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NEW TENDON-TRANSFER SURGERY FOR ULNAR-MEDIAN NERVE PALSY USING EMBEDDED ADAPTIVE ENGINEERING MECHANISMS

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INTRODUCTION

Upper-extremity tendon-transfer surgeries are performed when muscle function is lost due to muscle or peripheral nerve trauma [1-4]. The surgeries, which were established over forty years ago, partially restore hand function by re-routing tendons from the affected muscle and suturing them to a still-functioning donor muscle.

A tendon-transfer surgery of particular interest is that which is commonly performed for patients afflicted by median-ulnar nerve palsy. Median-ulnar nerve palsy, amongst its many effects, disables the flexor digitorum profundus (FDP) muscle, weakening grip strength and adversely affecting the performance of the activities of daily living. To recover full flexion capability in all the fingers, the tendon transfer surgery currently performed directly sutures the extensor carpi radialis longus (ECRL) muscle to the FDP tendons of the fingers (see Fig 1a), so that as the ECRL muscle contracts, the fingers flex. However, this procedure results in an undesired behavior. Since the ECRL muscle is directly sutured (coupled) to multiple recipient tendons, if one distal joint is stopped when the hand makes contact with an object during grasping, all other joints are also rendered immobile. This prevents the joints from adapting independently to the object shape during the grasping process, resulting in poor grasping ability and may require unnatural wrist and arm movement to complete the grasp.

We propose to rectify this drawback in current tendon-transfer procedures by using simple passive engineering mechanisms called “adaptive coupling mechanisms” to interface between the donor muscle and the recipient tendons. Adaptive coupling mechanisms belong to the class of differential mechanisms [5] and take different forms, such as moving pulley systems. Recently they have made a strong impact in robot hand design [6-8].

Our proposed tendon-transfer surgical procedure for median-ulnar nerve palsy will use a hierarchical seesaw mechanism to interface between the ECRL muscle and the FDP tendons (Figure 1b). As the ECRL muscle contracts, the entire seesaw mechanism will translate. But as each finger makes contact, each seesaw mechanism will naturally rotate to allow continued flexion of the other fingers. We hypothesize that adaptive mechanisms, when utilized in tendon-transfer surgeries, enable the finger joints powered by the donor muscle to adapt independently, travel through greater angles, and produce greater forces on the object during physical interaction, even if actuated by a single donor muscle. As a first step towards exploring the proposed procedure, a biomechanical simulation was built in OpenSim, an open-source biomechanics software platform [9].

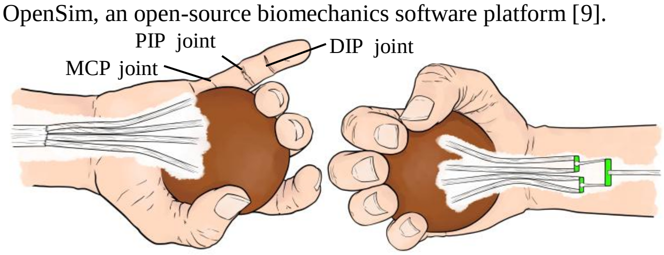

Figure 1: Artist’s representation of a) a traditional ECRL 4-tailed tendon transfer and associated non-normative grasp and b) the proposed experimental mechanism and associated improved grasp.

METHODS

The Stanford VA Upper Extremity Model [10], available freely to the OpenSim community, was modified for this study. The weld joints in the original Stanford VA model at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the third, fourth, and fifth digits were replaced with flexion/extension joints. In order to focus the study on the effects of replacing the FDP muscle with the ECRL muscle using the conventional and proposed procedures, all other muscles were deleted from the model. Inertial and weight parameters were added based on properties found in several different papers [4, 11-14]. For model simplicity the distal interphalangeal (DIP), wrist and arm joints were locked during forward dynamics simulations.

To study the conventional ECRL 4-tailed tendon transfer procedure model (Figure 2a), a weightless body with full freedom of movement was added to the forearm to act as the interface between the ECRL muscle and the FDP tendons. For the proposed procedure incorporating the seesaw mechanism (Figure 2b), three weightless bodies were added to the forearm; one was given complete freedom of movement and rotation, while the others were attached to the first body and given rotation about the Z axis on either side of the center of rotation of the first body. The ECRL muscle was attached to the center of the first body, and the FDP tendons were attached to either side of the center of rotation of the other two bodies.

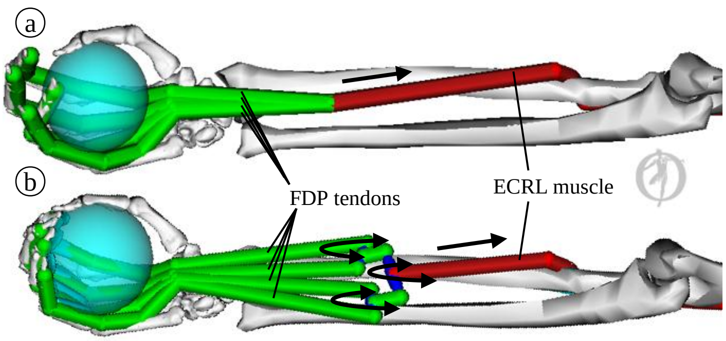

Figure 2: Graphic representations of the Opensim models utilized in this paper: a) traditional model; b) experimental model. Arrows indicate freedom of movement.

A large sphere was placed in the center of the hand to simulate the grasping of a ball. Compliant contact spheres were added to the fingertips to model the compliant contact between the ball and the fingertips. Contact parameters were defined using the Hunt-Crossley model, with a large stiffness constant k (1500000), small dissipation constant (0.1), and a high Columbic friction coefficient ($\mu = 100$).

A forward dynamics simulation of a ball grasp was run using each model, driven by an excitation profile supplied to the ECRL (a linear ramp over 1.75 seconds from 0.05 to 1.0 and then held at 1.0 for 0.5 seconds). OpenSim's Force Reporter was used to calculate the contact forces exerted by the fingertips. The joint angles of each digit were measured.

RESULTS

The proposed procedure enabled all the fingers to travel through larger angles and close in on the object independently. In contrast, finger movement after the conventional tendon-transfer procedure stopped after one of the fingers made contact with the object, and fingers were unable to adapt to the object shape. In the conventional tendon transfer model, only the ring finger that makes contact (contact is denoted by the vertical dotted lines on Figure 3) at 1.1 seconds. In the proposed procedure, the index finger struck first at 0.7 seconds. Then the seesaw mechanism swung to allow contact of the little finger at 0.8 seconds, the middle finger at 1.4 seconds, and finally the ring finger at 1.5 seconds.

Grasps created by the hand after the proposed procedure resulted in greater total steady-state force than the forces produced by grasps after the conventional procedure. ECRL activation and force production was identical in both models, so the increase in contact forces is entirely a product of the increased fingertip contact with the object.

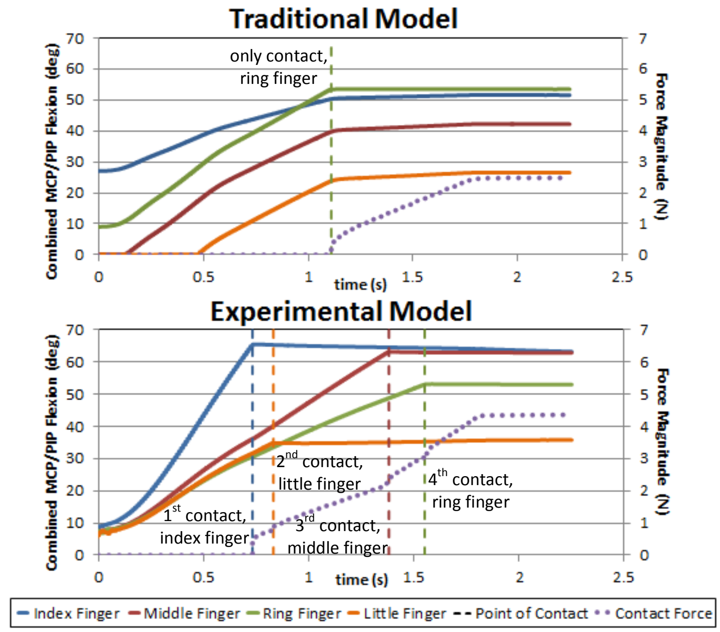

Figure 3: Simulation results of finger flexion and force magnitude exerted on the ball by the fingertips for the traditional and experimental models.

DISCUSSION

The simulations showed that hand function after the proposed tendon transfer procedure using an adaptive coupling mechanism performed as hypothesized in terms of independent and greater finger movement and force production. More importantly, hand function after the proposed procedure more closely fit ideal surgical outcomes than hand function after the conventional tendon-transfer procedure. Specifically, since the proposed procedure enables the fingers to adapt independently to the object shape, the patient is able to perform better grasps, a key goal of the original surgery.

Further research using cadaver hands and evaluating grasping performance on other objects is on-going.

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REFERENCES

[1] Green, DP et al., Green's Operative Hand Surgery, 2005; [2] Cooney, WP et al., *J Hand Surg*, 9A:777–786, 1984; [3] Sammer DM et al., *Plstc & Recnstr Surg*, 124(3):212e–221e, 2009; [4] Özkan, T et al., *J Hand Surgery*, 28(1):35-43, 2003; [5] Wikipedia, Differential (mechanical device). [6] Balasubramanian, R et al., *J Mech & Robtcs*, 4(2):21-13, 2012; [7] Balasubramanian, R et al., *IEEE Internat Conf*, 3489-3496, 2011; [8] Birglen, L et al., Underactuated Robotic Hands, 2008; [9] Delp S et al., *IEEE Trans on Biomed Engng*, 2007; [10] Holzbaur, K et al, *A Biomed Engng*, 33(6):829-840, 2005; [11] Drillis, R, "Body Segment Parameters," 1968; [12] Le Minor, JM et al., *A Anatomy*, 183(6):537-543, 2001; [13] Mansour, G et al., *ICMEN*, 2008; [14] de Leva, P, *J Biomech*, 29(9):1223-1230, 1996.