1 **Using Electromyography as a Research Tool in Food Science.**

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48 Abstract

49 The jaw muscles play key functional roles during feeding. During contraction, a bioelectrical
50 signal propagates along the muscle cell helping to coordinate muscle contraction. This signal can be
51 measured via electromyography (EMG). Food scientists have increasingly adopted EMG as a tool for
52 studying the relationships among food textures and oral processing. Specifically, food scientists have
53 used EMG from the feeding muscles as 1) a general measure of food texture, 2) a measure of oral
54 physiology, 3) an estimate of absolute force and 4) a measure of muscle work. Unfortunately,
55 physiological research indicates that estimates of absolute force and mechanical work are not reliably
56 indicated from EMG as it is best considered an indicator of muscle activity and relative recruitment
57 levels.

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Introduction

The jaw opening and closing muscles play key functional roles during chewing by positioning the teeth and generating the occlusal forces needed to break down food. Similarly, muscles in the tongue and throat generate the movements required to safely swallow a bolus. During contraction, a bioelectrical signal propagates along the sarcolemma, or muscle cell membrane, that helps coordinate contraction within the muscle cell. This signal can be measured via electromyography (Loeb & Gans, 1986). Electromyography, or EMG, is classically defined by Basmajian and De Luca [1:1] as “the study of muscle function through the inquiry of the electrical signal the muscles emanate”. Food scientists have increasingly adopted EMG as a tool for studying the relationships among food textures and oral processing (Fig. 1). Given its growth and establishment as a research technique, we consider it appropriate to briefly review electromyography and its application in food science research.

We are not attempting an exhaustive review of electromyography, its physiological basis, its approaches or applications in this short review. The physiological literature is replete with excellent reviews and texts on electromyography [e.g., 1, 2, 3, 4]. In particular, De Luca [5] remains an excellent review of surface EMG for practical applications such as those commonly used in food science research. Food scientists also have provided compelling reviews of how EMG is used in food science research [6]. Our goal is a targeted review of how the use of EMG in food science research aligns with best practices in other fields. Through this review, we hope to continue establishing EMG as a useful tool in understanding how foods and oral processing interact during feeding.

What is the EMG signal and what does it tell us?

Muscle contraction begins when a nerve impulse traverses the motor end plate, where nerve and muscle meet. Muscle cells are excitable carrying a negative charge inside the cell membrane. The nerve impulse initiates the depolarization of the sarcolemma of the muscle cell creating an action

potential. The muscle action potential travels along the sarcolemma and into the transverse tubular (T-tubule) system that penetrates deeply into the muscle cell. Calcium ions stored in the sarcoplasmic reticulum are subsequently released inside the cell initiating contraction as myosin binds to actin followed by myosin and actin sliding past one another. This cross-bridging between actin and myosin results in muscle force production and continues as long as the energy source ATP is available or until the cessation of the neural signal causes sequestering of calcium as the muscle cell returns to its non-contractile state. Spatially, a single nerve axon may innervate and excite multiple muscle fibers, forming a motor unit that contracts simultaneously. Temporally, nerve impulses may fire faster than a single contraction event resulting in summation of forces generated by a muscle. Through this excitation-contraction coupling, muscle cells collectively move and generate forces throughout the body [see 7].

The electrical activity of one or typically more motor units is recorded extracellularly as the EMG signal during contraction (Fig. 2). Because the EMG electrode (i.e., surface or indwelling electrode) is documenting the traveling electrical wave front along the depolarizing cell membrane, it is neither measuring the force ultimately generated by the muscle nor the contractile events occurring during cross-bridging. As such, it is a middle range technique that primarily demonstrates muscle activity during contraction [1, 2, 5, 7]. Given the physiological basis of the EMG signal, we can argue that the EMG signal demonstrates 1) when a muscle is active, 2) the timing of contraction in a muscle, or a group of motor units in a muscle, and 3) the timing of contraction relative to both behavioral events (e.g., maximum jaw closing) and other muscles. Many researchers go beyond timing events to consider the muscle's recruitment level using the EMG signal. In these cases, the raw signal (Fig. 2A) is typically rectified (i.e., converted to positive by taking absolute values) (Fig. 2B) and integrated to generate a single waveform (i.e., by applying some type of low-pass filter) (Fig. 2C) that is often interpreted as relative force or with much more concern absolute force levels produced by a muscle.

Why is EMG appealing?

EMG can provide useful information about muscle physiology related to both timing of activation and relative recruitment levels [e.g., 8, 9]. Reliable physiological data combined with ease of use are two of the main reasons why EMG is appealing in basic physiological research, clinical settings as well as applied research such as food science [5]. EMG can also be relatively painless as surface electrodes can be affixed on the skin with tape-like adhesives and replaced without major concern for subjects' health. Many physiologists caution, however, that the ease of use can lead to over interpreting of EMG data: "To its detriment, electromyography is too easy to use and consequently too easy to abuse." [5:135; see also 2, 10]. Despite EMG telling us less than we likely hope for, it does provide valuable information about muscle physiology during oral processing that food scientists can use.

How is EMG commonly used in food science?

Food scientists have used electromyography for decades to study the interactions between foods and oral processing. Looking across the different ways EMG has been applied in food science research, we consider four basic (non-mutually exclusive) themes for this technology. First, EMG has been used for broadly assessing variation in food texture [e.g., 11, 12, 13, 14, 15, 16, 17, 18, 19, 20*]. Boyar and Kilcast [11] were one of the first to advocate this approach highlighting EMG as a means of bridging the gap between instrument-based assessments of foods and the physiological processes occurring during feeding. In this approach, muscle activity is essentially a biological assessment of food texture that incorporates food mechanical properties, food size and shape as well as other textural attributes perceived in the oral cavity by the consumer [6]. Although at times it can be difficult to relate specific oral processing parameters to aspects of food texture, this basic approach has been successful in differentiating foods based on how they are processed during feeding.

130 Researchers studying food science have also examined the associations between specific aspects
131 of oral physiology and food properties using EMG data [e.g., 21, 22, 23, 24, 25, 26*, 27*, 28*, 29*]. In
132 many ways this second theme is simply a logical extension of using EMG as a basic biological
133 measurement of food texture. Essentially this second approach takes a more in-depth look at how
134 foods are broken down during oral processing to identify specific relationships among textural and
135 physiological parameters. Based on these studies, we can expect to develop and test specific
136 hypotheses relating textural properties to how consumers perceive foods during oral processing.

137 The final two themes consider specific physiological parameters linked to EMG output. Food
138 science research has quantified EMG output to estimate the force generated by a muscle [e.g., 11, 12,
139 16, 30, 31, 32]. Similarly, food scientists have quantified EMGs as a measure of muscle work during
140 food processing [e.g., 17, 21, 22, 31, 32, 33, 34, 35, 36, 37*]. The idea that quantified EMG data can
141 provide accurate estimates of muscle force or work is compelling as it would offer a non-invasive and
142 economical method for acquiring important information about muscle function, but both arguments
143 have received significant criticism and concern in the physiological literature. To further elaborate these
144 issues requires a more detailed examination of both the biological and non-biological factors influencing
145 the EMG signal.

146 147 Can we measure absolute force or work from the EMG signal?

148 Most of the discussion concerning whether EMG data can accurately estimate force and
149 mechanical work has focused on force. (Although not always clearly articulated, researchers have
150 applied EMG output to estimate both the absolute forces generated by a muscle and forces external to
151 the muscle such as a bite force). Because muscle mechanical work is equal to the product of force and
152 distance [38], accurate measures of force are required to quantify work as well. Given this relationship,

we primarily consider issues related to approximating forces, knowing these concerns apply to both force and work estimates.

The arguments against using EMG data to estimate forces focus on three general points. The first point considers what the EMG signal conveys relative to the actual mechanical events occurring within a muscle. Currently, the physiological literature consistently recognizes that it is not possible to reliably estimate absolute muscle force using EMG output during normal activities [see e.g., 3, 5, 7, 10, 39]. The force a muscle can generate is strongly influenced by the length of a muscle and the velocity of contraction [7, 10, 40]. When contracting, muscles can shorten (concentric contraction), be lengthened (eccentric contraction) or remain the same length (isometric contraction). When contracting isometrically, EMG data can be linearly or non-linearly related to the force generated by the muscle [3, 10, 41, 42, 43]. Any potential relationship tends to be context specific. When a muscle is changing length during contraction, experimental data show that the EMG signal does not closely correlate with the force produced by a muscle [10, 40]. These studies collectively demonstrate that the EMG signal conveys information on the extent of muscle activation, but that activation is not a reliable indicator of the amount of force generated by the muscle [10]. These issues are further exacerbated by fatigue-related changes in force production that are not necessarily reflected in the EMG signal as well as variation in motor unit recruitment patterns across contractions [7, 10]. As succinctly summarized by Lieber [7:89]: “Since muscle force is highly dependent on length (due to the length-tension property) and velocity (due to the force-velocity property), electrical activity alone cannot possibly provide an accurate measurement of muscle force.”

In addition to not capturing significant details of muscle dynamics during contraction, there are other biologically-relevant factors that impact EMG output. These issues often apply when using EMG data to estimate forces external to the muscle. For example, the jaw muscles have to produce occlusal forces and move the jaw during feeding. It can be difficult to discriminate between these events using

only EMG data (Fig. 3). There are multiple ways a muscle can generate submaximal forces, particularly external forces [see e.g., 44]. Because an electrode only captures activity of some of the motor units in a muscle, variation in motor unit recruitment during submaximal force production potentially confounds comparison of forces across repetitive events such as chewing cycles. This issue is compounded when multiple muscles contribute to an external force (e.g., bite force) that is being estimated using EMG output from a subset of these muscles. Changes in bite point location as food is moved throughout the oral cavity potentially impact leverage and subsequently muscle recruitment [45]. Finally, variation in masticatory apparatus morphology, age, (dis)ability and preference can each impact EMG variation within and among electrodes [46].

Third, there is a potentially long list of factors related to instrumentation, methods and their interactions with the subject that potentially impact the EMG signal [1, 2, 5, 47]. Instrumental factors include; electrode type, inter-electrode distance, length of the electrode wire, recording/output frequency, choice of amplifiers, gains and filters, as well as electrical noise from several potential sources. Key interactive factors include where the electrode is positioned in or on a muscle, the orientation of the electrode recording elements relative to the muscle, the amount of subcutaneous tissue between the electrode and muscle (for surface electrodes) as well as individual effects related to anatomy, age and/or preference [5]. Two additional important influences are 1) movement artifacts recorded by electrodes that do not represent muscle contraction but rather result from electrode movement [1] and 2) crosstalk where an electrode records activity from a different muscle than intended [48]. Collectively, these factors reduce the biological interpretation and comparability of absolute voltage output from an electrode.

The common approach to addressing these issues is to discuss quantified EMG signals in terms of relative recruitment levels after scaling electrode output to an internal or external criterion. Because absolute voltage can vary across electrodes and within an electrode over longer time scales (e.g.,

between sessions) for several non-biological reasons, output from two (or more) different electrodes should not be directly compared prior to this normalization [e.g., 5, 49]. Normalization can be accomplished in multiple ways. Both internal criterion, such as examining EMG relative to a maximal or submaximal observed output from an electrode [27*, 50, 51, 52], and external criterion, such as scaling EMG output during a behavior (e.g., chewing a control food) for relative comparison to other behaviors [21, 25], are used. Relative comparisons generate new issues to consider as inter-individual variation in scaling parameters may contribute to unwanted variation among normalized EMG values [e.g., 53]. Despite these challenges, relative recruitment levels are generally favored by physiologists examining levels of muscle activation during behaviors.

Estimates of muscle mechanical work require both an estimate of muscle force and length changes during contraction [10, 38, 54]. From the physiological perspective, EMG output simply cannot demonstrate the changes in muscle length required to calculate muscle work [55] (Fig. 3). Yet the food science literature has routinely identified EMG amplitudes (either peak or area under the curve) as estimates of muscle work [e.g., 17, 21, 22, 31, 32, 33, 34, 35, 36, 37*].

In part the prevalence of the term muscle “work” may reflect the history of use in food science research. Several publications trace their use of the term to Brown [33: 6] where “the electrical activity of the muscle is an index of the amount of muscle work performed in terms of the number of muscles fibres involved and their firing rate.” This description provides a different meaning to the term muscle work than is commonly used in the physiological literature. In all likelihood, Brown [33] did not intend to argue that EMG was demonstrating the mechanical work of the muscle during contraction but rather intended it act as shorthand of overall muscle activity. We argue that using work as shorthand for relative activity level should be avoided as it 1) can cause confusion with food scientists and other researchers as to what mechanical events are being considered in a study and 2) will inhibit integration of food science research into the larger physiological community. Simply referring to normalized EMG

as a measure of relative recruitment or relative activity levels when comparing scaled EMG data across foods or treatments is consistent with most research goals in food science without the additional baggage of applying the term work in a way that is different from the more standard physiological usage.

Conclusions

Electromyography provides a non-invasive method for documenting muscle activation and relative recruitment levels during feeding. These data can be extremely useful for understanding the physiological interactions elicited by varying food textures during oral processing. Unfortunately, EMG probably conveys less physiological information than is hoped for by most researchers. This is potentially problematic when combined with its relative ease of use. As pointed out by De Luca [5], EMG is easy to use and easy to abuse. EMG cannot reliably indicate absolute forces either generated within muscles or created by muscles elsewhere in the body. Similarly, because EMGs do not include information on muscle length changes during contraction, they cannot provide information on muscular mechanical work. Food scientists should avoid using EMG to interpret these physiological variables to maximize their integration with other fields. Comparison of relative recruitment levels across foods or groups is reasonable and addresses most research goals in food science. Careful consideration of EMG interpretation, experimental setup, recording and analysis are all vital to effectively applying this physiological tool in useful ways for understanding the interactions between foods and oral processing.

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Figure Captions

Figure 1. Use of EMG is increasing in food science research. Histogram illustrating the number of publications including EMG in the Journal of Texture Studies from 1970 to 2015. The number of publications is significantly positively correlated with year of publication suggesting an increase in EMG-related publications over time (Pearson's Correlation, $R=0.47$; $P=0.02$).

Figure 2. Plots of A) raw, B) rectified and C) integrated EMG signals. EMGs represent two chewing cycles from the superficial masseter during bagel chewing. Raw EMGs (A) were collected using indwelling electrodes sampling at 10 kHz. Rectified EMGs (B) represent the absolute value of raw EMGs. The single waveform shown by the integrated EMG (C) is based on a root-mean-square averaging of the raw EMG signal using a sliding average based on a 42 ms window [see 51]. Y-axis units are arbitrary and not displayed.

Figure 3. EMG cannot differentiate jaw movements from static clenching. Surface EMG from the superficial masseter where the subject was asked to open and close their jaw without occlusal contact (A) versus clenching with the teeth in occlusion without moving their jaw (B). Qualitative comparison of the two sets of results suggests that EMG cannot demonstrate muscle length changes with minimal force production (A) versus minimal muscle movement and isometric force production (B). Y-axis units are arbitrary and not displayed.

Figure 1

Figure 2

Figure 3