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The sensitivity of endpoint forces produced by the extrinsic muscles of the thumb to posture

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ABSTRACT

This study utilizes a biomechanical model of the thumb to estimate the force produced at the thumb-tip by each of the four extrinsic muscles. We used the principle of virtual work to relate joint torques produced by a given muscle force to the resulting endpoint force and compared the results to two separate cadaveric studies. When we calculated thumb-tip forces using the muscle forces and thumb postures described in the experimental studies, we observed large errors. When relatively small deviations from experimentally reported thumb joint angles were allowed, errors in force direction decreased substantially. For example, when thumb posture was constrained to fall within $\pm 15^\circ$ of reported joint angles, simulated force directions fell within experimental variability in the proximal–palmar plane for all four muscles. Increasing the solution space from $\pm 1^\circ$ to an unbounded space produced a sigmoidal decrease in error in force direction. Changes in thumb posture remained consistent with a lateral pinch posture, and were generally consistent with each muscle's function. Altering thumb posture alters both the components of the Jacobian and muscle moment arms in a nonlinear fashion, yielding a nonlinear change in thumb-tip force relative to muscle force. These results explain experimental data that suggest endpoint force is a nonlinear function of muscle force for the thumb, support the continued use of methods that implement linear transformations between muscle force and thumb-tip force for a specific posture, and suggest the feasibility of accurate prediction of lateral pinch force in situations where joint angles can be measured accurately.

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1. Introduction

The opposable thumb has helped humans develop fine motor skills, allowing manipulation of a wide variety of objects. In particular, the ability to hold an object between the thumb and the lateral aspect of the index finger (lateral pinch) is an important component of hand function. For example, the ability to complete selected functional tasks has been accurately predicted for individuals with significant deficits in lateral pinch strength based on the magnitude of pinch force they could produce (Smaby et al., 2004).

The thumb consists of the carpometacarpal (CMC), metacarpophalangeal (MCP), and interphalangeal (IP) joints, connecting four bones, the trapezium, the first metacarpal, the proximal phalanx, and the distal phalanx. Anatomical studies describe five degrees of freedom among these three joints, including flexion/extension and abduction/adduction at the CMC joint, flexion/extension and abduction/adduction at the MCP joint, and flexion/extension at the IP joint (Hollister et al., 1992; Giurintano et al., 1995; Hollister et al., 1995). Each degree of freedom has a single axis of rotation, and these axes have been demonstrated to be non-orthogonal and non-intersecting. Nine muscles actuate the thumb; the five intrinsic muscles of the thumb both originate and insert within the hand and the four extrinsic muscles originate in the forearm.

Despite the existence of biomechanical models of the thumb that replicate experimental measurements of muscle moment arms (Valero-Cuevas et al., 2003; Holzbaur et al., 2005; Towles et al., 2008; Vigouroux et al., 2009; Wu et al., 2009), thumb models do not accurately predict lateral pinch force (Valero-Cuevas et al., 2003). Notably, the mathematical transformation between muscle force and endpoint force used in biomechanical models is linear for a given posture (Valero-Cuevas et al., 2000). In contrast, experimental measurements obtained from cadaveric specimens suggest that endpoint force is a nonlinear function of muscle force for the thumb (Pearlman et al., 2004). That is, when different levels of muscle force were applied while the thumb was in the same initial posture, nonlinear changes in endpoint force

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were observed. Pearlman et al. attributed the experimentally observed nonlinearities to load-dependent viscoelastic tendon paths and load-dependent motion of the trapezium. In a separate study, Towles et al. (2008) illustrated that, theoretically, translation of the trapezium can cause the thumb to assume a different overall posture.

The main objective of this study is to evaluate the sensitivity of endpoint forces produced by the four extrinsic muscles of the thumb to posture. The extrinsic muscles are flexor pollicis longus (FPL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), and abductor pollicis longus (APL). We hypothesized that the errors between endpoint forces produced by individual muscles simulated using a biomechanical model (Holzbaur et al., 2005) and measured experimentally in two studies (Pearlman et al., 2004; Towles et al., 2004) would decrease if deviations from the experimentally reported joint angles were allowed. In both experimental studies, joint angle measurements were performed manually before the muscles were loaded and it was noted anecdotally that thumb posture visibly changed during data collection. Because the thumb always maintained a posture that was consistent with lateral pinch in these experimental studies, we hypothesized that the deviations in overall posture required to produce acceptable errors between simulated and measured endpoint forces would be relatively small.

2. Methods

To estimate the force produced at the thumb-tip by the individual extrinsic muscles, we used the principle of virtual work to relate the joint torques produced by a given muscle force to the resulting force at a point of interest on the distal phalanx:

$$\overline{F} = (\boldsymbol{J}\boldsymbol{J}^T)^{-1}\boldsymbol{J}\overline{L}_{MA}f_{muscle}, \tag{1}$$

where $\overline{F}$ is the endpoint force, $\boldsymbol{J}$ the 3×4 Jacobian matrix, $\overline{L}_{MA}$ the 4×1 vector of muscle moment arms, and f_{muscle} the given muscle force of the extrinsic muscle of interest. In this study, we specified the magnitude of a given muscle force, f_{muscle}, to replicate the load applied to that muscle in the experimental studies described above.

The remaining components of Eq. (1) were developed using a kinematic model of the thumb, with the goal of transforming muscle force into a pure point force at the thumb-tip, assuming any moments caused by the distal phalanx slipping or rotating to be equal to zero. The thumb model has been described previously as a part of a general musculoskeletal model of the upper limb, including bone geometry, joint kinematics, and muscle–tendon paths consistent with a healthy, 50th percentile male (Holzbaur et al., 2005). The thumb is modeled as four separate hinge joints, with the axes and centers of rotation for the thumb joints based on detailed experimental studies (Fig. 1) (Hollister et al., 1992, 1995). Specifically, four independent angular rotations occur about non-intersecting, non-orthogonal axes of rotation where all abduction and adduction thumb movement occurs at the CMC joint.

To convert the force specified for a given muscle into the thumb joint torques it produces, we used the musculoskeletal model to calculate the moment arm of each of the extrinsic muscles about each axis of rotation over the full range of motion. The muscle moment arms estimated using the biomechanical model are consistent with experimental data (Smutz et al., 1998). The moment arms for a given muscle defined the 4×1 vector, $\overline{L}_{MA}$, which varies as a function of joint posture.

To derive the Jacobian, $\boldsymbol{J}$, we first calculated the three-dimensional position of the thumb-tip with respect to the wrist center as a function of the four degrees of freedom of the thumb. We then calculated the partial derivative of each position component with respect to each degree of freedom. The resulting 3×4 matrix is dependent on the axes of rotation (defined above), segment lengths, and joint angles from the thumb model. The segment lengths were determined from the musculoskeletal model using the distances between the centers of rotation for the thumb joints. Joint angles were measured relative to the neutral position of the thumb, as defined in Holzbaur et al. (2005). The Moore–Penrose pseudoinverse was used to calculate $\boldsymbol{J}^{-T}$ due to the non-square nature of the matrix.

Towles et al. (2004) reported thumb-tip force vectors produced when the FPL was loaded with 10 N of force in 7 cadaveric specimens. We first performed 7 simulations to estimate the transformation from FPL muscle force to thumb-tip force for each specimen. In these simulations, we used the joint angles reported in the experimental study, which differed for each specimen. We then calculated the 7 thumb postures that resulted in the smallest absolute errors compared with the

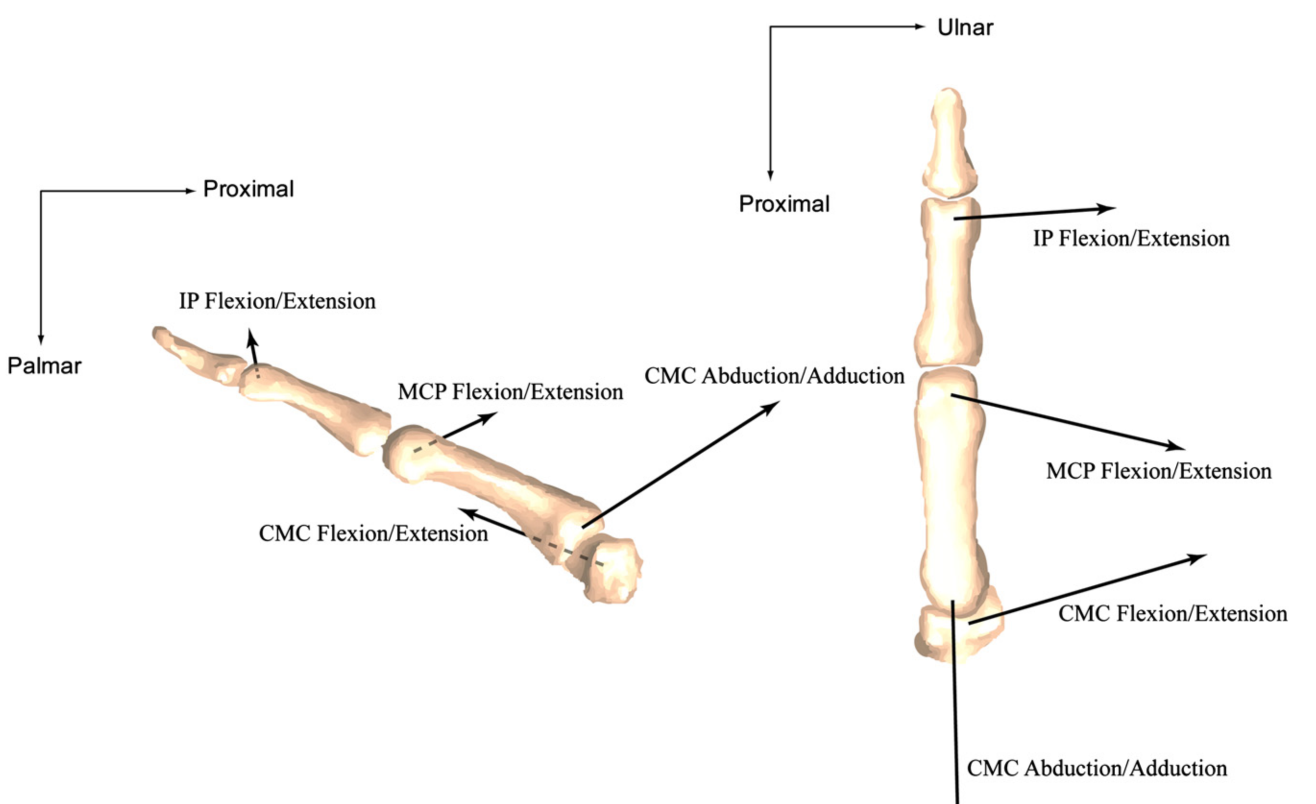

Fig. 1. The axes and centers of rotation for the thumb joints used in the musculoskeletal computer model. Note that all abduction/adduction movement of the thumb model occurs at the CMC joint.