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Effects of the index finger position and force production on the flexor digitorum superficialis moment arms at the metacarpophalangeal joints — a magnetic resonance imaging study

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ABSTRACT

Background: The purpose of this study was to use magnetic resonance imaging to measure the moment arm of the flexor digitorum superficialis tendon about the metacarpophalangeal joint of the index, middle, ring, and little fingers when the position and force production level of the index finger was altered. A secondary goal was to create regression models using anthropometric data to predict moment arms of the flexor digitorum superficialis about the metacarpophalangeal joint of each finger.
Methods: The hands of subjects were scanned using a 3.0 T magnetic resonance imaging scanner. The metacarpophalangeal joint of the index finger was placed in: flexion, neutral, and extension. For each joint configuration subjects produced no active force (passive condition) and exerted a flexion force to resist a load at the fingertip (active condition).
Results: The following was found: (1) The moment arm of the flexor digitorum superficialis at the metacarpophalangeal joint of the index finger (a) increased with the joint flexion and stayed unchanged with finger extension; and (b) decreased with the increase of force at the neutral and extended finger postures and did not change at the flexed posture. (2) The moment arms of the flexor digitorum superficialis tendon of the middle, ring, and little fingers (a) did not change when the index metacarpophalangeal joint position changed ($P > 0.20$); and (b) The moment arms of the middle and little fingers increased when the index finger actively produced force at the flexed metacarpophalangeal joint posture. (4) The moment arms showed a high correlation with anthropometric measurements.
Interpretation: Moment arms of the flexor digitorum superficialis change due to both changes in joint angle and muscle activation; they scale with various anthropometric measures.

1. Introduction

Precise coordination of the fingers is necessary in order to perform numerous everyday tasks. The contact forces produced by fingertips result from the interaction of numerous architectural and physiological properties of the hand, forearm, and central nervous system (CNS). A better understanding of these properties is crucial for advancing many fields concerned with hand function such as motor control, biomechanics, motor disorders, rehabilitation and finger related surgeries (i.e. tendon transfers, joint replacements, etc.). It is well known that altering the angles of finger joints significantly affects the maximal fingertip force and the moments about the joints (Kamper et al., 2006). The effects of one finger activation and/or position changes on other fingers are much less understood.

Individual finger movements are not independent of other fingers (reviewed by Schieber and Santello, 2004) due to: 1) mechanical links provided by connective tissue (Fahrer 1981; Kilbreath and Gandevia, 1994; Leijnse, 1997), 2) multi-finger motor units in the extrinsic finger muscles (Kilbreath and Gandevia, 1994; Schieber, 1995), and 3) overlapping cortical representations of the finger muscles (Schieber, 1991; Sanes et al., 1995; Rathelot and Strick, 2006). The result of these constraints is a behavior referred to as enslaving (Zatsiorsky et al., 1998, 2000): When a single finger *intentionally* moves or produces force, other fingers also *unintentionally* move or produce force. It is generally accepted that enslaving is due to a combination of the three previously mentioned constraints on individuated finger movements; however, the relative contribution of each is unknown. It is unknown whether the activation of the finger flexors of one finger and/or change of the finger position will change the moment arms of the flexors of other fingers.

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Magnetic resonance imaging (MRI; Wilson et al., 1999; Fowler et al., 2001), as well as cadaver based methods (An et al., 1983; Armstrong and Chaffin, 1978; Brand et al., 1975; Youm et al., 1978) has previously been used to measure moment arms (MAs) of the flexor digitiorum superficialis (FDS) and flexor digitorum profundus (FDP) muscles about the metacarpophalangel (MCP) finger joint. The Wilson et al. (1999) study used 3D MRI imaging to compute the moment arm of the FDP with the index finger positioned in various flexion postures. Moment arms were computed using: (a) a 3D tendon excursion method, (b) a 3D geometric method, and (c) a 2D geometric method. All three methods were found to produce approximately the same mean moment arm values per posture; however, the variance between repeated measurements was lowest for the 3D tendon excursion method and highest for the 2D geometric method. In the Fowler et al. (2001) study 3D MRI imaging was applied on a single female subject to compute 3D moment arms of multiple muscles that cross the distal interphalangeal (DIP), proximal interphalangeal (PIP), and MCP joints. Again, only passive force production was investigated. Both studies found an increase in the moment arm at greater flexion angles.

In the cadaver studies tension was applied to the extrinsic flexor tendons to artificially simulate active force production (An et al., 1983; Armstrong and Chaffin, 1978; Brand et al., 1975; Youm et al., 1978). This may not be an accurate depiction of what occurs *in vivo* as *in vivo* muscular force development may be different. Co-contraction of other muscles crossing the MCP joint is neglected and the cadaver hand data may not be an accurate representation of a young, healthy hand. These studies all found that as the flexion angle of the MCP joint increased the moment arms of the FDS and FDP also increased. Another significant finding was that the center of rotation of the MCP was located at the geometric center of the MCP head (Youm et al., 1978).

To the best of our knowledge, the effects of the muscle force levels on the moment arms of the fingers have not been addressed in the literature. With regard to other joints, the data are scarce and controversial. Zatsiorsky et al. (1985) and Aruin et al. (1987) applied a pulling force to the *m. triceps surae* of a cadaver leg and did not find substantial changes in the magnitude of the moment arms while Maganaris et al. (1998, 1999) and Maganaris (2004) found large changes in moment arms of the tibialis anterior and Achilles tendon during maximum voluntary contractions (MVC) at the ankle compared to rest. At the wrist level, a change in tension of one of the extrinsic flexor tendons has been shown to change the moment arm of that tendon and transmit force to neighboring tendons (Agee et al., 1998).

Unfortunately, many of the previous studies are limited in that they have: (1) been performed on cadavers, and/or (2) only looked at passive conditions in which no active contraction of the muscle was occurring. The purpose of this study was to measure in vivo changes in moment arms of the flexor digitorum superficialis (FDS) about the metacarpophalangeal (MCP) joints of the 2–5 fingers due to: (1) changes in joint posture of the index finger MCP joint and 2) changes in muscle force production levels (passive vs. active flexion force). A secondary goal was to create regression models using anthropometric data to predict moment arms of the FDS about the MCP joint of each finger.

2. Methods

2.1. Subjects

Ten male subjects volunteered to be in the study. The subjects were all young, healthy and had no history of musculoskeletal injury or disease of the upper limbs. Subjects provided informed consent and the experiment followed a protocol that was approved by the Institutional Review Board of the Pennsylvania State University.

2.2. Experimental procedure

Prior to the MRI scan a number of anthropometric measures were taken from the subjects (Supplementary Material Table S1). Supplementary Fig. S1 provides an illustration of the boundary points of specific measurements. Hand length was measured from the most distal crease at the wrist to the tip of the longest finger. Hand breadth was measured on the palmar surface at the level of the MCP joints of fingers 2–5 with the fingers in a relaxed state of ab/adduction. Measurements of the fingers were taken on the dorsal surface. Phalange distances were measured from the approximate joint centers, based on visual inspection. Phalange circumferences were measured around the approximate midpoint of each phalange. Individual and four-finger flexion MVCs were recorded. Subjects placed their four fingers on uni-dimensional force transducers (208C02, PCB Piezotronics, Depew, NY, USA) and were instructed to press as hard as they could for 5 s. Two trials of each MVC were recorded and the average computed.

2.3. MRI equipment and scans

The MRI scans were performed using a 3.0 Tesla MRI scanner (Siemens Magnetom Trio 3T, Siemens Corporation, Germany) at the Social, Life, and Engineering Imaging Center (SLEIC) facility of the Pennsylvania State University by a trained MRI technician. Subjects were required to lie prone on the scanning table with their right arms extended, above their heads, inside of the head coil and positioned in the custom made finger positioning apparatus (Fig. 1). The index finger was in three MCP joint postures: 1) Neutral (0), 2) Flexed (30 of flexion), and 3) Extended (15 of extension). The middle, ring, and little fingers were lightly taped together so that their posture did not change during the scans. The distal interphalangeal, proximal interphalangeal, and MCP joint postures of the non-index fingers was 180° for all scans. For each index finger MCP posture two sets of scans were obtained: 1) passive force and 2) active flexion force. The passive scans were always performed first. The subjects were then removed from the scanner and a 400 g mass was hung from the apparatus then looped around their index fingertip. The suspended load generated an extension moment about the MCP joint. To resist the load, subjects had to produce a small active flexion force with their index finger. It was necessary to use a low amount of resistive force since subjects were required to maintain the contraction for several minutes. For most subjects the suspended load required them to exert 10–15% of their index MVC during the active flexion force

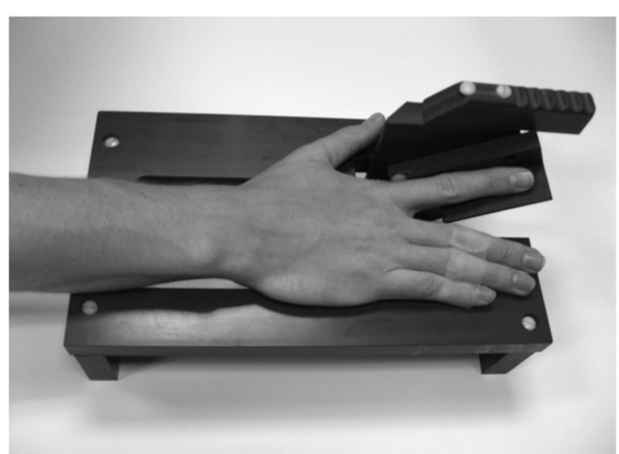

Fig. 1. Schematic of finger positioning apparatus.