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Orofacial and thumb-index finger ramp-and-hold isometric force dynamics in young neurotypical adults

Steven M. Barlow [a,b,c,*], Mohsen Hozan [a,b,c], Jaehoon Lee [d], Jake Greenwood [a,b,c], Rebecca Custead [a,c], Brianna Wardyn [a], Kaytlin Tippin [a]

[a] Department of Special Education and Communication Disorders, University of Nebraska, 141 Barkley Memorial Center, Lincoln, NE 68583-0738, USA
[b] Department of Biological Systems Engineering, University of Nebraska, 230 L.W. Chase Hall, Lincoln, NE 68583-0726, USA
[c] Center for Brain, Biology, and Behavior, University of Nebraska, C89 East Stadium, Lincoln, NE 68588-0156, USA
[d] Department of Educational Psychology & Leadership, Texas Tech University, PO Box 41071, Lubbock, TX 79409, USA

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ABSTRACT

The relation among several parameters of the ramp-and-hold isometric force contraction (peak force and dF/dt_{max} during the initial phase of force recruitment, and the proportion of hold-phase at target) was quantified for the right and left thumb-index finger pinch, and lower lip midline compression in 40 neurotypical right-handed young adults (20 female/20 males) using wireless force sensors and data acquisition technology developed in our laboratory. In this visuomotor control task, participants produced ramp-and-hold isometric forces as 'rapidly and accurately' as possible to end-point target levels at 0.25, 0.5, 1 and 2 Newtons presented to a computer monitor in a randomized block design. Significant relations were found between the parameters of the ramp-and-hold lip force task and target force level, including the peak rate of force change (dF/dt_{max}), peak force, and the criterion percentage of force within ±5% of target during the contraction hold phase. A significant performance advantage was found among these force variables for the thumb-index finger over the lower lip. The maximum voluntary compression force (MVCF) task revealed highly significant differences in force output between the thumb-index fingers and lower lip (~4.47–4.70 times greater for the digits versus lower lip), a significant advantage of the right thumb-index finger over the non-dominant left thumb-index finger (12% and 25% right hand advantage for males and females, respectively), and a significant sex difference (~1.65–1.73 times greater among males).

1. Introduction

Precise regulation of active muscle force is essential for fine motor control of distal extremities and orofacial structures (Barlow, 1998; Cole, 2015; Latash et al., 2010). Skilled movements associated with speech, eating, facial expression, digital manipulation and grip involve a stream of phasic and tonic muscle contractions produced in the presence of a background of controlled stiffness and sensorimotor mechanisms to rapidly adapt to external loads (Barlow and Müller, 1991; Oluwatosin and Oluwatosin, 1998; Shiller et al., 2002; Chu et al., 2010).

Damage to the brain associated with cerebrovascular stroke and traumatic brain injury often results in a degradation of fine motor performance that negatively impacts object manipulation, speech and deglutition, activities of daily life and safety. Injury or disease that affects cortical upper motor neurons also may affect lower motor neurons and associated striated muscle fibers through transsynaptic mechanisms; especially in monosynaptic motor neuron pools serving digit and perioral muscles (Frontera et al., 1997; Hara et al., 2004; Lukacs 2005; Schimmel et al., 2013).

Impaired motor function of the lower face may lead to increased effort maintaining oral continence, reduced speech intelligibility, and impaired facial gesture (Andreatta and Barlow, 2009; Weeks et al., 2013; Arce-McShane et al., 2014; Dai et al., 2015; Schimmel et al., 2017). Similarly, fine force aberrancies in thumb-finger grip can adversely affect finger strength, digit force stability, movement accuracy during manipulation, and individuation of digit control (Kamper et al., 2014; Seo et al., 2015; Kang and Cauraugh 2015; Dias et al., 2017).

* Corresponding author at: Department of Special Education and Communication Disorders, University of Nebraska, 141 Barkley Memorial Center, Lincoln, NE 68583-0738, USA.

E-mail addresses: steven.barlow@unl.edu (S.M. Barlow), mhozan2@unl.edu (M. Hozan), jaehoon.lee@ttu.edu (J. Lee), jacob.greenwood@huskers.unl.edu (J. Greenwood), rcustead@huskers.unl.edu (R. Custead), Brianna.wardyn@huskers.unl.edu (B. Wardyn), Kaytlin.tippin@huskers.unl.edu (K. Tippin).

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The relation between dysregulation of force dynamics and impairments in orofacial and hand-digit movements underscores the need to better understand active force dynamics in these structures. The ability to measure residual fine force dynamics among muscle systems important for skilled, daily activities such as manipulation (hand-digits) and speech (orofacial) will allow clinicians to create individualized motor rehabilitation strategies and gauge the efficacy of new therapeutics for survivors of stroke and traumatic brain injury.

The objectives of the present study included (1) creation of a normative database of ramp-and-hold force dynamics for the thumb-index finger of each hand and lower face in young adults using a wireless force sensing technology and updated signal processing algorithms, and (2) linear mixed modeling of fine force control measures for the lower lip and thumb-index finger pinch during isometric compression as a function of target force level and sex. Several dependent variables of fine force dynamics, including peak force, maximum rate of force change during recruitment, mean force during hold-phase, and the proportion of contraction hold-phase maintained within a criterion (±5%) force target were hypothesized to show significant changes as a linear function of target force. A significant sex effect for these variables was not expected. Significant differences on the variables related to fine force dynamics was expected between thumb-finger and lower lip due to known differences in musculoskeletal anatomy and neural organization. Males were predicted to show significantly greater maximum voluntary compression forces (MVCF) compared to females. An MVCF advantage was expected for the thumb-finger pinch compared to the lower lip compression gesture.

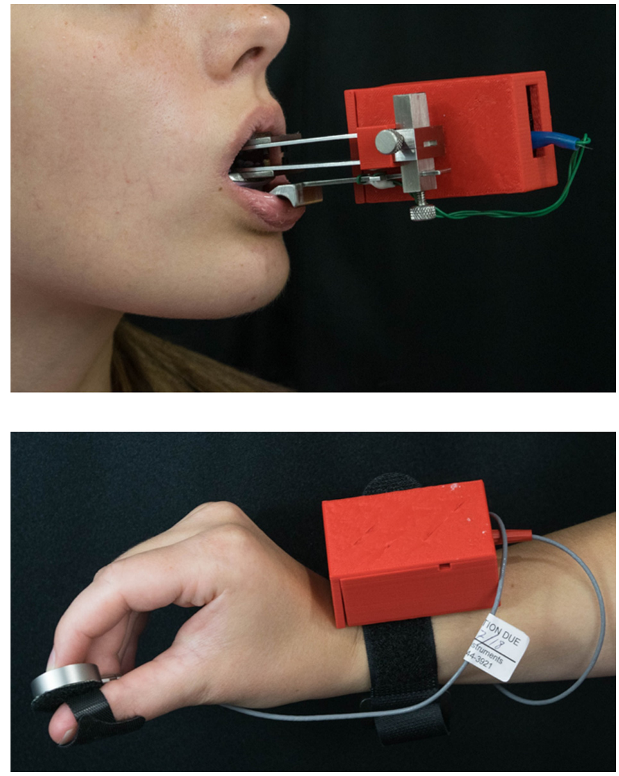

Fig. 1. Wireless strain gage sensors. (a) Orofacial, and (b) finger force transduction *in situ*.

2. Materials and methods

2.1. Participants

Forty (40) neurotypical adults (20F/20M, 22.23 [SD = 2.07] years old) were recruited regardless of race or ethnicity. Written informed consent, approved by the University of Nebraska Institutional Review Board, was obtained for each participant. Participants were compensated for their participation in this study. Inclusion criteria: right-handed, no report of neurological illness or injury, not taking regular medication, and normal corrected vision. Exclusion criteria: neurological, sensory and/or muscular deficits, trauma to face and/or hand and fingers, or with abnormal skin sensitivity on face or hand.

2.2. Instrumentation

Participants were seated at a workstation table. A laptop (MS WIN10 ×64) with a 15″ HD touchscreen monitor was positioned approximately 18″ from the participant's face. This computer ran the wireless data acquisition and stimulus control system (ForceWIN10) developed in our laboratory (Greenwood & Barlow, 2018). The ForceWIN10 system features wireless Bluetooth low-energy (BLE) strain gage sensors configured to sample thumb-index finger pinch force, and lower lip compression force (midline). The sensitivity of the lip force cantilever is 2.03 mV/V at 100% load (40 N), and the sensitivity of the finger load cell is 1.17 mV/V at 100% load (111 N). The custom-designed BLE data acquisition card features 24-bit ADC (±5 V) at 120 samples per second and provides DC excitation and amplification As shown in Fig. 1a, the lip cantilever has integrated fixtures for beam translation in the anterior-posterior as well as inferior-superior dimensions to accommodate a wide range of maxillofacial anatomy and dental bite relations among participants. The lip cantilever is referenced to a stainless steel jaw cantilever with integrated 3D-printed titanium mandibular and maxillary dental trays available in various sizes to fit individual maxillofacial anatomy. A polyvinylsiloxane impression material (Kerr Extrude XP, Kerr Corporation, Romulus, MI, USA) was used to create a custom dental mold that impregnates the perforations in each jaw tray. The dental mold was completed within 2 min and resulted in a remarkably stable and comfortable mounting platform for active force generation on the lower lip force cantilever.

As shown in Fig. 1b, thumb-index finger pinch forces were transduced by a Cooper Instruments load cell (Model LKCP 410-25 lb; Warrenton, VA, USA) and conditioned by a BLE wireless signal conditioning module worn on the wrist and powered by a miniature Li-ion (LIB) battery.

2.3. Protocol

The test protocol consisted of a series of participant-generated 'ramp-and-hold' isometric contractions cued by software generated target force levels displayed on a 15″ laptop HD monitor. Participants were instructed to produce the contractions 'as rapidly and accurately as possible' to the target cursor and maintain the force until an auditory cue 'beep' signaled the end of the 5-s trial, and then relax. The target force levels for this visuomotor tracking task included 0.25, 0.5, 1, and 2 Newtons (N). Participants were cued to produce 10 repetitions of the 'ramp-and-hold' contraction, using either the right or left thumb-index finger, or lower lip at each of the 4 target force levels. Intertrial intervals were randomized between 0.5 and 3 s. Test order for sensor-structure type and target force level were randomized across participants. Three additional 5-s trials were sampled to measure the MVCF. Participants were instructed to squeeze as hard as possible using the selected muscle system for approximately 2 s and then relax. Thus, data