INTRODUCTION
Many of the muscles that control hand movement cross more than one joint. In particular, the extrinsic muscles of the hand originate in the forearm and cross the wrist. This complex musculoskeletal anatomy creates passive mechanical linkages between joints; the passive moment about a given joint is highly dependent on the position of all of the joints a multi-articular muscle crosses [1]. In nonimpaired individuals, the passive coupling between the wrist and hand facilitates opening and closing of the fingers during grasping tasks. Because of the passive forces produced by the extrinsic finger muscles, wrist flexion assists opening of the fingers and wrist extension facilitates closing of the fingers. This coupling can be altered in the impaired hand. For example, stroke survivors have difficulty opening their fingers to grasp an object even in flexed wrist postures. Understanding the mechanisms that alter this coupling is imperative to enhancing rehabilitation techniques.

We used a multi-joint musculoskeletal model of the upper limb to evaluate how the passive properties of the multi-articular extrinsic finger muscles affect the resting position of the metacarpophalangeal (MCP) joint of the index finger. The objective of this study was to demonstrate the importance of including the passive coupling between the wrist and the fingers in biomechanical models.

METHODS
A computer-graphics based kinematic model of the upper-extremity [2] was utilized to facilitate a static equilibrium analysis. The model consists of 3D surface representations of all the bones of the thorax, arm, forearm, wrist, and hand, joint kinematics for 15 degrees of freedom of the upper limb, and muscle-tendon paths and force generating properties of 50 muscles and muscle compartments. We defined the inertial properties of the upper limb to be consistent with published data describing a 50th percentile male [3]. With the exception of the MCP and wrist joints, we constrained all joints within the model. We also defined a “restraining moment” for the MCP joint to enforce the limits of the range of motion. The restraining moment is independent of adjacent joint postures and reflects the elastic moments produced by the joint capsule, ligaments, the intrinsic muscles, and other soft tissues. The restraining moment for the MCP joint was defined based on experimental data [1].

With the model in a posture in which gravity opposes wrist extension (90° elbow flexion, 90° pronation), we calculated the joint angle (θ) at which the net passive moments about the MCP joint equal 0 Nm. That is;

\[ M_g(\theta, \varphi) + M_R(\theta) + M_{FDP}(\theta, \varphi) + M_{FDS}(\theta, \varphi) + M_{EI}(\theta, \varphi) + M_{EDC}(\theta, \varphi) = 0 \]

Where \( M_g \) is the moment produced by the mass of the distal, middle, and proximal phalanges of the finger, \( M_R \) is the restraining moment, and the remaining terms are the passive moments produced by the extrinsic muscles of the index finger: flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor indices (EI), and extensor digitorum communis (EDC).

The passive moments calculated for the individual extrinsic muscles were estimated using the model [2]. The kinematic model allows calculations of muscle length, forces, and joint moments as a function of all the joints the muscle crosses. The published model prescribed the optimal length of muscles near the anatomical neutral position of the hand. We adjusted the tendon slack lengths of the extrinsic muscles of the index finger to replicate the passive moments produced by the extrinsic muscles of the index fingers reported experimentally [1].
At each wrist position, we evaluated the work done passively by the individual extrinsic muscles to resist motion of the MCP joint:

$$W_i(\varphi) = \int_{-5\pi/18}^{\pi/2} |M_i| \, d\theta$$

where $W_i$ is the work of the $i$th extrinsic muscle over the MCP range of motion, -50 to 90 degrees flexion (converted to radians), at wrist angle $\varphi$, and $M_i$ is the moment of the $i$th muscle at MCP angle $\theta$. The work done by the passive intrinsic structures to resist motion over the MCP range of motion was calculated similarly. To simulate a flexion contracture, the optimal fiber lengths of the extrinsic flexor muscles were decreased to 95% of nominal lengths [4]. The passive work of the flexor muscles was recalculated to assess the potential for a flexion contracture to limit motion.

RESULTS AND DISCUSSION

Our simulations of the resting position of the MCP joint of the index finger replicate the natural passive coupling observed between the fingers and the wrist in the nonimpaired hand. As the wrist rotates from an extended to a flexed posture, the rest position of the MCP joint moves from a flexed to an extended posture, respectively (Fig. 1). In extended wrist postures, the primary musculoskeletal structures resisting motion at the MCP joint passively are the extrinsic flexors (Fig. 2). This resistance decreases substantially as the wrist moves to neutral, and then is replaced by the actions of the extrinsic extensors when the wrist is flexed. The work done passively by the structures intrinsic to the hand is relatively small.

The work done by the flexors nearly doubled in extended wrist postures when we simulated even a very small adaptation in muscle fiber length. These simulations suggest that even minimal structural changes to the extrinsic muscles of the hand can have a large effect on the passive resistance to motion.

CONCLUSIONS

This study describes a musculoskeletal model of the hand that can be used to study the functional consequences of the mechanical couplings that results from the complex musculoskeletal anatomy of the upper limb. Expanding our simulations to incorporate multiple joints of the index finger, as well as including multiple fingers and the thumb should lend insight to the study of neuromuscular control of functional hand motion and its rehabilitation.

REFERENCES


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Figure 1. Resting position of the MCP joint as a function of wrist position.

Figure 2. The work done passively to resist motion of the MCP by the extrinsic flexor muscles (black bars), extrinsic extensors (gray bars) and structures intrinsic to the hand (open bars).