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Analysis of musculoskeletal loading in an index finger during tapping

John Z. Wu[a,*], Kai-Nan An[b], Robert G. Cutlip[a], Kristine Krajnak[a], Daniel Welcome[a], Ren G. Dong[a]

[a]National Institute for Occupational Safety and Health, NIOSH/CDC, 1095 Willowdale Road, MS-2027, Morgantown, WV 26505, USA
[b]Mayo Clinic College of Medicine, Rochester, MN 55905, USA

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Abstract

Since musculoskeletal disorders of the upper extremities are believed to be associated with repetitive excessive muscle force production in the hands, understanding the time-dependent muscle forces during key tapping is essential for exploring the mechanisms of disease initiation and development. In the current study, we have simulated the time-dependent dynamic loading in the muscle/tendons in an index finger during tapping. The index finger model is developed using a commercial software package AnyBody, and it contains seven muscle/tendons that connect the three phalangeal finger sections. Our simulations indicate that the ratios of the maximal forces in flexor digitorum superficialis (FS) and flexor digitorum profundus (FP) tendons to the maximal force at the fingertip are 0.95 and 2.9, respectively, which agree well with recently published experimental data. The time sequence of the finger muscle activation predicted in the current study is consistent with the EMG data in the literature. The proposed model will be useful for bioengineers and ergonomic designers to improve keyboard design minimizing musculoskeletal loadings in the fingers.
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Keywords: Index finger; Muscle force; Muscle–tendon excursion; Tapping; Simulations

1. Introduction

In the last 10 years, computer use has become prevalent both in the workplace and at home. According to the U.S. Census Bureau, 56.1% of employed adults use computers at work. In addition, 61.8% of U.S. households have computers, and in those households, 66.1% of adults and 82.6% of children (age 3–18) use computers (Day et al., 2005). Epidemiological studies have demonstrated that excessive computer use could result in an increased risk of developing musculoskeletal disorders (MSDs) of the upper extremities (e.g., Cail and Aptel, 2003; Faucett and Rempel, 1996; Gerr et al., 2006; Hales et al., 1994; Marcus and Gerr, 1996). For example, a prospective study examining the effects of occupational computer use in workers over a 3 year period demonstrated that workers using computers for at least 15 h each week were at an increased risk for developing neck/shoulder and hand/arm symptoms and disorders (Gerr et al., 2006). The primary injuries to the hands and arms were tendonitis of the extensor tendons and the digital flexor tendons.

Electromyography (EMG) studies evaluating muscle activity during typing suggest that MSDs in the upper extremities are related to excessive repetitive musculoskeletal loading. For example, Gerard et al. (1999) have examined EMG activity to evaluate the effects of typing force and keypad stiffness on MSDs and Woods and Babski-Reeves (2005) analyzed the EMG of the hand–arm to determine the effects of posture on MSDs. The relationships among tendon force, contact force at the fingertip, and finger posture have been investigated by using a force transducer mounted directly onto the flexor digitorum superficialis (FS) and flexor digitorum profundus (FD) tendons of the fingers (Schuind et al., 1992; Dennerlein et al., 1999; Kursa et al., 2005). The reported ratio of the force in the FS tendon to the contact force at the fingertip varied from 1.5 ± 1.0 (Kursa et al., 2005) and 1.7 ± 1.5 (Schuind et al., 1992) to 3.3 ± 1.4 (Dennerlein et al., 1999). The reported ratio of the FP tendon force to

*Corresponding author. Tel.: +1 304 285 5832; fax: +1 304 285 6265.
E-mail address: jwu@cdc.gov (J.Z. Wu).

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the fingertip force showed more variance, from 2.4 ± 0.7 (Kursa et al., 2005) to 7.9 ± 6.3 (Schuind et al., 1992). Dennerlein et al. (1998) compared the experimentally measured tendon force with that calculated using an inverse dynamic approach and found that the measured tendon force is consistently greater than that predicted by the model with the muscle in an isometric contraction. The dynamic force distribution in the finger muscles during tapping has not been investigated either experimentally or theoretically.

Because the experimental evaluation of the dynamic loading in individual muscles of the hand during typing is technically difficult, researchers have studied the dynamic contact force between the fingertip and keypad, and joint angle motions, and assumed that these indices are related to the muscle/tendon excursions (e.g., Gerard et al., 1999; Nelson et al., 2000). The most extensive analyses were performed by Jindrich et al. (2004) who analyzed joint torques and kinematic energy of the finger sections during tapping. Dennerlein et al. (1998) assessed muscle activities during the keystroke task; their results suggested that the role of the extrinsic finger flexors during a keystroke is to overcome the activation force of the keyswitch, while the extrinsic extensors are to perform the upswing rather than stop the downswing. Kuo et al. (2006) analyzed the relationship among joint coordination, kinematics, muscle activation patterns, and energy profiles during the tapping task and found that the activation of the intrinsic muscles began slightly before the initiation of the downswing motion, while the activation of the extrinsic flexors started after the initiation of the downward finger motion. However, a quantitative analysis of the dynamic loading in each individual muscle and tendon in a finger has not been performed during the tapping test.

One of the most promising theoretical approaches for exploring the muscle forces in fingers during typing is a multi-body biomechanical model. In such models, a finger is modeled as bony sections that are connected with muscles and tendons. Multiple biomechanical models of the hands and fingers have been developed to simulate different scenarios. For example, Sancho-Bru et al. (2001, 2003) developed a whole hand model simulating the muscle loading for static gripping and free movements; Brook et al. (1995) developed a biomechanical model of the dynamics of the index finger and applied their model to simulate the muscle forces in pinch grip and disc rotation; Biggs and Horch (1999) proposed a 3D kinematic long-finger model and validated their model via the experimental data of tendon/muscle excursions. All these mathematical hand models were formulated analytically and rely on certain simplifying assumptions. The most "realistic" biomechanical finger models were proposed by Valero-Cuevas et al. (2003, 2005), who included anatomically realistic tendon/muscle network connections into their models.

The goal of the current study is to analyze the dynamic muscle forces in an index finger during tapping using a universal finger model developed on a platform of the commercial software package AnyBody (AnyBody Technology Inc., Aalborg, Denmark). Specifically, we are going to theoretically analyze the joint torques and muscle forces and their relationships to the impact force at the fingertip and the mass moment of inertia of the finger sections. Furthermore, the theoretically predicted muscle force variations in the finger will be compared with the EMG signals of the previous study (Kuo et al., 2006). The proposed model will be applicable for realistic problems and it will include realistic bony shapes, nonlinear mechanical properties of the ligaments and tendons and physiological muscle models.

2. Methods

2.1. Index finger model

The finger model was developed on the platform of the commercial software package AnyBody. The index finger model consists of four phalanges: distal, middle, proximal, and metacarpal phalanges. These four phalanges are connected by three joints: distal interphalangeal joint (DIP), proximal interphalangeal joint (PIP), and metacarpophalangeal joint (MCP). Figs. 1(a) and (b) illustrate the index finger model at the beginning of motion ($t = 0$) and in touch with the keypad, respectively. The DIP and

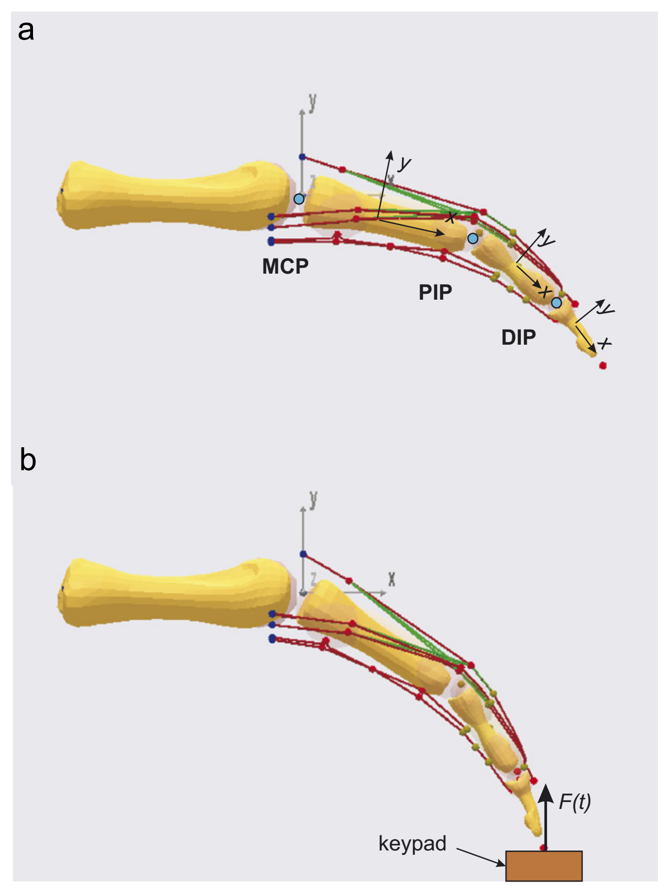

Fig. 1. Index finger model. (a) The index finger model consists of distal, middle, proximal, and metacarpal phalanges, which are linked by DIP, PIP, and MCP joints. (b) The finger is in contact with the keypad during tapping. The interface impact force $F(t)$ is treated as external loading applied on the fingertip.