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The effect of the extensor mechanism on maximum isometric fingertip forces: A numerical study on the index finger

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ABSTRACT

The extensor mechanism is a tendinous network connecting intrinsic and extrinsic muscles of the finger and its function has not yet been fully understood. The goal of this study was to assess the effect of the extensor mechanism on the maximum isometric fingertip forces – a parameter which is essential for grasping. For this purpose, maximum fingertip forces in all directions (i.e. feasible force sets) of two musculoskeletal models of the index finger were compared: the wEM model included a full representation of the extensor mechanism, whereas in the noEM model the extensor mechanism was replaced by a single extensor tendon without connectivity to intrinsic muscles. The feasible force sets were computed in the flexion-extension plane for nine postures. Forces in four predefined directions (palmar, proximal, dorsal, and distal), and the peak resultant forces were evaluated. Averaged forces in all four predefined directions were considerably larger in the wEM model (+187.6%). However, peak resultant forces were slightly lower in the wEM model (−4.3% on average). The general advantage of the wEM model could be explained by co-contraction of intrinsic and extrinsic extensor muscles which allowed reaching larger activation levels of the extrinsic flexors. Only within a narrow range of force directions the co-contraction of intrinsic muscles limited the fingertip forces and lead to lower peak resultant forces in the wEM model. Rather than maximizing peak resultant forces, it appears that the extensor mechanism is a sophisticated tool for increasing maximum fingertip forces over a broad range of postures and force directions – making the finger more versatile during grasping.

1. Introduction

An accurate biomechanical model of the human finger is highly relevant in multiple fields including robotics (Inouye and Valero-Cuevas, 2014), medicine (Fowler and Nicol, 2000), ergonomics (Ikeda et al., 2009), and anthropology (Rolian et al., 2011). Due to its complexity, finger biomechanics are still not fully understood and modelling remains a challenge (Lee et al., 2015; Allouch et al., 2015; Vignais and Marin, 2014). This complexity partly results from the so-called extensor mechanism. The extensor mechanism is a tendinous network which distributes forces of intrinsic muscles and extrinsic extensor muscles across interphalangeal joints (IP) (Lee and Kamper, 2014; Clavero et al., 2003; Hurlbut and Adams, 1995). It has two biomechanically important consequences: first, intrinsic muscle contraction causes flexion of the metacarpophalangeal (MCP) joint, but extension of the IP joints (Brand and Hollister, 1999). Second, only part of the extrinsic extensor forces are transmitted to the IP joints (Lee et al., 2008a; Chao et al., 1989).

Numerous experimental and numerical studies have explored the effects of those mechanisms on the finger biomechanics. Previous studies investigated the relevance of the extensor mechanism for coordinated finger movements (Landsmeer, 1949; Leijnse and Spoor, 2012), the force distribution within the extensor mechanism (Valero-Cuevas et al., 2007, Hu et al., 2014b; Lee et al., 2008a), or estimated effective moment arms of intrinsic and extrinsic extensor muscles at the IP joints (Lee et al., 2008b; An et al., 1983). The use of musculoskeletal models has also facilitated comparisons of the muscle activation patterns in a normal finger to a hypothetical finger without extensor mechanism (Li et al., 2001; Hu et al., 2014a). No study has yet investigated the effect of the extensor mechanism on the force producing capabilities of the finger, even though well directed and sufficiently large forces are key determinants for successful grasping (Valero-Cuevas, 2005; Inouye and Valero-Cuevas, 2014). Evaluating the maximum fingertip forces in all directions, i.e. the feasible force set, has proven useful to investigate the finger's force producing capabilities (Inouye and Valero-Cuevas, 2014;

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Valero-Cuevas et al., 1998) but the contribution of the extensor mechanism remains unclear.

The influence of the extensor mechanism on the force producing capabilities of the finger is not straight forward. For instance, the coupling of intrinsic muscles to IP joint extension would suggest that their activation counteracts the generation of large palmar forces required for grasping. Nonetheless, electromyographic (EMG) studies reported considerable intrinsic muscle activation levels during maximum palmar force generation or pinch grip (Long et al., 1970; Valero-Cuevas et al., 1998). Simulated paralysis of intrinsic muscles even leads to a decrease of maximum palmar fingertip forces of more than 50% (Valero-Cuevas et al., 2000). It remains unclear whether this effect can be solely attributed to the intrinsic muscles as MCP joint flexors or whether the relevance of intrinsic muscles relies on the complex tendon routing governed by the extensor mechanism (Long et al., 1970).

The goal of this study was to investigate the effect of the extensor mechanism on the maximum isometric fingertip forces of a human finger. In particular, it was hypothesized that the complex tendon routing of intrinsic and extrinsic extensor muscles dictated by the extensor mechanism enhances the finger's force producing capabilities.

2. Materials and methods

2.1. Study design

In order to test the hypothesis, two musculoskeletal index finger models were generated and compared based on the maximum isometric fingertip forces in all directions (i.e. the feasible force sets, see Fig. 1). The two models differed only with respect to their tendon routing: the first model (wEM model) included a full representation of the extensor mechanism, connecting to the intrinsic and extrinsic extensor muscles (Fig. 2, left). The second model (noEM model) simplified the extensor mechanism to a single extensor tendon without connectivity to intrinsic muscles (Fig. 2, right) following previous comparative studies (Li et al., 2001; Hu et al., 2014a). Feasible force sets were computed in the flexion-extension plane for nine different postures within the working range of the finger to ensure generality of the results (Section 2.3). Differences between the models were interpreted based on two additional computations: First, feasible force subsets were evaluated to identify contributions of the two main features of the extensor mechanism (intrinsic muscle coupling and extrinsic extensor force distribution) to any increase or decrease of maximum forces (Section 2.4). Second, muscle activation levels and contributions to joint torques were evaluated to investigate the role of each muscle for reaching maximal forces (Section 2.5).

2.2. Musculoskeletal models

Both the wEM and noEM models were generated based on the normative model of the human hand (An et al., 1979) (Figs. 1 and 2). The model consists of three movable (proximal, middle, and distal phalanx) and one fixed (metacarpal) bone segments interconnected by three joints, namely the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints (Fig. 1, top). PIP and DIP are hinge joints with one degree of freedom (flexion/extension) and the MCP joint is condylar with two degrees of freedom (flexion/extension and abduction/adduction). Six muscles actuate the model: Flexor digitorum profundus (FDP) and superficialis (FDS) are the extrinsic flexors, radial interosseus (RI), ulnar interosseus (UI) and lumbrical (LU) are the intrinsic muscles, and the long extensor (LE) lumps together the two extrinsic extensor muscles: extensor digitorum communis (EDC) and extensor indicis (EI).

The extensor mechanism of the wEM model was included using the common Winslow's rhombus simplification (Zancolli, 1979; Valero-Cuevas et al., 1998). It consists of two slips and two bands, namely the central slip, terminal slip, ulnar band, and radial band. The LE and all intrinsc muscles, except for the RI (An et al., 1983), are attached to the extensor mechanism (Fig. 2, left). In the noEM model, the intrinsic muscles directly attach to the proximal phalanx and the LE is connected to a tendon crossing all three joints (Fig. 2, right).

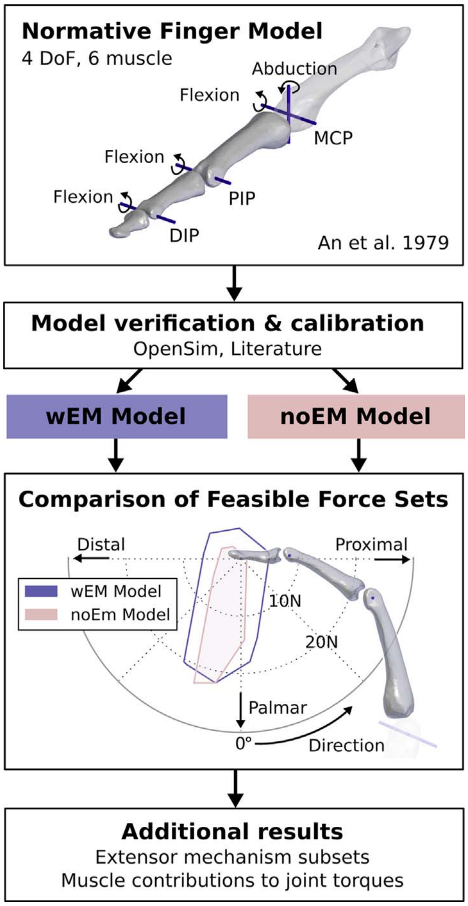

Fig. 1. Graphical abstract of the study. Two musculoskeletal models, one with (wEM), one without (noEM) the extensor mechanism, were generated based on a verified and calibrated generic finger model. They were compared based on the maximum isometric forces at the fingertip in all directions, i.e. their feasible force sets. Additional results were computed to interpret possible differences.

The parameters of the models were adapted from the literature (An et al., 1979; Lieber et al., 1992; Jacobson et al., 1992; Qiu and Kamper, 2014). Normalized bone segment lengths and tendon path via-point coordinates were taken from the work of An et al. (1979). For each tendon, the via-points were defined using two points at each joint (one proximal and one distal). Proximal and distal via-points were considered fixed with respect to proximal and distal bones, respectively. Maximum muscle forces were computed as the product of physiological cross sectional areas (PCSA) (Lieber et al., 1992; Jacobson et al., 1992) and the maximum muscle stress 35.4 N/cm^2 (Zajac, 1989; Valero-Cuevas et al., 1998). In the wEM model, the ratio of force transmitted to central and terminal slips was set to 50:50 for the LU and UI muscles and 60:40 for the LE muscle following Qiu and Kamper (2014).

Both models were custom-implemented in Python (Python Software Foundation, www.python.org) to allow incorporating complex tendon topologies. Posture dependent moment arms of all tendon parts (see Fig. 2) were calculated in analogy to OpenSim (Delp et al., 2007) using the generalized force method (Sherman et al., 2013). Bowstringing was assumed for all flexor muscles and lateral bands (radial and ulnar band) of the extensor mechanism (An et al., 1979). Landsmeer's model 1 (Chao et al., 1989) was used for the remaining extensor tendon parts (LE, central slip and terminal slip). In order to ensure validity of the model predictions, the model parameters were slightly calibrated to best fit the experimental results presented by Qiu and Kamper (2014). Details on the methodology and results of the calibration are presented in the appendix (Appendix A). In brief, the force vector direction and magnitude at the fingertip resulting from single muscle activation under isometric conditions was computed and compared to averaged in vitro experimental results (Qiu and Kamper, 2014) in nine postures using the wEM model. To achieve model predictions that agreed well with the experimental data, modifications were made to the coordinates of the proximal tendon via-points at the MCP joint, as recommended by Qiu and Kamper (2014). The final model parameters for both the wEM and noEM models are presented in the supplementary material (Appendix B).

2.3. Computation and comparison of feasible forces sets

The feasible force set can be interpreted as the set of forces which can be produced at the fingertip in all possible directions. The boundary of this force set is determined by maximum muscles forces as well as additional constraints (e.g. limited fingertip torque) and can be computed using theory of linear programming (Chao et al., 1989; Chao and An, 1978; Valero-Cuevas et al., 1998). The methodology to compute feasible force set boundaries is briefly described below.

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