64*(11), e177–e182. https://doi.org/10.1111/jgs.14491

Binazzi, B., Lanini, B., Bianchi, R., Romagnoli, I., Nerini, M., Gigliotti, F., Duranti, R., Milic-Emili, J., & Scano, G. (2006). Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiologica*, *186*(3), 233–246. https://doi.org/10.1111/j.1748-1716.2006.01529.x

Black, L. F., & Hyatt, R. E. (1969). Maximal respiratory pressures: normal values and relationship to age and sex. *The American Review of Respiratory Disease*, *99*(5), 696–702. https://doi.org/10.1164/ARRD.1969.99.5.696

Boliek, C. A., Bakhtiari, R., Pedersen, L., Esch, J., & Cummine, J. (2019). Differential cortical control of chest wall muscles during pressure- and volume-related expiratory tasks and the effects of acute expiratory threshold loading. *Motor Control*, *23*(1), 13–33. https://www.ncbi.nlm.nih.gov/pubmed/29902955

Boliek, C. A., Hixon, T. J., Watson, P. J., & Jones, P. B. (2009). Refinement of speech breathing in healthy young children ages 4 to 6 years of life. *Journal of Speech, Language and Hearing Research*, *52*(August), 990–1008.

Boliek, C. A., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1997). Vocalization and breathing during the second and third years of life. *Journal of Voice*, *11*(4), 373–390. https://doi.org/10.1016/S0892-1997(97)80033-1

Bóna, J. (2014). Temporal characteristics of speech: The effect of age and speech style. *The Journal of the Acoustical Society of America*, *136*(2), EL116–EL121. https://doi.org/10.1121/1.4885482

Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. *Frontiers in Human Neuroscience*, *7*(DEC), 1–2. https://doi.org/10.3389/FNHUM.2013.00855

Boonstra, T. W., & Breakspear, M. (2012). Neural mechanisms of intermuscular coherence: implications for the rectification of surface electromyography. *Journal of Neurophysiology*, *107*(3), 796–807. https://doi.org/10.1152/jn.00066.2011

Boonstra, T. W., Daffertshofer, A., van As, E., van der Vlugt, S., & Beek, P. J. (2007). Bilateral motor unit synchronization is functionally organized. *Experimental Brain Research*, *178*, 79–88. https://doi.org/10.1007/s00221-006-0713-2

Boonstra, T. W., Farmer, S. F., & Breakspear, M. (2016). *Using Computational Neuroscience to Define Common Input to Spinal Motor Neurons*. *10*(June), 2013–2016. https://doi.org/10.3389/fnhum.2016.00313

Boucher, V. J. (2001). A stumbling block in the development of motor theories of speech: Relating EMG to force-related changes in articulation. *Clinical Linguistics and Phonetics*, *15*(1–2), 123–127. https://doi.org/10.1080/026992001461433

Boucher, V. J., Ahmarani, C., & Ayad, T. (2006). Physiologic features of vocal fatigue: Electromyographic Spectral-Compression in laryngeal muscles. *The Laryngoscope*, *116*(6), 959-965.

Bronson-Lowe, C. R., Loucks, T., Ofori, E., & Sosnoff, J. J. (2013). Aging Effects on Sensorimotor Integration: A Comparison of Effector Systems and Feedback Modalities. *Article in Journal of Motor Behavior*. https://doi.org/10.1080/00222895.2013.784239

Bruce, E. N., & Ackerson, L. M. (1986). High-frequency oscillations in human electromyograms during voluntary contractions. *Journal of Neurophysiology*, *56*(2), 542–553. http://www.ncbi.nlm.nih.gov/pubmed/3760934

Bruce, E. N., & Goldman, M. D. (1983). High-frequency oscillations in human respiratory electromyograms during voluntary breathing. *Brain Research*, *269*(2), 259–265. https://doi.org/10.1016/0006-8993(83)90135-X

Campbell, M. J., McComas, A. J., & Petito, F. (1973). Physiological changes in ageing muscles. *Journal of Neurology, Neurosurgery, and Psychiatry*, *36*(2), 174–182. https://doi.org/10.1136/JNNP.36.2.174

Castronovo, A. M., Mrachacz-Kersting, N., Stevenson, A. J. T., Holobar, A., Enoka, R. M., & Farina, D. (2018). Decrease in force steadiness with aging is associated with increased power of the common but not independent input to motor neurons. *Journal of Neurophysiology*, *120*(4), 1616–1624. https://doi.org/10.1152/JN.00093.2018/ASSET/IMAGES/LARGE/Z9K0091847490005.JPEG

Castronovo, A. M., Negro, F., Conforto, S., & Farina, D. (2015). The proportion of common synaptic input to motor neurons increases with an increase in net excitatory input. *Journal of Applied Physiology*, *119*(11), 1337–1346. https://doi.org/10.1152/japplphysiol.00255.2015

Cattell, J. M. (1885). Ueber die Zeit der Erkennung und Benennung von Schriftzeichen, Bildern und Farben. *Philosophische Studien*, *2*, 635–650. https://www.mpi.nl/publications/item2309357/ueber-die-zeit-der-erkennung-und-benennung-von-schriftzeichen-bildern-und

Caviness, J. N., Liss, J. M., Evidente, C., & Adler, V. (2006). *Electromyographic Coherence Elicited by Speech and Oral Nonspeech Tasks in Parkinson's Disease*. *49*(April), 424–439.

Chang, Y. J., Chou, C. C., Chan, H. L., Hsu, M. J., Yeh, M. Y., Fang, C. Y., Chuang, Y. F., Wei, S. H., & Lien, H. Y. (2012). Increases of Quadriceps Inter-Muscular Cross-Correlation and Coherence during Exhausting Stepping Exercise. *Sensors 2012, Vol. 12, Pages 16353-16367*, *12*(12), 16353–16367. https://doi.org/10.3390/S121216353

Choo, A. L., Robb, M. P., Dalrymple-Alford, J. C., Huckabee, M. L., & O'Beirne, G. A. (2010). Different lip asymmetry in adults who stutter: Electromyographic evidence during speech and non-speech. *Folia Phoniatrica et Logopaedica*, *62*(3), 143–147. https://doi.org/10.1159/000287213

Clair-Auger, J. M., Gan, L. S., Norton, J. A., & Boliek, C. A. (2015). Simultaneous Measurement of Breathing Kinematics and Surface Electromyography of Chest Wall Muscles during Maximum Performance and Speech Tasks in Children: Methodological Considerations. *Folia Phoniatrica et Logopaedica*, *67*(4), 202–211. https://doi.org/10.1159/000441326

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of Reading Aloud: Dual-Route and Parallel-Distributed-Processing Approaches. *Psychological Review*, *100*(4), 589–608. https://doi.org/10.1037/0033-295X.100.4.589

Connaghan, K. P., Moor, C. A. M., & Higashakawa, M. (2014). Respiratory Kinematics During Vocalization and Nonspeech Respiration in Children From 9 to 48 Months. *Journal of Speech Language and Hearing Research*, *41*(1), 70–84. https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE

Conway, B. A., Halliday, D. M., Farmer, S. F., Shahani, U., Maas, P., Weir, A. I., & Rosenberg, J. R. (1995). Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. *The Journal of Physiology*, *489*(3), 917–924. https://doi.org/10.1113/JPHYSIOL.1995.SP021104

Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders*. Saunders.

Davis, P. J., Bartlett, D., & Luschei, E. S. (1992). Coordination of the Respiratory and Laryngeal Systems in Breathing and Vocalization. *NCVC Status and Progress Report*, 59–81.

Davis, P. J., Zhang, S. P., Winkworth, A., & Bandler, R. (1996). Neural control of vocalization: respiratory and emotional influences. *Journal of Voice : Official Journal of the Voice Foundation*, *10*(1), 23–38. https://doi.org/10.1016/S0892-1997(96)80016-6

De Marchis, C., Severini, G., Castronovo, A. M., Schmid, M., & Conforto, S. (2015). Intermuscular coherence contributions in synergistic muscles during pedaling. *Experimental Brain Research*, *233*(6), 1907–1919. https://doi.org/10.1007/S00221-015-4262-4/METRICS

De Miranda Marzullo, A. C., Neto, O. P., Ballard, K. J., Robin, D. A., Chaitow, L., & Christou, E. A. (2010). Neural control of the lips differs for young and older adults following a perturbation. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *206*(3), 319. https://doi.org/10.1007/S00221-010-2411-3 de Vries, I. E. J., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, *116*(6), 2576–2585. https://doi.org/10.1152/jn.00460.2016

Denny, M., & Smith, A. (2000). Respiratory control in stuttering speakers: evidence from respiratory high-frequency oscillations. *Journal of Speech, Language, and Hearing Research*, *43*(4), 1024–1037. http://www.ncbi.nlm.nih.gov/pubmed/11386469

Dietsch, A. M., Clark, H. M., Steiner, J. N., & Solomon, N. P. (2015). Effects of Age, Sex, and Body Position on Orofacial Muscle Tone in Healthy Adults. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1145–1150. https://doi.org/10.1044/2015_JSLHR-S-14-0325

Dromey, C., & Bates, E. (2005). Speech Interactions With Linguistic, Cognitive, and Visuomotor Tasks. *Journal of Speech, Language, and Hearing Research*, *48*(2), 295–305. https://doi.org/10.1044/1092-4388(2005/020)

Dromey, C., & Ramig, L. O. (1998a). Intentional Changes in Sound Pressure Level and Rate: Their Impact on Measures of Respiration, Phonation, and Articulation. In *Journal of Speech Language and Hearing Research* (Vol. 41, Issue October, pp. 1003–1018). https://doi.org/10.1044/jslhr.4105.1003

Dromey, C., & Ramig, L. O. (1998b). The Effect of Lung Volume on Selected Phonatory and Articulatory Variables. *Journal of Speech, Language, and Hearing Research*, *41*(3), 491–502. https://doi.org/10.1044/jslhr.4103.491

Dromey, C., & Shim, E. (2008). The Effects of Divided Attention on Speech Motor, Verbal Fluency, and Manual Task Performance. *Journal of Speech, Language, and Hearing Research*, *51*(5), 1171–1182. https://doi.org/10.1044/1092-4388(2008/06-0221)

Duffy, J. R. (2013). *Motor Speech Disorders : Substrates, Differential Diagnosis, and Management* (3rd ed.). Elsevier Mosby. https://search.library.ualberta.ca/catalog/5911036

Enright, P. L., Kronmal, R. A., Manolio, T. A., Schenker, M. B., & Hyatt, R. E. (1994). Respiratory muscle strength in the elderly. Correlates and reference values. Cardiovascular Health Study Research Group. *American Journal of Respiratory and Critical Care Medicine*, *149*(2), 430–438. https://www.academia.edu/12497747/Respiratory_muscle_strength_in_the_elderly_Correlates_and_reference_values_Cardiovascular_Health_Study_Research_Group

Etter, N. M., McKeon, P. O., Dressler, E. V., & Andreatta, R. D. (2018). Effects of ageing on orofacial fine force control and its relationship with parallel change in sensory perception. *International Journal of Speech-Language Pathology*, *20*(5), 502–515. https://doi.org/10.1080/17549507.2017.1318303

Faaborg-andersen, K., Edfeldt, Å. W., & Nykøbing, F. (1958). Electromyography of intrinsic and extrinsic laryngeal muscles during silent speech: Correlation with Reading activity: Preliminary report. *Acta Oto-Laryngologica*, *49*(1), 478–482. https://doi.org/10.3109/00016485809134778

Farina, D., Merletti, R., & Enoka, R. M. (2014). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, *114*, 1215–1230. https://doi.org/10.1152/japplphysiol.01070.2003

Farina, D., & Negro, F. (2015). Common Synaptic Input to Motor Neurons , Motor Unit Synchronization , and Force Control. *Exercise and Sport Sciences Reviews*, *43*(1), 23–33.

Farina, D., Negro, F., & Dideriksen, J. L. (2014). *The effective neural drive to muscles is the common synaptic input to motor neurons*. *16*, 3427–3441. https://doi.org/10.1113/jphysiol.2014.273581

Farmer, S. F., Gibbs, J., Halliday, D. M., Harrison, L. M., James, L. M., Mayston, M. J., & Stephens, J. A. (2007). Changes in EMG coherence between long and short thumb abductor muscles during human development. *Journal of Physiology*, *579*(2), 389–402. https://doi.org/10.1113/jphysiol.2006.123174

Fisher, R. J., Galea, M., Brown, P., & Lemon, R. N. (2002). Digital nerve anaesthesia decreases EMG-EMG coherence in a human precision grip task. *Experimental Brain Research*, *145*, 207–214. https://doi.org/10.1007/s00221-002-1113-x

Glaser, W. R. (1992). Picture naming. *Cognition*, *42*(1–3), 61–105. https://doi.org/10.1016/0010-0277(92)90040-O

Goffman, L., & Smith, A. (1994). Motor Unit Territories in the Human Perioral Musculature. *Journal of Speech and Hearing Research*, *37*(5), 975–984. https://doi.org/10.1044/JSHR.3705.975

Green, J. R., Moore, C. A., Higashikawa, M., & Steeve, R. W. (2000). The Physiologic Development of Speech Motor Control: Lip and Jaw Coordination. *Journal of Speech Language and Hearing Research*, *43*, 239–255. https://doi.org/10.1037//1082-989X.5.2

Green, J. R., Moore, C. A., & Reilly, K. J. (2002). The Sequential Development of Jaw and Lip Control for Speech. *Journal of Speech, Language and Hearing Research*, *45*, 66–79.

Grosse, P., Cassidy, M. J., & Brown, P. (2002). EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: Physiological principles and clinical applications. *Clinical Neurophysiology*, *113*, 1523–1531. https://doi.org/10.1016/S1388-2457(02)00223-7

Guyenet, P. G., & Bayliss, D. A. (2016). *Neural control of breathing and CO2 homeostasis*. *25*(3), 289–313. https://doi.org/10.1007/s11065-015-9294-9.Functional

Hartman, D. E., & Danhauer, J. L. (1976). Perceptual features of speech for males in four perceived age decades. *The Journal of the Acoustical Society of America*, *59*(3), 713–715. https://doi.org/10.1121/1.380894

Haug, H., & Eggers, R. (1991). Morphometry of the human cortex cerebri and corpus striatum during aging. *Neurobiology of Aging*, *12*(4), 336–338. http://www.ncbi.nlm.nih.gov/pubmed/1961364

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the Chest Wall during Speech Production: Volume Displacements of the Rib Cage, Abdomen, and Lung. *Journal of Speech and Hearing Research*, *16*(1), 78–115. https://doi.org/10.1044/jshr.1601.78

Hixon, T. J., Mead, J., & Goldman, M. D. (1976). Dynamics of the chest wall during speech production: function of the thorax, rib cage, diaphragm, and abdomen. *Journal of Speech and Hearing Research*, *19*(2), 297–356. https://doi.org/10.1044/jshr.1902.297

Hixon, T. J., & Weismer, G. (1995). Perspectives on the Edinburgh Study of Speech Breathing. *Journal of Speech, Language, and Hearing Research*, *38*(1), 42–60. https://doi.org/10.1044/jshr.3801.42

Hixon, T. J., Weismer, G., & Hoit, J. D. (2014). *Preclinical Speech Science : Anatomy, Physiology, Acoustics, Perception* (2nd ed.). Plural Publishing. https://search.library.ualberta.ca/catalog/6111374

Hoit, J. D., & Hixon, T. J. (1987). Age and Speech Breathing. *Journal of Speech and Hearing Research*, *30*, 351–366.

Hoit, J. D., Hixon, T. J., Altman, M. E., & Morgan, W. J. (1989). Speech breathing in women. *Journal of Speech and Hearing Research*, *32*(2), 353–365. https://doi.org/10.1044/JSHR.3202.353

Hoit, J. D., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1990). Speech Breathing in Children and Adolescents. *Journal of Speech and Hearing Research*, *33*, 51–69.

Hoit, J. D., Plassman, B. L., Lansing, R. W., & Hixon, T. J. (1988). Abdominal muscle activity during speech production. *Journal of Applied Physiology*, *65*(6), 2656–2664. https://doi.org/10.1152/jappl.1988.65.6.2656

Hoit, J. D., Watson, P. J., Hixon, K. E., McMahon, P., & Johnson, C. L. (1994). Age and Velopharyngeal Function During Speech Production. *Journal of Speech, Language, and Hearing Research*, *37*(2), 295–302. https://doi.org/10.1044/jshr.3702.295

Huang, C. N., Chen, C. H., & Chung, H. Y. (2005). The review of applications and measurements in facial electromyography. *Journal of Medical and Biological Engineering*, *25*(1), 15–20.

Huber, J. E. (2008). Effects of Utterance Length and Vocal Loudness on Speech Breathing in Older Adults. *Respiratory, Physiology and Neurobiology*, *164*(3), 323–330. https://doi.org/10.1016/j.resp.2008.08.007.Effects

Huber, J. E., Darling, M., Francis, E. J., & Zhang, D. (2012). Impact of typical aging and Parkinson’s disease on the relationship among breath pausing, syntax, and punctuation. *American Journal of Speech-Language Pathology*, *21*(4), 368–379. https://doi.org/10.1044/1058-0360(2012/11-0059)

Huber, J. E., & Spruill III, J. (2012). Age-Related Changes to Speech Breathing with Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047).Age-Related

Huber, J. E., & Spruill, J. (2008). Age-Related Changes to Speech Breathing With Increased Vocal Loudness. *Journal of Speech, Language, and Hearing Research*, *51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047)

Hwang, K., Jin, S., Hwang, S. H., & Chung, I. H. (2006). Innervation of upper orbicularis oris muscle. *The Journal of Craniofacial Surgery*, *17*(6), 1116–1117. https://doi.org/10.1097/01.SCS.0000235107.70118.06

Jacewicz, E., Fox, R. A., O'Neill, C., & Salmons, J. (2009). Articulation rate across dialect, age, and gender. *Language Variation and Change*, *21*(2), 233–256. https://doi.org/10.1017/S0954394509990093

Jaiser, S. R., Baker, M. R., & Baker, S. N. (2016). Intermuscular coherence in normal adults: Variability and changes with age. *PLoS ONE*, *11*(2), 1–16. https://doi.org/10.1371/journal.pone.0149029

Jeffery R. Cram. (2011). *Cram's Introduction to Surface Electromyography* (E. Eleanor Criswell, Ed.; Second Edition). https://books.google.ca/books/about/Cram_s_Introduction_to_Surface_Electromy.html?id=RgfX5jXrmzMC&printsec=frontcover&source=kp_read_button&redir_esc=y#v=onepage&q&f=false

Kahane, J. C., & Kahn, A. R. (1984). Weight measurements of infant and adult intrinsic laryngeal muscles. *Folia Phoniatrica*, *36*(3), 129–133. http://www.ncbi.nlm.nih.gov/pubmed/6469156

Kattla, S., & Lowery, M. M. (2010). *Fatigue related changes in electromyographic coherence between synergistic hand muscles*. 89–99. https://doi.org/10.1007/s00221-009-2110-0

Kent, R. D. (2000). Research on Speech Motor Control and Its Disorders: a Review and Prospective. *Journal of Communication Disorders*, *33*, 391–428. https://doi.org/10.1016/S0021-9924(00)00023-X

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020). Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, *124*(4), 1045–1055. https://doi.org/10.1152/JN.00231.2020

Khoddami, S. M., Nakhostin Ansari, N., Izadi, F., & Talebian Moghadam, S. (2013). The assessment methods of laryngeal muscle activity in muscle tension Dysphonia: A review. *The Scientific World Journal*, *2013*(1). https://doi.org/10.1155/2013/507397

Kilner, J. M., Baker, S. N., Salenius, S., Jousmäki, V., Hari, R., & Lemon, R. N. (1999). Task-dependent modulation of 15-30 Hz coherence between rectified EMGs from human hand and forearm muscles. *The Journal of Physiology*, *516.2*, 559–570. http://www.ncbi.nlm.nih.gov/pubmed/10087353

Kilner, J. M., Fisher, R. J., & Lemon, R. N. (2003). *Coupling of Oscillatory Activity Between Muscles Is Strikingly Reduced in a Deafferented Subject Compared With Normal Controls*. 790–796.

Kuhlmann, L. L., & Iwarsson, J. (2021). Effects of Speaking Rate on Breathing and Voice Behavior. *Journal of Voice*. https://doi.org/10.1016/J.JVOICE.2021.09.005

Kuriki, H. U., Mícolis De Azevedo, F., Sanae, L., Takahashi, O., & Mello, M. (2012). The Relationship Between Electromyography and Muscle Force. In M. Schwartz (Ed.), *EMG Methods for Evaluating Muscle and Nerve Function* (pp. 31–52). www.intechopen.com

Laine, C. M., & Valero-Cuevas, F. J. (2017). Intermuscular coherence reflects functional coordination. *Journal of Neurophysiology*, *118*(3), 1775–1783. https://doi.org/10.1152/jn.00204.2017

Lametti, D. R., Nasir, S. M., & Ostry, D. J. (2012). Sensory Preference in Speech Production Revealed by Simultaneous Alteration of Auditory and Somatosensory Feedback. *Journal of Neuroscience*, *32*(27), 9351–9358. https://doi.org/10.1523/jneurosci.0404-12.2012

Lemon, R. N. (2008). *Descending Pathways in Motor Control*. *Cm*. https://doi.org/10.1146/annurev.neuro.31.060407.125547

Levitzky M.G.(Ed.), (2017). *Pulmonary Physiology, 9e*. McGraw Hill. https://accessmedicine-mhmedical-com.login.ezproxy.library.ualberta.ca/content.aspx?bookid=2288&sectionid=178857560

Liss, J. M., Weismer, G., & Rosenbek, J. C. (1990). Selected Acoustic Characteristics of Speech Production in Very Old Males. *Journal of Gerontology*, *45*(2), P35–P45. https://doi.org/10.1093/geronj/45.2.P35

Liu, P., Chen, Z., Jones, J. A., Huang, D., & Liu, H. (2011). Auditory feedback control of vocal pitch during sustained vocalization: A Cross-Sectional study of adult aging. *PLoS ONE*, *6*(7), 0–7. https://doi.org/10.1371/journal.pone.0022791

Loucks, T. M. J., Poletto, C. J., Simonyan, K., Reynolds, C. L., & Ludlow, C. L. (2007). Human brain activation during phonation and exhalation : Common volitional control for two upper airway functions. *Human Brain Mapping Journal*, *36*, 131–143. https://doi.org/10.1016/j.neuroimage.2007.01.049

MacPherson, M. K. (2019). Cognitive load affects speech motor performance differently in older and younger adults. *Journal of Speech, Language, and Hearing Research*, *62*(5), 1258–1277. https://doi.org/10.1044/2018_JSLHR-S-17-0222

Manda, Y., Maeda, N., Pan, Q., Sugimoto, K., Hashimoto, Y., Tanaka, Y., Kodama, N., & Minagi, S. (2016). New method of neck surface electromyography for the evaluation of tongue-lifting activity. *Journal of Oral Rehabilitation*, *43*(6), 417–425. https://doi.org/10.1111/joor.12389

McClean, M. D., & Tasko, S. M. (2002). Association of orofacial with laryngeal and respiratory motor output during speech. *Experimental Brain Research*, *146*(4), 481–489. https://doi.org/10.1007/s00221-002-1187-5

McClean, M. D., & Tasko, S. M. (2006). Association of Orofacial Muscle Activity and Movement During Changes in Speech Rate and Intensity. *Journal of Speech, Language, and Hearing Research*, *46*(6), 1387–1400. https://doi.org/10.1044/1092-4388(2003/108)

McFarland, D. H., & Smith, A. (1989). Surface recordings of respiratory muscle activity during speech: some preliminary findings. *Journal of Speech and Hearing Research*, *32*(3), 657–667. http://www.ncbi.nlm.nih.gov/pubmed/2779209

Mckay, L. C., Evans, K. C., Frackowiak, R. S. J., & Corfield, D. R. (2003). *Neural correlates of voluntary breathing in humans*. 1170–1178.

Mendes, A., Ferreira, L., Jorge, A., Rothman, H., Tavares, D., & Garcez, I. (2017). Respiratory physiology during reading aloud tasks. *Distúrbios Da Comunicação*, *29*(3), 519–528. https://doi.org/10.23925/2176-2724.2017v29i3p519-528

Mendes Balata, P. M., Da Silva, H. J., Rocha De Moraes, K. J., De Araújo Pernambuco, L., & Arruda De Moraes, S. R. A. (2013). Use of surface electromyography in phonation studies: An integrative review. *International Archives of Otorhinolaryngology*, *17*(3), 329–339. https://doi.org/10.7162/S1809-977720130003000014

Merletti, R., & Muceli, S. (2019). Tutorial. Surface EMG detection in space and time: Best practices. *Journal of Electromyography and Kinesiology*, *49*(August), 102363. https://doi.org/10.1016/j.jelekin.2019.102363

Mima, T., & Hallett, M. (1999). Corticomuscular coherence: a review. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society*, *16*(6), 501–511. https://doi.org/10.1097/00004691-199911000-00002

Mitchell, H. L., & Hoit, J. D. (1996). Cognitive-Linguistic Demands and Speech Breathing. *Journal of Speech, Language, and Hearing Research*, *39*(1), 93–104. https://doi.org/10.1044/jshr.3901.93

Mitsukawa, N., Moriyama, H., Shiozawa, K., & Satoh, K. (2014). Study on distribution of terminal branches of the facial nerve in mimetic muscles (orbicularis oculi muscle and orbicularis oris muscle). *Annals of Plastic Surgery*, *72*(1), 71–74. https://doi.org/10.1097/SAP.0B013E318284ECA0

Mohr, M., Nann, M., Von Tscharner, V., Eskofier, B., & Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *PLOS ONE*, *10*(11), e0142048. https://doi.org/10.1371/JOURNAL.PONE.0142048

Mohr, M., Schön, T., von Tscharner, V., & Nigg, B. M. (2018). Intermuscular coherence between surface EMG signals is higher for monopolar compared to bipolar electrode configurations. *Frontiers in Physiology*, *9*(MAY), 566. https://doi.org/10.3389/FPHYS.2018.00566/BIBTEX

Moore, C. A., Caulfield, T. J., & Green, J. R. (2001). Relative Kinematics of the Rib Cage and Abdomen During Speech and Nonspeech Behaviors of 15-Month-Old Children. *Journal of Speech, Language, and Hearing Research*, *44*(1), 80–94. https://doi.org/10.1044/1092-4388(2001/008)

Nasir, S. M., & Ostry, D. J. (2006). Somatosensory Precision in Speech Production. *Current Biology*, *16*(19), 1918–1923. https://doi.org/10.1016/j.cub.2006.07.069

Nazarpour, K., Barnard, A., & Jackson, A. (2012). Flexible cortical control of task-specific muscle synergies. *Journal of Neuroscience*, *32*(36), 12349–12360. https://doi.org/10.1523/JNEUROSCI.5481-11.2012

Negro, F., & Farina, D. (2011). *Linear transmission of cortical oscillations to the neural drive to muscles is mediated by common projections to populations of motoneurons in humans*. *3*, 629–637. https://doi.org/10.1113/jphysiol.2010.202473

Nguyen, H. B., Lee, S. W., Harris-love, M. L., & Lum, P. S. (2017). Control of Movement Neural coupling between homologous muscles during bimanual tasks : effects of visual and somatosensory feedback. *Journal of Neurophysiology*, *117*, 655–664. https://doi.org/10.1152/jn.00269.2016

Nip, I. S. B., & Green, J. R. (2013). Increases in Cognitive and Linguistic Processing Primarily Account for Increases in Speaking Rate With Age. *Child Development*, *84*(4), 1324–1337. https://doi.org/10.1111/CDEV.12052

Nishimura, Y., Morichika, Y., & Isa, T. (2009). A subcortical oscillatory network contributes to recovery of hand dexterity after spinal cord injury. *Brain*, *132*(3), 709. https://doi.org/10.1093/BRAIN/AWN338

Nojima, I., Watanabe, T., Saito, K., & Tanabe, S. (2018). Modulation of EMG-EMG Coherence in a Choice Stepping Task. *Frontiers in Human Neuroscience*, *12*, 1–11. https://doi.org/10.3389/fnhum.2018.00050

Norton, J. A., & Gorassini, M. (2006). Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *Journal of Neurophysiology*, *95*, 2580–2589. https://doi.org/10.1152/jn.01289.2005

Ohashi, H., & Ostry, D. J. (2021). Neural Development of Speech Sensorimotor Learning. *Journal of Neuroscience*, *41*(18), 4023–4035. https://doi.org/10.1523/JNEUROSCI.2884-20.2021

Omlor, W., Patino, L., Hepp-Reymond, M. C., & Kristeva, R. (2007). Gamma-range corticomuscular coherence during dynamic force output. *NeuroImage*, *34*(3), 1191–1198. https://doi.org/10.1016/J.NEUROIMAGE.2006.10.018

Pattinson, K. T. S. (2008). Opioids and the control of respiration. *British Journal of Anaesthesia*, *100*(6), 747–758. https://doi.org/10.1093/BJA/AEN094

Peladeau-Pigeon, M., & Steele, C. M. (2017). Age-Related Variability in Tongue Pressure Patterns for Maximum Isometric and Saliva Swallowing Tasks. *Journal of Speech, Language, and Hearing Research*, *60*(11), 3177–3184. https://doi.org/10.1044/2017_jslhr-s-16-0356

Peters, H. F. M., & Boves, L. (1988). Coordination of Aerodynamic and Phonatory Processes in Fluent Speech Utterances of Stutterers. *Journal of Speech and Hearing Research*, *31*(3), 352–361. https://doi.org/10.1044/JSHR.3103.352

Poletto, C. J., Verdun, L. P., Strominger, R., & Ludlow, C. L. (2004). Correspondence between laryngeal vocal fold movement and muscle activity during speech and nonspeech gestures. *Journal of Applied Physiology*, *97*(3), 858–866. https://doi.org/10.1152/japplphysiol.00087.2004

Poston, B., Santos, A. D. Dos, Jesunathadas, M., Hamm, T. M., & Santello, M. (2010). Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping. *Journal of Neurophysiology*, *104*(2), 1141–1154. https://doi.org/10.1152/JN.00185.2010/ASSET/IMAGES/LARGE/Z9K0081002390008.JPEG

Price, C. J. (2012). A review and synthesis of the first 20years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, *62*(2), 816–847. https://doi.org/10.1016/j.neuroimage.2012.04.062

Price, C. J., McCrory, E., Noppeney, U., Mechelli, A., Moore, C. J., Biggio, N., & Devlin, J. T. (2006). How reading differs from object naming at the neuronal level. *NeuroImage*, *29*(2), 643–648. https://doi.org/10.1016/J.NEUROIMAGE.2005.07.044

Purcell, D. W., & Munhall, K. G. (2006). Adaptive control of vowel formant frequency: Evidence from real-time formant manipulation. *The Journal of the Acoustical Society of America*, *120*(2), 966–977. https://doi.org/10.1121/1.2217714

Purves, D. (2018). *Neuroscience* (D. Purves, G. J. Augustine, D. Fitzpatrick, W. C. Hall, A.-S. LaMantia, R. D. Mooney, M. L. Platt, & L. E. White, Eds.; Sixth edition). Oxford University Press. https://search.library.ualberta.ca/catalog/8297154

Quanjer, P. H., Stanojevic, S., Cole, T. J., Baur, X., Hall, G. L., Culver, B. H., Enright, P. L., Hankinson, J. L., Ip, M. S. M., Zheng, J., Stocks, J., & Schindler, C. (2012). Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. *The European Respiratory Journal*, *40*(6), 1324–1343. https://doi.org/10.1183/09031936.00080312

Reed, A., Cummine, J., Bakhtiari, R., & Boliek, C. (n.d.-a). *The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Chest Wall* .

Reed, A., Cummine, J., Bakhtiari, R., & Boliek, C. (n.d.-b). *The Effects of Respiratory, Laryngeal, Articulatory and Cognitive-linguistic Demands on Intermuscular Coherence in the Orbicularis Oris*.

Reed, A., Cummine, J., Bhat, N., Jhala, S., Bakhtiari, R., & Boliek, C. A. (2021). Changes in Intermuscular Coherence as a Function of Age and Phase of Speech Production During an Overt Reading Task. *Motor Control*, *25*(2), 295–314. https://doi.org/10.1123/MC.2020-0003

Reyes, A., Laine, C. M., Kutch, J. J., & Valero-Cuevas, F. J. (2017). Beta Band Corticomuscular Drive Reflects Muscle Coordination Strategies. *Frontiers in Computational Neuroscience*, *11*(April), 1–10. https://doi.org/10.3389/fncom.2017.00017

Riès, S., Legou, T., Burle, B., Alario, F. X., & Malfait, N. (2012). Why does picture naming take longer than word reading? The contribution of articulatory processes. *Psychonomic Bulletin & Review*, *19*(5), 955–961. https://doi.org/10.3758/S13423-012-0287-X

Rong, P., & Pattee, G. L. (2021). A potential upper motor neuron measure of bulbar involvement in amyotrophic lateral sclerosis using jaw muscle coherence. Amyotrophic lateral sclerosis & frontotemporal degeneration, 22(5-6), 368–379. https://doi.org/10.1080/21678421.2021.1874993

Rosenberg, J. R., Amjad, A. M., Breeze, P., Brillinger, D. R., & Halliday, D. M. (1989). The Fourier approach to the identification of functional coupling between neuronal spike trains. *Progress in Biophysics and Molecular Biology*, *53*(1), 1–31. https://doi.org/10.1016/0079-6107(89)90004-7

Rowe, H. P., Stipancic, K. L., Lammert, A. C., & Green, J. R. (2021). Validation of an Acoustic-Based Framework of Speech Motor Control: Assessing Criterion and Construct Validity Using Kinematic and Perceptual Measures. *Journal of Speech, Language, and Hearing Research*, *64*(12), 4736–4753. https://doi.org/10.1044/2021_JSLHR-21-00201

Ruark, J. L., & Moore, C. A. (1997). Coordination of Lip Muscle Activity by 2-Year-Old Children During Speech and Nonspeech Tasks. *Journal of Speech, Language, and Hearing Research : JSLHR*, *40*(6), 1373. https://doi.org/10.1044/JSLHR.4006.1373

Ryan, W. J. (1972). Acoustic aspects of the aging voice. *Journal of Gerontology*, *27*(2), 265–268. https://doi.org/10.1093/geronj/27.2.265

Sasaki, C. T., & Leder, S. B. (2013). Surface electromyography for speech and swallowing systems: Measurement, analysis, and interpretation: Comment. *Dysphagia*, *28*(1), 116–117. https://doi.org/10.1007/s00455-012-9431-z

Segovia, G., Porras, A., Del Arco, A., & Mora, F. (2001). Glutamatergic neurotransmission in aging: A critical perspective. *Mechanisms of Ageing and Development*, *122*, 1–29. https://doi.org/10.1016/S0047-6374(00)00225-6

Semmler, J. G., Ebert, S. A., & Amarasena, J. (2013). Eccentric muscle damage increases intermuscular coherence during a fatiguing isometric contraction. *Acta Physiologica*, *208*(4), 362–375. https://doi.org/10.1111/apha.12111

Semmler, J. G., Kornatz, K. W., & Enoka, R. M. (2006). Motor-Unit Coherence During Isometric Contractions Is Greater in a Hand Muscle of Older Adults. *Journal of Neurophysiology*, *90*(2), 1346–1349. https://doi.org/10.1152/jn.00941.2002

Semmler, J. G., Steege, J. W., Kornatz, K. W., & Enoka, R. M. (2000). Motor-Unit Synchronization Is Not Responsible for Larger Motor-Unit Forces in Old Adults. *Journal of Neurophysiology*, *84*(1), 358–366. https://doi.org/10.1152/jn.2000.84.1.358

Shen, C., & Janse, E. (2020). Maximum speech performance and executive control in young adult speakers. *Journal of Speech, Language, and Hearing Research*, *63*(11), 3611-3627.

Smith, A. (2006). Speech motor development: Integrating muscles, movements, and linguistic units. *Journal of Communication Disorders*, *39*(5), 331–349. https://doi.org/10.1016/j.jcomdis.2006.06.017

Smith, A., & Denny, M. (1990). High-frequency oscillations as indicators of neural control mechanisms in human respiration, mastication, and speech. *Journal of Neurophysiology*, *63*(4), 745–758.

Smith, A., Luschei, E., Denny, M., Wood, J., & Hirano, M. (1993). Spectral Analyses of Activity of Laryngeal and Orofacial Muscles in Stutters. *Journal of Neurology, Neurosurgery and Psychiatry*, *56*, 1303–1311.

Smith, A., & Zelaznik, H. N. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology*, *45*(1), 22–33. https://doi.org/10.1002/dev.20009

Smith, J. C., Abdala, A. P. L., Borgmann, A., Rybak, I. A., & Paton, J. F. R. (2014). Brainstem respiratory networks: building blocks and microcircuits. *Trends in Neurosciences*, *36*(3), 152–162. https://doi.org/10.1016/j.pain.2013.06.005.Re-Thinking

Smith, Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech and Hearing Research*, *30*(4), 522–529. http://www.ncbi.nlm.nih.gov/pubmed/3695445

Sonies, B. C., Baum, B. J., & Shawker, T. H. (1984). Tongue Motion in Elderly Adults: Initial in Situ Observations. *Journal of Gerontology*, *39*(3), 279–283. https://doi.org/10.1093/geronj/39.3.279

Sperry, E. E., & Klich, R. J. (1992). Speech breathing in senescent and younger women during oral reading. *Journal of Speech and Hearing Research*, *35*(6), 1246–1255. https://doi.org/10.1044/JSHR.3506.1246

Standring, S. (Ed.). (2021). *Gray's anatomy : the anatomical basis of clinical practice* (Forty-second edition). Elsevier.

Stathopoulos, E. T., Huber, J. E., Sussman, J. E., & Lafayette, W. (2011). *Changes in Acoustic Characteristics of the Voice Across Life Span*. *54*(August), 1011–1021. https://doi.org/10.1044/1092-4388(2010/10-0036)b

Stathopoulos, E. T., & Sapienza, C. (1993). Respiratory and laryngeal function of women and men during vocal intensity variation. *Journal of Speech and Hearing Research*, *36*(1), 64–75. https://doi.org/10.1044/JSHR.3601.64

Stathopoulos, E. T., & Sapienza, C. (2005). Respiratory and laryngeal measures of children during vocal intensity variation. *The Journal of the Acoustical Society of America*, *94*(5), 2531–2543. https://doi.org/10.1121/1.407365

Stathopoulos, E. T., & Sapienza, C. M. (1997). Developmental Changes in Laryngeal and Respiratory Function With Variations in Sound Pressure Level. *Journal of Speech, Language, and Hearing Research*, *40*(3), 595–614. https://doi.org/10.1044/JSLHR.4003.595

Statistics Canada. (2002). *2001 Participation and Activity Limitation Survey*.

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & Mcmurtrey, J. R. (2008). Babbling, Chewing, and Sucking: Oromandibular Coordination at 9 Months. *Journal of Speech Language and Hearing Research*, *51*(December), 1390–1405.

Steeve, R. W., Moore, C. A., Green, J. R., Reilly, K. J., & McMurtrey, J. R. (2008). Babbling, chewing, and sucking: oromandibular coordination at 9 months. *Journal of Speech, Language, and Hearing Research : JSLHR*, *51*(6), 1390–1404. https://doi.org/10.1044/1092-4388(2008/07-0046)

Steeve, R. W., & Price, C. M. (2010). Investigating the use of coherence analysis on mandibular electromyograms to investigate neural control of early oromandibular behaviours: A pilot study. *Clinical Linguistics & Phonetics*, *24*(6), 485–501. https://doi.org/10.3109/02699200903506312

Stepp, C. E. (2012). Surface Electromyography for Speech and Swallowing Systems: Measurement, Analysis, and Interpretation. *Journal of Speech, Language and Hearing*, *55*, 1232–1247. https://doi.org/10.1044/1092-4388(2011/11-0214)a

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2010). Use of Neck Strap Muscle Intermuscular Coherence as an Indicator of Vocal Hyperfunction. *IEEE Trans Neural Syst Rehabil Eng.EEE Trans Neural Syst Rehabil Eng.*, *18*(3), 329–335. https://doi.org/10.1158/0008-5472.CAN-10-4002.BONE

Stepp, C. E., Hillman, R. E., & Heaton, J. T. (2011). Modulation of neck intermuscular Beta coherence during voice and speech production. *Journal of Speech, Language, and Hearing Research*, *54*, 836–844. https://doi.org/10.1044/1092-4388(2010/10-0139)

Tang, J., & Stathopoulos, E. T. (2005). Vocal efficiency as a function of vocal intensity: A study of children, women, and men. *The Journal of the Acoustical Society of America*, *97*(3), 1885–1892. https://doi.org/10.1121/1.412062

Tomczak, C. R., Greidanus, K. R., & Boliek, C. A. (2013). Modulation of chest wall intermuscular coherence: effects of lung volume excursion and transcranial direct current stimulation. *Journal of Neurophysiology*, *110*, 680–687. https://doi.org/10.1152/jn.00723.2012

Tourville, J. A., & Guenther, F. H. (2011). The DIVA model: A neural theory of speech acquisition and production. *Language and Cognitive Processes*, *26*(7), 952–981. https://doi.org/10.1080/01690960903498424

Tourville, J. A., Reilly, K. J., & Guenther, F. H. (2008). Neural mechanisms underlying auditory feedback control of speech. *NeuroImage*, *39*(3), 1429–1443. https://doi.org/10.1016/j.neuroimage.2007.09.054

Tremblay, S., Shiller, D. M., & Ostry, D. J. (2003). Somatosensory basis of speech production. *Nature*, *423*(6942), 866–869. https://doi.org/10.1038/nature01710

United Nations. (2015). *World Population Ageing United Nations*.

Usler, E. R., Wei, X., Simione, M., Richburg, B., Stipancic, K. L., & Green, J. R. (2020). Modulation of Intermuscular Beta Coherence in Different Rhythmic Mandibular Behaviors. *Frontiers in Human Neuroscience*, *14*, 302. https://doi.org/10.3389/FNHUM.2020.00302/BIBTEX

Valente, A., Pinet, S., Alario, F. X., & Laganaro, M. (2016). "When" does picture naming take longer than word reading? *Frontiers in Psychology*, *7*(JAN), 31. https://doi.org/10.3389/FPSYG.2016.00031/BIBTEX

Van Asseldonk, E. H. F., Campfens, S. F., Verwer, S. J. F., Van Putten, M. J. A. M., & Stegeman, D. F. (2014). Reliability and agreement of intramuscular coherence in tibialis anterior muscle. *PLoS ONE*, *9*(2), 1–10. https://doi.org/10.1371/journal.pone.0088428

Vanderwegen, J., Guns, C., Van Nuffelen, G., Elen, R., & De Bodt, M. (2013). The influence of age, sex, bulb position, visual feedback, and the order of testing on maximum anterior and posterior tongue strength and endurance in healthy Belgian adults. *Dysphagia*, *28*(2), 159–166. https://doi.org/10.1007/s00455-012-9425-x

Villacorta, V. M., Perkell, J. S., & Guenther, F. H. (2007). Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception. *The Journal of the Acoustical Society of America*, *122*(4), 2306–2319. https://doi.org/10.1121/1.2773966

von Tscharner, V., Ullrich, M., Mohr, M., Comaduran Marquez, D., & Nigg, B. M. (2018). Beta, gamma band, and high-frequency coherence of EMGs of vasti muscles caused by clustering of motor units. *Experimental Brain Research*, *236*(11), 3065–3075. https://doi.org/10.1007/S00221-018-5356-6/METRICS

Walsh, B., & Smith, A. (2002). Articulatory Movements in Adolescents: Evidence for Protracted Development of Speech Motor Control Processes. *Journal of Speech, Language and Hearing Research*, *45*, 1119–1133.

Wang, Y. T., Green, J. R., Nip, I. S. B., Kent, R. D., & Kent, J. F. (2010). Breath Group Analysis for Reading and Spontaneous Speech in Healthy Adults. *Folia Phoniatrica et Logopaedica*, *62*(6), 297–302. https://doi.org/10.1159/000316976

Watson, P. J., Ciccia, A. H., Weismer, G., & Soc, J. A. (2003). The relation of lung volume initiation to selected acoustic properties of speech. *The Journal of the Acoustical Society of America*, *113*(5), 2812–2819. https://doi.org/10.1121/1.1567279

Wohlert, A. B., & Smith, A. (1998). Spatiotemporal stability of lip movements in older adult speakers. *Journal of Speech, Language, and Hearing Research : JSLHR*, *41*(1), 41–50. http://www.ncbi.nlm.nih.gov/pubmed/9493732

Wohlert, A. B., & Smith, A. (2002). Developmental Change in Variability of Lip Muscle Activity During Speech. *Journal of Speech, Language, and Hearing Research*, *45*(6), 1077–1087. https://doi.org/10.1044/1092-4388(2002/086)

Woods, M. J., Nicholas, C. L., Semmler, J. G., Chan, J. K. M., Jordan, A. S., & Trinder, J. (2015). Common drive to the upper airway muscle genioglossus during inspiratory loading. *Journal of Neurophysiology*, *114*(5), 2883–2892. https://doi.org/10.1152/jn.00738.2014

Zajac, D. J. (1997). Velopharyngeal function in young and older adult speakers: Evidence from aerodynamic studies. *The Journal of the Acoustical Society of America*, *102*(3), 1846–1852. https://doi.org/10.1121/1.420091

Appendix 1: Word Lists

List 1

tomb
must
does
wipe
both
pusk
shed
wage
hoog
hook
food
home
ease
Earn
gawn
kast
your
nane
loss
welf
push
gool
bulk
hoos
some
pape
sour
soal
toor
pour
full
eaze
plad
hame
hite
soid
wune
forl
yeer
darf

List 2

hood
role
boss
feel
dole
four
sole
toom
saim
door
feal
whom
gess

soul
woth
pune
much
bord
bull
well
wair
kost
bave
loce
vale
foun

noce
hoam
pull
heaf
rulf
hoot
lose
soun
hurd
gurl
foat
shoe
goes
womb

Appendix 2: List of Images

List 1:

- rake
- panda
- church
- bathtub
- octopus
- shirt
- tank
- Ice cream cone
- girl
- throw
- fence
- slip
- laugh
- make
- zip
- swat
- banjo
- hair
- rain
- fish
- row
- jumprope
- trip
- lighthouse
- push
- crib
- knit
- Fire hydrant
- mop
- pay
- highchair
- reach
- juggle
- music
- curtsey
- sunbathe
- toilet
- sneeze
- catch
- car

List 2

stairs
write
fire
box
pet
ladybug
mailbox
peel
thumb
tie
baby
snow
iron
fall

paperclip
moose
jump
dustpan
cry
plate
window
handcuffs
soldier
skate
peacock
hinge
wink
dip

tear
letter
vacuum
llama
light
lawnmower
shower
propose
wrap
sing
surf
tent
golf

Appendix 3: Tongue Twisters

Tongue Twisters Set 1

Brief beastly beach breezes

Fine fresh free fish

Floyd’s fourth floor fort

Gloria’s Greek green gloves

Kick six sticks quick

Luke’s ducks like lakes

Luther’s moose’s loosest tooth

Plastic potted pansy plants

Santa’s short suit shrunk

Shops seldom sell shellfish

Swizzle scissors sizzle thistles

Three short sword sheaths

Trish's ritzy Irish wristwatches

Which wished which wish

Willy’s real rear wheel

Tongue Twisters Set 2

Brad’s burned bran buns

Chef’s sooty shoe soles

Chop shops stock chops

Five frantic fat frogs

Flea-free fruit flies

Kate takes Tate’s cake

Larry’s really rarely leery

Proper copper coffee pot

Richard’s wretched ratchet wrench

Simon’s minimum cinnamon synonym

Six thick thistle sticks

This sister’s sixth zither

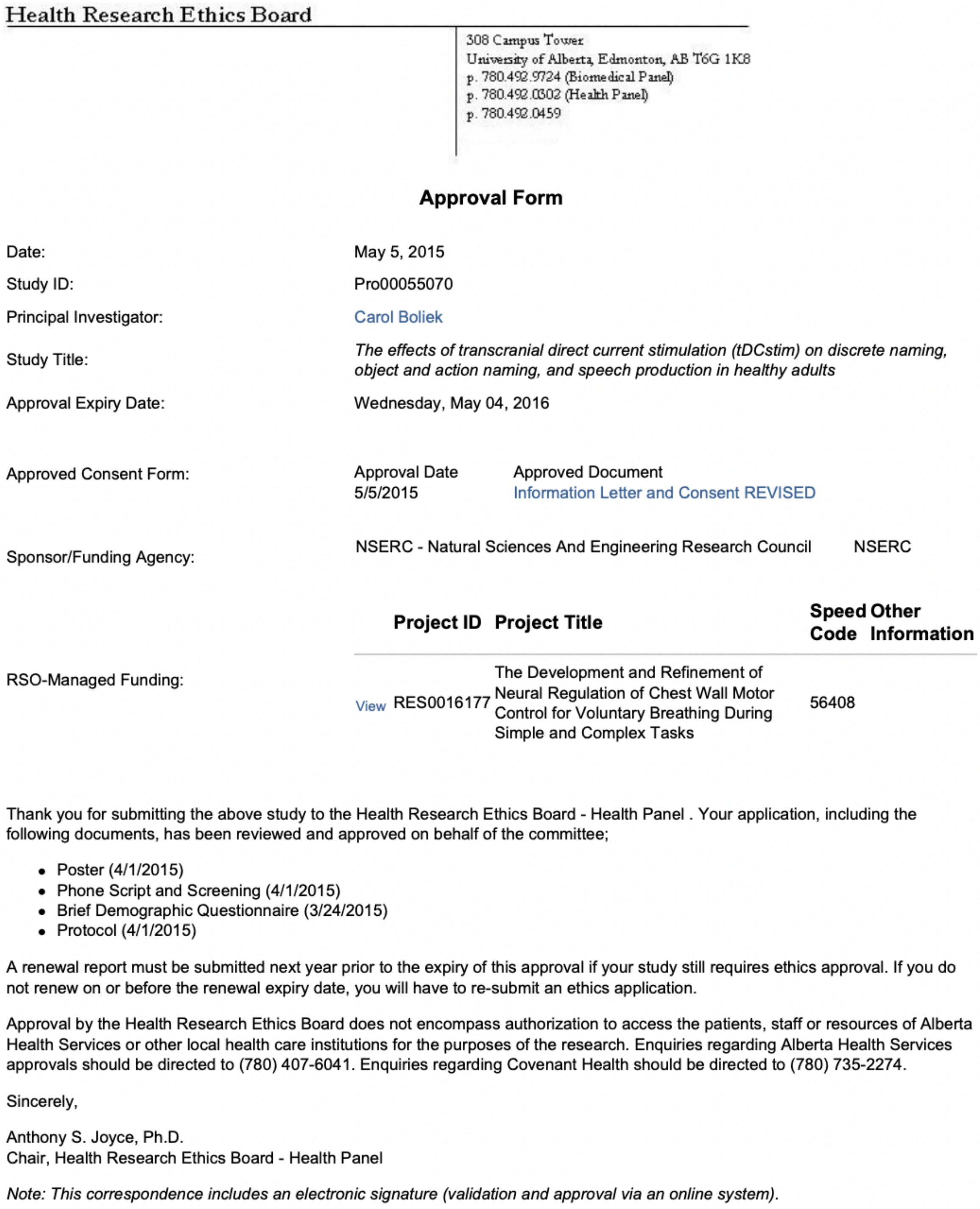
Three tree twigs twine

Which Swiss witch switched?

Whistle softer thistle sifter

Appendix 4: Ethics Approvals

Ethics approval for data used in study 1, 2 and 3.



Health Research Ethics Board

308 Campus Tower
University of Alberta, Edmonton, AB T6G 1K8
p. 780.492.9724 (Biomedical Panel)
p. 780.492.0302 (Health Panel)
p. 780.492.0459

Approval Form

Date:	May 5, 2015
Study ID:	Pro00055070
Principal Investigator:	Carol Boliek
Study Title:	*The effects of transcranial direct current stimulation (tDCstim) on discrete naming, object and action naming, and speech production in healthy adults*
Approval Expiry Date:	Wednesday, May 04, 2016

Approved Consent Form:

Approval Date	Approved Document
5/5/2015	Information Letter and Consent REVISED

Sponsor/Funding Agency: NSERC - Natural Sciences And Engineering Research Council NSERC

RSO-Managed Funding:

	Project ID	Project Title	Speed Code	Other Information
View	RES0016177	The Development and Refinement of Neural Regulation of Chest Wall Motor Control for Voluntary Breathing During Simple and Complex Tasks	56408	

Thank you for submitting the above study to the Health Research Ethics Board - Health Panel . Your application, including the following documents, has been reviewed and approved on behalf of the committee;

- Poster (4/1/2015)
- Phone Script and Screening (4/1/2015)
- Brief Demographic Questionnaire (3/24/2015)
- Protocol (4/1/2015)

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

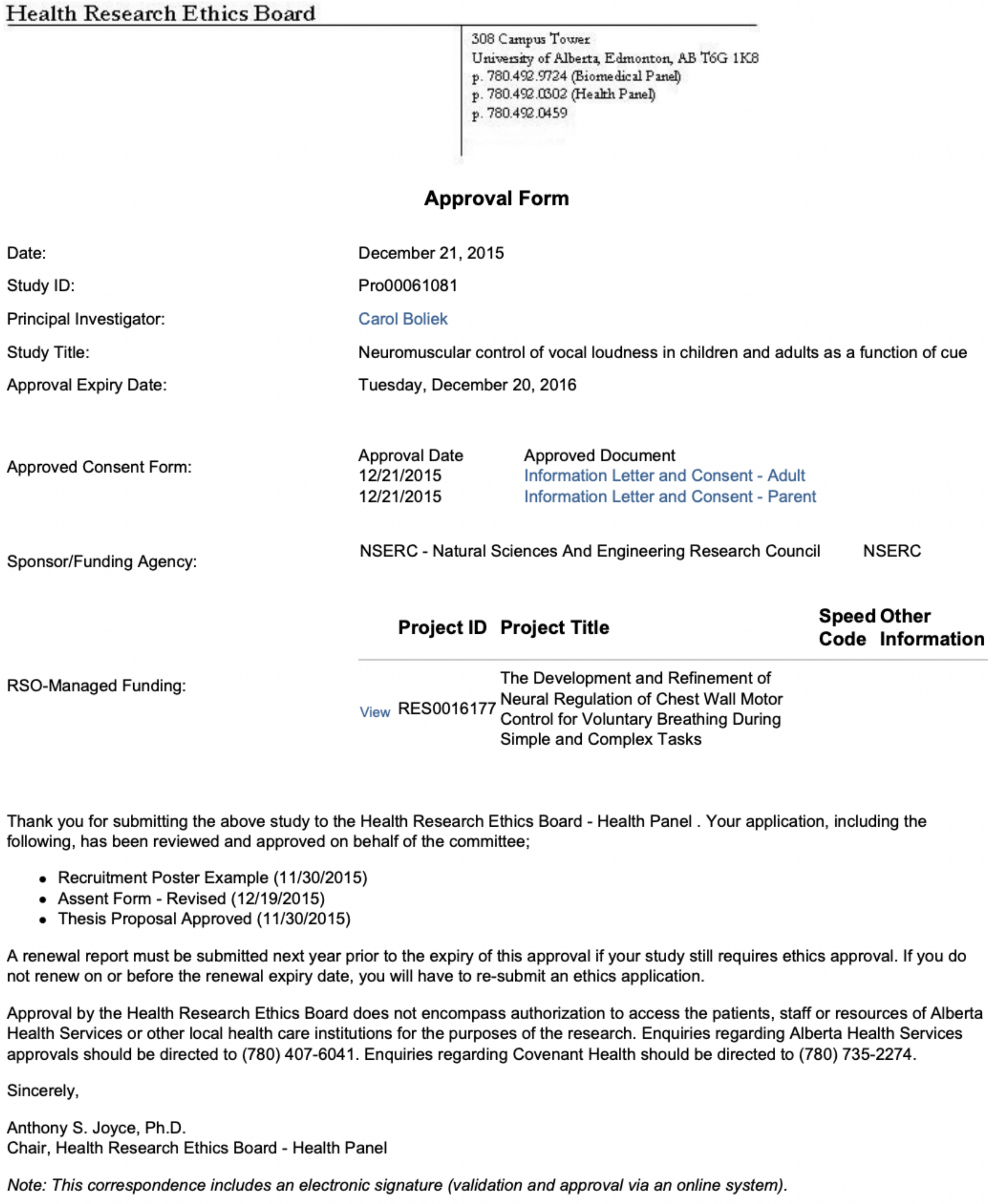
Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Alberta Health Services or other local health care institutions for the purposes of the research. Enquiries regarding Alberta Health Services approvals should be directed to (780) 407-6041. Enquiries regarding Covenant Health should be directed to (780) 735-2274.

Sincerely,

Anthony S. Joyce, Ph.D.
Chair, Health Research Ethics Board - Health Panel

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Ethics approval for data used in study 3



Health Research Ethics Board

308 Campus Tower
University of Alberta, Edmonton, AB T6G 1K8
p. 780.492.9724 (Biomedical Panel)
p. 780.492.0302 (Health Panel)
p. 780.492.0459

Approval Form

Date:	December 21, 2015
Study ID:	Pro00061081
Principal Investigator:	Carol Boliek
Study Title:	Neuromuscular control of vocal loudness in children and adults as a function of cue
Approval Expiry Date:	Tuesday, December 20, 2016

Approved Consent Form:

Approval Date	Approved Document
12/21/2015	Information Letter and Consent - Adult
12/21/2015	Information Letter and Consent - Parent

Sponsor/Funding Agency: NSERC - Natural Sciences And Engineering Research Council NSERC

RSO-Managed Funding:

	Project ID	Project Title	Speed Code	Other Information
View	RES0016177	The Development and Refinement of Neural Regulation of Chest Wall Motor Control for Voluntary Breathing During Simple and Complex Tasks		

Thank you for submitting the above study to the Health Research Ethics Board - Health Panel . Your application, including the following, has been reviewed and approved on behalf of the committee;

- Recruitment Poster Example (11/30/2015)
- Assent Form - Revised (12/19/2015)
- Thesis Proposal Approved (11/30/2015)

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

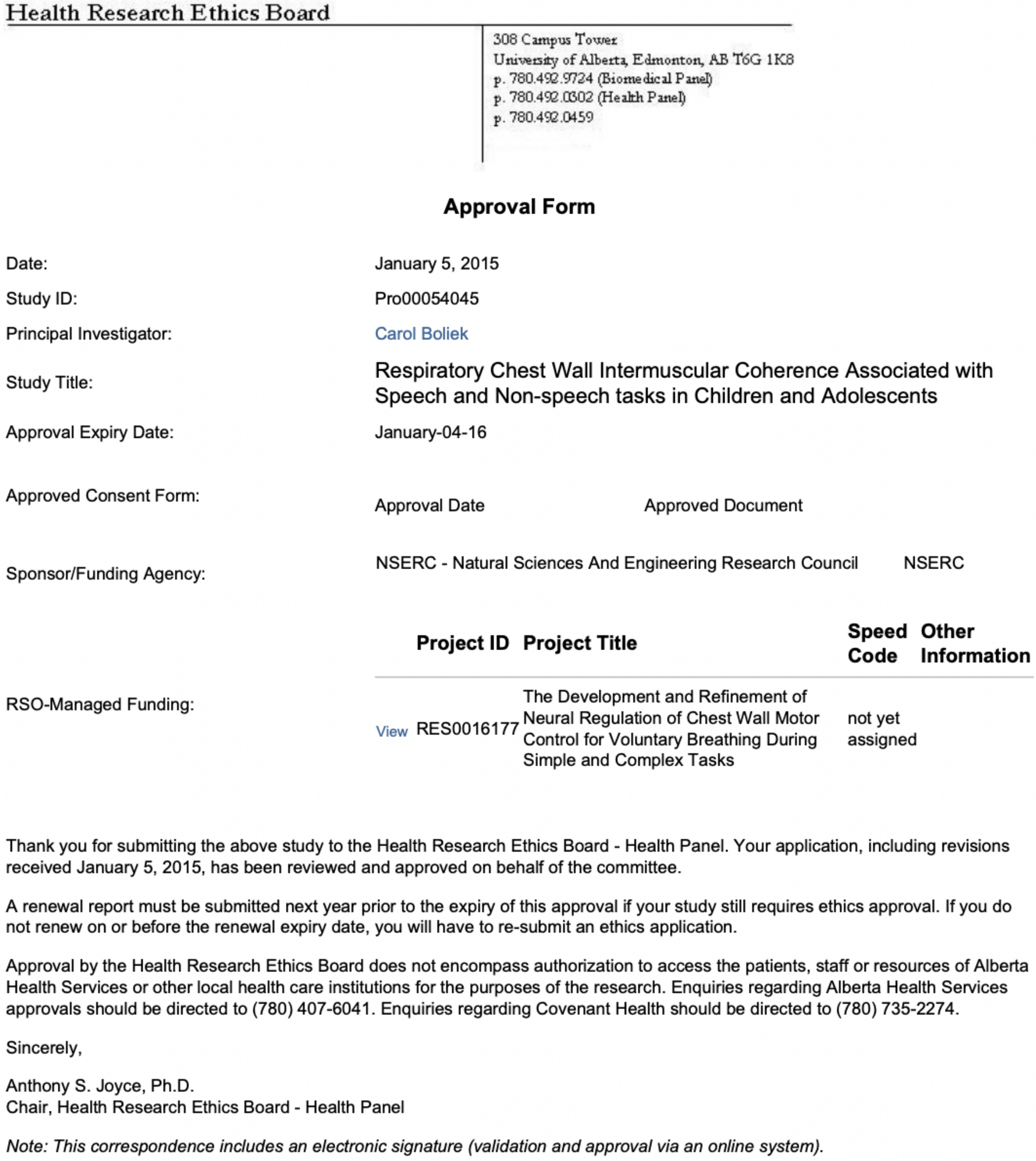
Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Alberta Health Services or other local health care institutions for the purposes of the research. Enquiries regarding Alberta Health Services approvals should be directed to (780) 407-6041. Enquiries regarding Covenant Health should be directed to (780) 735-2274.

Sincerely,

Anthony S. Joyce, Ph.D.
Chair, Health Research Ethics Board - Health Panel

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Ethics approval for data used in study 3



Health Research Ethics Board

308 Campus Tower
University of Alberta, Edmonton, AB T6G 1K8
p. 780.492.9724 (Biomedical Panel)
p. 780.492.0302 (Health Panel)
p. 780.492.0459

Approval Form

Date:	January 5, 2015
Study ID:	Pro00054045
Principal Investigator:	Carol Boliek
Study Title:	Respiratory Chest Wall Intermuscular Coherence Associated with Speech and Non-speech tasks in Children and Adolescents
Approval Expiry Date:	January-04-16
Approved Consent Form:	Approval Date Approved Document
Sponsor/Funding Agency:	NSERC - Natural Sciences And Engineering Research Council NSERC

RSO-Managed Funding:

	Project ID	**Project Title**	**Speed Code**	**Other Information**
View	RES0016177	The Development and Refinement of Neural Regulation of Chest Wall Motor Control for Voluntary Breathing During Simple and Complex Tasks	not yet assigned	

Thank you for submitting the above study to the Health Research Ethics Board - Health Panel. Your application, including revisions received January 5, 2015, has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

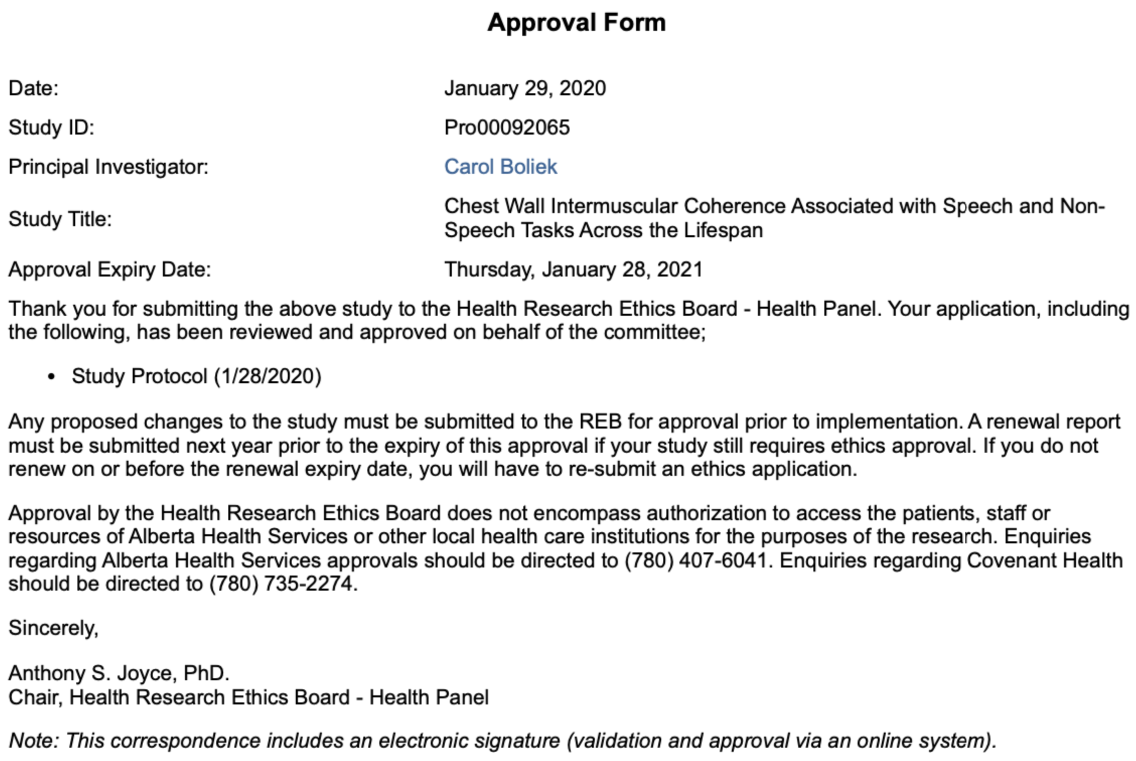
Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Alberta Health Services or other local health care institutions for the purposes of the research. Enquiries regarding Alberta Health Services approvals should be directed to (780) 407-6041. Enquiries regarding Covenant Health should be directed to (780) 735-2274.

Sincerely,

Anthony S. Joyce, Ph.D.
Chair, Health Research Ethics Board - Health Panel

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Ethics approval for secondary analysis of data in study 3



Approval Form

Date:	January 29, 2020
Study ID:	Pro00092065
Principal Investigator:	Carol Boliek
Study Title:	Chest Wall Intermuscular Coherence Associated with Speech and Non-Speech Tasks Across the Lifespan
Approval Expiry Date:	Thursday, January 28, 2021

Thank you for submitting the above study to the Health Research Ethics Board - Health Panel. Your application, including the following, has been reviewed and approved on behalf of the committee;

- Study Protocol (1/28/2020)

Any proposed changes to the study must be submitted to the REB for approval prior to implementation. A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Alberta Health Services or other local health care institutions for the purposes of the research. Enquiries regarding Alberta Health Services approvals should be directed to (780) 407-6041. Enquiries regarding Covenant Health should be directed to (780) 735-2274.

Sincerely,

Anthony S. Joyce, PhD.
Chair, Health Research Ethics Board - Health Panel

Note: This correspondence includes an electronic signature (validation and approval via an online system).