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Relationships between chewing rate, occlusion, cephalometric anatomy, muscle activity, and masticatory performance

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ABSTRACT

Objective: Mastication consists of rhythmic jaw openings and closings. Recent studies suggest that muscle mechanical properties determine the rhythmic rate; however, speed-accuracy tradeoffs may also play a role. This study evaluated how variation in chewing rate affected chewing performance, how masticatory muscle activity varied with chewing rate, and whether morphology and demographics contributed to performance.
Design: Chewing performance and muscle activity were sampled in 23 healthy, fully-dentate adults, who chewed a standardized test food to a metronome set at 0.5, 0.75, 1, 2 and 3 times their 'natural' chewing rates. Subjects produced ten chews per trial, and five trials for each of the five rates. Surface electromyographic (EMG) activity was sampled from masseter and temporalis muscles bilaterally. Demographic, occlusal, and cephalometric data were also obtained.
Results: Chewing performance, defined by median particle size, was inversely related to chewing rate; however, performance was not remarkably improved at rates slower than the natural chewing rate. Above the natural chewing rate, variability in EMG bursts diminished, suggesting a reduction in muscle activity modulation at fast rates. Occlusal contacts and most morphological features appeared to play a limited or no role in performance.
Conclusions: Results support the hypothesis that the 'natural' chewing rate is selected to be as fast as possible while providing sufficient time to allow EMG modulation for improved performance. The interplay between EMG modulation and individual variation in skeletal morphology is likely critical for optimal chewing performance.

1. Introduction

Mastication is a mammalian chewing method for reducing food rapidly and efficiently (Wall & Smith, 2001). It is controlled in part by ponto-medullary pattern generating circuitry, which has been modeled as consisting of a central timing network that generates the rhythm or tempo at which jaw openings and closings occur, and interneuron circuits that control the sequencing of muscle activity patterns (Nakamura & Katakura, 1995). Recent work suggests that additional networks are involved in rhythmogenesis as well (Morquette et al., 2012). It is also noteworthy that most animal studies have focused on the trigeminal system (Westberg & Kolta, 2011); however, facial and hypoglossal motor systems (Lund & Kolta, 2006) as well as numerous suprabulbar sites play roles during mastication (Onozuka et al., 2002; Quintero, Ichesco, Myers, Schutt, & Gerstner, 2013; Quintero, Ichesco, Schutt et al., 2013).

Mastication must be efficient due, in part, to the fact that the mammalian respiratory and digestive systems share a common pathway in the oropharynx (Matsuo & Palmer, 2009). Also, because of their high metabolic rates relative to ectotherms (Krosniunas & Gerstner, 2003), mammals are limited in terms of how long they can cease breathing. Since there is a brief interruption in respiration when swallowing occurs (Matsuo & Palmer, 2009), food must be well-chewed and mixed with saliva to minimize swallowing time and the concomitant brief cessation in breathing. However, mammals have lost the ancestral ability to replace teeth multiple times (Whitlock & Richman, 2013);

Abbreviations: A_{MI}, occlusal contact area in maximum intercuspation (Fig. 4); ANB, angle formed between point A nasion and point B (Fig. 2); CoGn, distance between condylion and gnathion (Fig. 2); CV, coefficient of variation; EMG, electromyography; FMA, angle formed by Frankfort horizontal and mandibular plane (Fig. 2); GoGn, distance between gonion and gnathion (Fig. 2); X_{50}, median particle size; N, particle size distribution (slope of the linear part of the Rosin-Rammler equation); SNA, angle formed between sella nasion and point A (Fig. 2); SNB, angle formed between sella nasion and point B (Fig. 2); SN-GoGn, angle formed by line segment through sella and nasion and line segment through gonion and gnathion (Fig. 2); T_C, chewing cycle duration from onset to onset of two successive EMG bursts (Fig. 3); T_B, EMG burst duration or time between onset and offset of an EMG burst (Fig. 3); T_P, EMG peak onset latency or time from EMG burst onset to time of peak activity (Fig. 3); UAFH/LAFH, ratio of upper anterior face height and lower anterior face height (Fig. 2)

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therefore, minimizing tooth wear is critical for their survival (Ungar, 2005). Indeed, excessive tooth wear has dire fitness consequences for mammals including reduced fecundity (King et al., 2005; Wright, King, Baden, & Jernvall, 2008) and increased mortality (Kojola, Helle, Huhta, & Niva, 1998; Veiberg et al., 2007). Hence, mastication must address the competing challenges of reducing food for safe deglutition while minimizing tooth wear that occurs with food reduction (Ross, Washington et al., 2009; Williams et al., 2011).

One unique feature of mastication is its relatively invariant rhythm (Ekuni, Furuta, Takeuchi, Tomofuji, & Morita, 2012; Ross et al., 2007). It was long believed that chewing rate was linked to jaw mass or lever arm biomechanics (Druzinsky, 1993; Gerstner, Madhavan, & Braun, 2014; Ross, Reed et al., 2009), but recent work suggests this is not the primary relationship (Carvalho & Gerstner, 2004; Gerstner, Cooper, & Helvie, 2010; Ross et al., 2017; Ross, Reed et al., 2009; Stover & Williams, 2011). Muscle mechanics and salivary flow rate have been proposed as playing roles (Virot, Ma, Clanet, & Jung, 2017).

However, we posit that speed-accuracy trade-offs may also play a role, based on the need to minimize tooth wear from food reduction and to reduce food sufficiently for safe swallowing, as discussed above. Specifically, modulation of bite force and jaw kinematics requires feedback from oral proprioceptors and mechanoreceptors (Lund & Kolta, 2006; Shimada et al., 2012; Svensson & Trulsson, 2011). Neuronal conduction velocity limits exist (More et al., 2010), and communication between peripheral and central trigeminal, facial and hypoglossal cranial nerve systems is required for masticatory modulation; therefore, chewing rate will be limited by time lags associated with requisite feedback and feedforward. Additionally, evidence suggests that speed-accuracy tradeoffs are governed by neurodynamical limits within central motor systems (Beamish, Bhatti, MacKenzie, & Wu, 2006); therefore, if suprabulbar central systems are involved in masticatory modulation, there will be time delays associated with involvement of these systems as well.

This study was undertaken to shed some light on these issues. We hypothesize that, as for most human motor behaviors, speed-accuracy tradeoffs exist (Beamish et al., 2006), i.e., slower chewing will allow more accurate kinematics, thus improving the per-chew rate of food reduction. But, because feeding competes for time with other behaviors, there are practical limits on how slow chewing rate can be. Hence, we hypothesize that chewing rate is just slow enough to allow feedback to improve accuracy and performance. We further hypothesize that specific morphological features, e.g., short faces (Kiliaridis, Johansson, Haraldson, Omar, & Carlsson, 1995; Proffit, Fields, & Nixon, 1983); (Hartstone-Rose, Perry, & Morrow, 2012) and large occlusal contact areas, will account for variation in chewing performance across subjects.

Inspired by previous studies (Buschang, Throckmorton, Travers, & Johnson, 1997; Plesh, Bishop, & McCall, 1987; Sanchez-Ayala, Farias-Neto, Campanha, & Garcia, 2013; Throckmorton, Buschang, Hayasaki, & Phelan, 2001), we manipulated chewing rate to study how rate affects performance. We further examined how chewing rate impacts muscle activity and how muscle activity impacts performance. Finally, the study considered the roles of demographic, occlusal and cephalometric variation in performance as well.

2. Materials and methods

2.1. Subjects

Twenty-three healthy, fully dentate adults served as subjects. Procedures, in which all subjects were involved, are summarized in Fig. 1 and described in more detail, below. Subjects' rights were protected by the University of Michigan Medical IRB (IRB-MED), and written informed consent was obtained from all subjects. Demographic data and informed consent were obtained after subjects were screened for the following inclusion criteria: (1) no chewing side preferences, (2) no chewing difficulties, (3) no gum chewing habits, (4) no orthodontic work within the previous year, (5) no temporomandibular disorders (TMD), as defined by RDC-TMD criteria (Dworkin & LeResche, 1992), (6) no musculoskeletal, gastrointestinal, nor neurological conditions, (7) no medication use with known oral motor side effects, (8) no history of eating disorders, (9) no recent radiation exposure. Intraoral exams confirmed Angle's Class I molar relationships and presence of full dentitions, sans third molars.

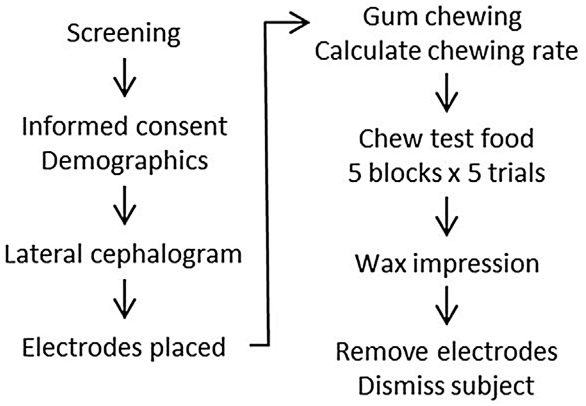

Fig. 1. Procedural steps for each subject.

2.2. Cephalometrics

Lateral cephalographs were taken from the right side. Landmarks on the skull and mandible were digitized with proprietary software (Dolphin Imaging, v.11.7, Dolphin Imaging and Management Solutions, Chatsworth, CA), from which standard clinical and custom measurements were made (Fig. 2). One orthodontically-trained investigator (B.F.) took two readings of each landmark, which were averaged before calculating variables.

2.3. Surface electromyography (EMG) signal recording and filtering

EMG activity of left and right superficial masseter and anterior temporalis muscles was measured with surface electrodes in bipolar configuration (Ag/AgCl, 1.8-m snap-on leads, MVAP Medical Supplies, Newbury Park, CA). A ground electrode was placed over the left mastoid process. Data were digitized at 1 kHz (Octal Bioamp, PowerLab 8/35, LabChart Pro v. 8.0.4, ADInstruments, Colorado Springs, CO), then processed and filtered as per (Ives & Wigglesworth, 2003), viz., band-pass filtered (20–500 Hz), notch-filtered (60 Hz), full-wave rectified, and smoothed with a moving average window set to 5% of the sampling rate.

2.4. Test food

Test food tablets (CutterSil Putty Plus, Universal Plus Hardener, Heraeus Kulzer, South Bend, IN) were formed using a circular template (Plexiglas, 4.76-mm thickness, 12-mm diameter), allowed to harden for 1 h, trimmed to remove flash, and weighed. Only tablets weighing 0.85 g + 0.05 g were used.

2.5. Experimental procedure

2.5.1. Subject chewing rates

Subjects were seated comfortably in a chair facing a table. Materials for subjects to use during the experiment, e.g., Styrofoam cups and test food tablets (see below), were placed conveniently on the table. Subjects were first instructed to chew gum (Trident Original, Mondelez International, Deerfield, IL). After chewing for at least 15 s, chews were