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Estimation of the effective static moment arms of the tendons in the index finger extensor mechanism

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Abstract

A novel technique to estimate the contribution of finger extensor tendons to joint moment generation was proposed. Effective static moment arms (ESMAs), which represent the net effects of the tendon force on joint moments in static finger postures, were estimated for the 4 degrees of freedom (DOFs) in the index finger. Specifically, the ESMAs for the five tendons contributing to the finger extensor apparatus were estimated by directly correlating the applied tendon force to the measured resultant joint moments in cadaveric hand specimens. Repeated measures analysis of variance revealed that the finger posture, specifically interphalangeal joint angles, had significant effects on the measured ESMA values in 7 out of 20 conditions (four DOFs for each of the five muscles). Extensor digitorum communis and extensor indicis proprius tendons were found to have greater MCP ESMA values when IP joints are flexed, whereas abduction ESMAs of all muscles except extensor digitorum profundus were mainly affected by MCP flexion. The ESMAs were generally smaller than the moment arms estimated in previous studies that employed kinematic measurement techniques. Tendon force distribution within the extensor hood and dissipation into adjacent structures are believed to contribute to the joint moment reductions, which result in smaller ESMA values.

Keywords: Finger; Moment arm; Extensor hood; Finger posture

1. Introduction

In human manual activities, the highly complex musculoskeletal system of the hand and forearm is well coordinated in order to generate proper fingertip forces (Valero-Cuevas, 2000) or finger movements (Long and Brown, 1964). Understanding of the mechanisms underlying this elaborate coordination would not only help to elucidate principles in motor control (Zajac, 1993), but would also be beneficial in various clinical applications (Herrmann and Delp, 1999; Shah et al., 2003; Alon et al., 2007). Thorough examination of the functions of muscle–tendon units involved in the finger dynamics should precede such investigations.

The contribution of muscle–tendon force to joint torque generation is fundamentally affected by the moment arm (MA), defined as the normal distance between joint center of rotation and muscle–tendon line of action. One popular technique for estimating MA values is the tendon excursion method, which entails computing the instantaneous MA from the slope of tendon excursion vs. joint angle (An et al., 1983; Delp et al., 1994; Buford et al., 1997; Herrmann and Delp, 1999). Due to the complex structure of the finger extensor apparatus, however, the finger joint moments generated by a given tendon force may not be solely dictated by the geometric MA length. Some tendons are inserted into multiple bones or interconnected with other tendons, thus the generated joint moments are affected by the reaction forces at distal/proximal joints transmitted from segments into which the tendon inserts. Tendon force distribution into different insertion sites influences the inter-segmental force transmission. MA values obtained from the 'kinematic' measurement (excursion method) cannot fully account for the 'kinetic' process of tendon force transmission to the joint moments.

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Tendon forces within the extensor mechanism, in relation to their contribution to the finger kinetics, were examined in various studies where optimization techniques, usually minimizing the weighted sum of muscle forces or maximizing the endurance, have been commonly employed to estimate tendon forces (Brook et al., 1995; Sancho-Bru et al., 2001; Vigouroux et al., 2006, 2007). Relationships between muscle activations (or tendon forces) and fingertip force/moment have been also investigated in both *in vivo* and *in vitro* studies (Maier and Hepp-Reymond, 1995a, b; Valero-Cuevas et al., 1998; Milner and Dhaliwal, 2002). It should be noted, however, that the contribution of an individual tendon to the finger kinetics has not been evaluated explicitly. More importantly, the effects of finger posture on the function of each muscle–tendon unit in generating fingertip forces or joint moments (Kamper et al., 2006) have not been systematically studied.

In other studies, the direct load measurement technique, correlating the measured moment to the applied tendon forces, has been implemented to evaluate finger tendon MAs (Buford et al., 2005; Koh et al., 2006). Similar techniques were utilized to quantify the contribution of intrinsic muscles to the metacarpophalangeal (MCP) joint moments (Lauer et al., 1999). However, the measured joint moments typically included passive joint moments produced by extrinsic (inactive muscle–tendon units) and intrinsic (cartilage, ligaments, etc.) tissues of the hand (Esteki and Mansour, 1996; Knutson et al., 2000). Thus, the obtained MA values are biased and may not accurately quantify the contribution of tendon force to joint moments.

Acknowledging the limitations of existing methods, we aim to provide a novel technique to measure the effective static moment arms (ESMAs) of finger tendons, which represent the net effects of the tendon force on joint moment production in static fingertip force/moment generation. The proposed methodology presents distinct advantages in evaluating the contributions of muscle–tendon units to the kinetics of fingertip force/moment exertion. Since each ESMA is estimated directly from the applied tendon forces and resultant joint moments, the technique accounts for the consequences of the tendon force distribution and the inter-segmental reactions involved in moment generation, while allowing for the removal of the effects of passive joint moments via a multiple measurement strategy. Also, experiments involving cadaveric specimens allow us to measure the effects of loading of individual tendons with known forces; it is difficult to load individual tendons or to measure tendon forces during *in vivo* experiments (Dennerlein et al., 1998; Kursa et al., 2005).

We analyzed five tendons in the finger extensor apparatus, as their contributions to the finger joint moments are especially difficult to assess due to the complex structure of the extensor hood. It was hypothesized that finger posture has a fundamental effect on the transmission of tendon forces to joint moments (Kamper et al., 2006), resulting in different ESMA values. In order to test this hypothesis, all ESMA values were estimated in nine different finger postures, and the repeated measures analysis-of-variance (ANOVA) was employed to test the impacts of posture on ESMAs.

2. Methods

2.1. Experimental protocol

Five fresh-frozen cadaveric hand specimens, transected midway between the wrist and elbow, were used for the experiment (index finger length mean $\pm$ S.D.: 101.8 $\pm$ 5.8 mm). The five tendons that compose the extensor apparatus of the index finger, i.e. extensor digitorum communis (EDC), extensor indicis proprius (EIP), first dorsal interosseous (FDI), first palmar interosseous (FPI), and lumbrical (LUM), were examined in this study (Fig. 1). Tendons for the extrinsic muscles (EDC and EIP) were exposed roughly 4 cm proximal to the wrist. Silk sutures (3-0) were fastened directly to the tendons, and secured to low-friction monofilament strings (Spiderwire, Pure fishing USA, Spirit Lake, IA). For each intrinsic muscle (FDI, FPI and LUM), the distal muscle–tendon junction was exposed, and a loop of 3-0 silk was sutured around the tendon and muscle at this junction. The string tied to each suture was routed through remaining ligament structures, such as the carpal tunnel, to maintain the anatomical line of action. For FDI, the line of action was maintained amid the deep and superficial heads of the muscle.

Three levels of tendon force were applied to each tendon (Table 1). A set of nine finger postures, which consist of three pairs of proximal and distal interphalangeal (PIP, DIP) joint angles (($0°$, $0°$), ($30°$, $20°$), and ($45°$, $30°$)) explored at each of three MCP angles ($0°$, $30°$, $60°$), were tested for each specimen. Joint angles were measured by placing a goniometer over the center of each joint.

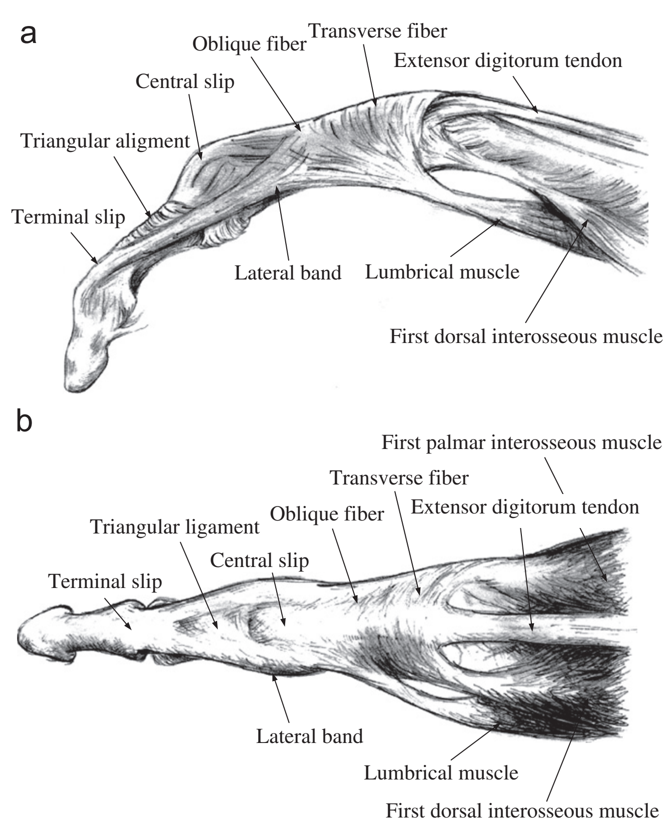

Fig. 1. Extensor hood of the index finger (right hand) and its components: (a) lateral view; (b) dorsal view.