INFLUENCE OF FLEXOR POLLICIS LONGUS MUSCLE'S JOINT MOMENTS ON THE DIRECTION AND MAGNITUDE OF ITS THUMB-TIP FORCE

Joseph Towles[1,2], Wendy Murray[1], Francisco Valero-Cuevas[4], Felix Zajac[1,2,3]
[1]Rehabilitation Research and Development Center, VA Palo Alto Health Care System;
[2]Biomechanical Engineering Division, Mechanical Engineering Department, Stanford University
[3]Department of Functional Restoration, School of Medicine, Stanford University
[4]Sibley School of Mechanical and Aerospace Engineering, Cornell University

Abstract

The purpose of this work was to show the effect of changing the ratio of the flexion-extension (FE) moment arms of the flexor pollicis longus muscle (FPLM) on its thumb-tip force production. Specifically, a moment-driven model of the thumb was used to simulate the thumb-tip force effect of increasing the FPLM's TMCJ moment arm by 25%. The results showed that a 25% increase in the TMCJ moment arm reduced the thumb-tip force by 21% and changed its orientation by 7° in the clockwise direction. These findings are important because muscle moment arm changes may have a non-intuitive effect on end-point force production. The FPLM is important for thumb function, and is often electrically stimulated to help restore grasp to persons with cervical spinal cord injury. Understanding how its moment arms effect the magnitude and direction of its thumb-tip force would be useful to evaluate surgeries that could augment FES interventions.

Introduction

Functional electrical stimulation (FES) restores hand function to individuals with cervical spinal cord injury (SCI) [1]. An understanding of how individual muscles contribute to the magnitude and direction of the grasp end-point force, produced at the thumb, would be useful for programming different grasp patterns and for evaluating reconstructive surgeries that could augment FES interventions.

Limited work has been done that concern the end-point forces of the muscles in the hand. In a study that involved FES-system users, Kilgore *et al*. [2] measured the change in thumb-tip forces, produced by several muscle groups, as a function of functional thumb postures. Valero-Cuevas *et al*. [3], in their study that quantified the reduction in fingertip force in the neurologically-impaired hand, measured the end-point forces of the index finger's seven muscles. Contributions like these are important for treating grasp-related impairments and scarce in the literature. This work used a bio-mechanic model to study the effect of changes to the flexor pollicis longus muscle's flexion-extension moment arm at the TMCJ on its thumb-tip force production. Specifically, we hypothesized that if the FE moment arm at trapezio-metacarpal joint was increased, then the FPLM's thumb-tip force's magnitude and direction would change due to skeletal kinematic requirements.

Methods

Based on *in-situ* measurements of moment arms [4], muscle architecture [5, 6] and three-dimensional digital joint kinematics [7, 8, 9], a static moment-driven skeletal model of the thumb was developed to study how FPLM's moment arm changes influence its thumb-tip force. The FPLM is essentially a pure thumb flexor; thus, its ab-adduction moment arms at the trapezio-metacarpal (TMCJ) and the metacarpo-phalangeal joints (MPJ) are negligible [4]. In the model, line segments approximate the structure of bones; and universal and hinge joints are used to represent joint kinematics (see Figure 1).

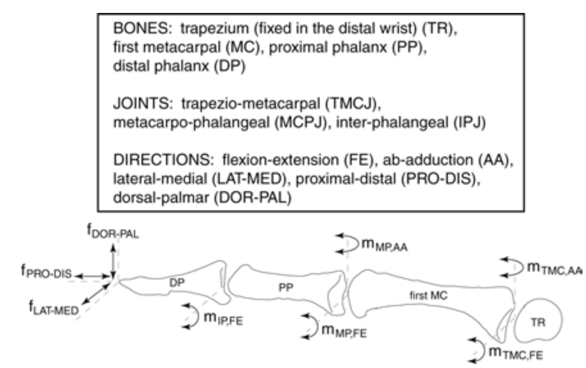

Figure 1: Static model of the right thumb in its plane of flexion-extension. Given its five degrees of freedom, five joint moments and three end-point force components can be independently produced [10].

Mathematically, the model is represented by the following matrix equation:

$$\mathbf{f}^{\mathbf{EP}} = \mathbf{Dm} \tag{1}$$

where the digital end-point force vector is defined as $\boldsymbol{f}^{EP} = \left[f_{LAT-MED} \quad f_{PRO-DIS} \quad f_{DOR-PAL} \right]^T$ and the joint moment vector is defined as $\boldsymbol{m}$ = $[m_{TMC,FE} \quad m_{TMC,AA} \quad m_{MP,FE} \quad m_{MP,AA} \quad m_{IP,FE}]^T$. In the study's simulation, the thumb was placed in a closed lateral pinch posture (TMCJ at 30°E, 0°A; MPJ at 30°F, 0°A; IPJ at 0°F). The FPLM generated 10 N of force, which, acted through its FE moment arms to produce FE moments at the TMCJ, MPJ and IPJ. The jacobian matrix D, which represents the model's skeletal kinematics, transformed the joint moments into thumb-tip forces. The magnitude and direction (with respect to the distal phalanx) of the nominal thumb-tip force was compared to the adjusted thumb-tip force that resulted from the change to the FPLM's TMCJ moment arm.

Results

In Figure 2, the FPLM's TMCJ moment arm was increased by 25% (black flexion arrow). The nominal end-point force (grey) was f^{EP}= 3.95 N at ϕ_1 = 155°. A twenty-five percent increase in FPLM'S TMCJ moment arm (represented by increase in joint flexion moment, shown in black) decreased end-point force by 21% to f^{EP}(black) = 3.12 N and rotated it by ϕ_2 = 7°.

Figure 2: End-point effect of increase in FPLM's TMCJ moment arm.

Discussion

This study used a bio-mechanic model to demonstrate how a change to the FE moment arm of the FPLM impacted its thumb-tip force production. It showed that if the TMCJ FE moment arm of the FPLM were increased, then both the magnitude and direction of its thumb-tip force would change (see Figure 2). This can be explained if the kinematics of the thumb are considered.

The kinematics of thumb—its posture, number of movable joints, bone segments, and bone segment lengths—transform joint moments into end-point forces. Figure 4 illustrates the separate end-point forces of the joint moments in the closed lateral pinch posture.

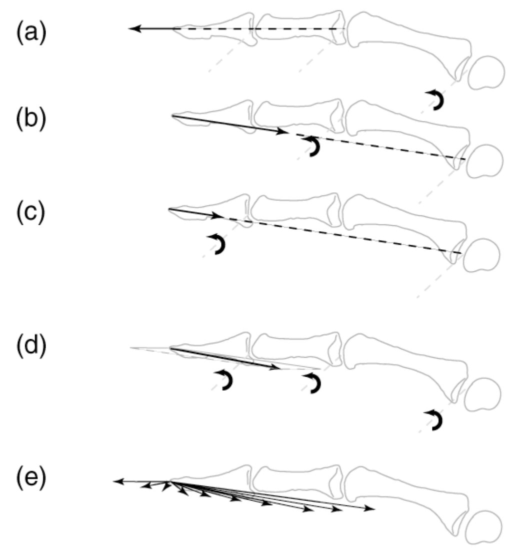

Figure 4: End-point joint vectors. (a) End-point joint vector of FPLM's TMCJ FE moment passes through MPJ and IPJ; (b) end-point force of FPLM's MPJ FE moment passes through TMCJ; (c) end-point force of FPLM's IPJ passes through TMCJ; (d) summed nominal end-point force of FPLM's TMCJ, MPJ, IPJ FE moments (the direction of the force vector agrees with the *in-vivo* measurement of FPLM vector reported in [2]); (e) the range of possible end-point forces, produced by FPLM, when TMCJ, MPJ and IPJ were increased up to 25% of their nominal values.

When a flexion moment is produced at the TMCJ, an outward-pointing, horizontal end-point joint vector (defined as a joint moment's end-point force) results. This occurs because the line of action of the end-point joint vector must intersect the IPJ's and MPJ's centers of rotation and the TMCJ's AA rotation axis (see Figures 4a and 1), as the joint moments at the MPJ and IPJ are zero. Because the IPJ angle is zero, the MPJ moments and IPJ moments have similarly directed end-point forces (see Figures 4b and 4c). That is, they both produce end-point joint vectors that pass through the TMCJ origin for reasons similar to those stated above. Since (1) is linear in $\boldsymbol{m}$, the summed end-point forces of the FE joint moments at all the joints produce the resultant end-point force in Figure 4d (the black arrow). Thus, any uniform change in the end-point joint vectors, such as what would've resulted if all joint moments were increased proportionately, will produce the same change in the magnitude of the resultant end-point force vector and no change in its direction. Conversely, any non-uniform change will result in an end-point force with both a new magnitude and a new direction. In Figure 2, when just the TMCJ moment was increased by 25%, the resulting end-point force was 21% less in magnitude and directed 7° closer to the distal phalanx's

DOR-PAL axis (see Figure 1). The outcome is non-intuitive, but makes sense when each joint's end-point joint vector is considered (see Figure 4a and 4d). When TMCJ moment is increased, its end-point joint vector increases in length. Consequently, the new sum of the end-point joint vectors is an end-point force that is shorter and more clockwise rotated. It is also interesting to note that the FPLM's thumb-tip force production is independent of TMCJ FE angle. This is because the relative orientation of each joint's end-point vector is TMCJ-angle independent (see Figure 4). They do, however, vary with MPJ angle. In their study, Kilgore *et al.* [2] reported a change in the FPLM's thumb-tip force when the MPJ was fully extended.

The FPLM constitute one of the major muscle groups that control the thumb [2]. An understanding of how variation in its moment arms influence the magnitude and direction of its thumb-tip force would be useful to evaluate reconstructive surgeries that could augment FES interventions. For instance, in the simulation depicted in Figure 4e, the FPLM's FE moment arms at the TMCJ, MPJ and IPJ were increased by as much as 25%. The results are the possible thumb-tip forces that range from small outward-point forces to large forces that point nearly exclusively in the opposite direction. Thus, FPLM's moment arms could be appropriately adjusted to so that the use of FES could have a broader effect on restoring grasp in persons with cervical SCI. Also, an understanding of how TMCJ and MPJ angle changes effect the FPLM's thumb-tip force would be useful for selecting FPLM-specific stimulus parameters when FPLM is electrically stimulated

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