

AN ABSTRACT OF THE THESIS OF

Jade Montgomery for the degree of Honors Baccalaureate of Science in Bioengineering
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Tendon Transfer Surgery for High Median-Ulnar Nerve Palsy: A Simulation Study with OpenSim.

Abstract approved:

Ravi Balasubramanian

The improvement of coupled tendon transfer surgeries through the insertion of an adaptive engineering mechanism was explored using biomechanical simulations performed in OpenSim. Tendon transfer surgeries are commonly performed on the upper extremity to restore hand function. A conventional 4-tailed tendon transfer procedure model and a modified 4-tailed procedure model with inserted adaptive see-saw mechanism were created for this study. Forward dynamics simulations were used to predict surgical outcomes. Using the inserted device in a tendon transfer surgery was found to improve overall finger flexion ability, grasp force magnitude, and direction of grasp force when compared with performance after the conventional surgery. The device was also able to mitigate the impact of minor surgical error in tendon length and moment arm variation on finger flexion capability. Simulation results conclusively indicate that insertion of an adaptive engineering mechanism into the modified Brand procedure is expected to improve surgical outcomes and post-surgical quality of life.

Key Words: biomechanics, computer modeling, tendon transfer

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Embedding Adaptive Engineering Mechanisms into a Coupled Tendon Transfer Surgery for
High Median-Ulnar Nerve Palsy: A Simulation Study with OpenSim

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Jade Montgomery, Author

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EMBEDDING ADAPTIVE ENGINEERING MECHANISMS INTO A COUPLED TENDON TRANSFER SURGERY FOR HIGH MEDIAN-ULNAR NERVE PALSY: A SIMULATION STUDY WITH OPENSIM

INTRODUCTION

TENDON TRANSFER SURGERIES

Tendon transfer surgeries involve separating one or more tendons from a non-functioning muscle and directly suturing the separated tendon(s) to a functioning donor muscle. Over 65,000 tendon-transfer surgeries are performed worldwide each year when muscle function is lost due to muscle or peripheral nerve trauma [1] [2] [3] [4]. Established over forty years ago, upper extremity tendon transfer surgeries focus on the restoration of hand function.

This paper focuses on an upper-extremity tendon transfer surgery known as the modified Brand procedure, commonly performed for patients afflicted by high median-ulnar nerve palsy. High median-ulnar nerve palsy, amongst its many effects, disables the flexor digitorum profundus (FDP) muscle, the main flexor of the fingers. The result of high median-ulnar nerve palsy is weakened grip strength, which significantly affects the performance of activities of daily living. To recover flexion capability in the fingers, the modified Brand procedure directly sutures the extensor carpi radialis longus (ECRL) muscle, an extensor of the wrist, to all four FDP tendons of the fingers so that as the ECRL muscle contracts, the fingers flex.

The modified Brand procedure, however, has several drawbacks. Since the ECRL muscle is directly sutured to multiple recipient tendons, the movement of all of the distal joints is directly coupled with the donor muscle's excursion. This prevents the joints from adapting independently to the object shape during physical interaction with the environment, resulting in poor grasping ability and general hand function. In other words, if a single fingertip makes contact during a grasp then all other the other fingers are similarly rendered immobile regardless of their lack of contact.

ADAPTIVE COUPLING MECHANISMS

Adaptive coupling mechanisms belong to the class of differential mechanisms, which can take a single input and passively generate a multitude of outputs that adapt to external constraints placed on the system [5]. Adaptive coupling mechanisms are present in both manmade and natural systems. A notable natural adaptive coupling mechanism is that of the human finger, where the proximal and distal joints are both rotated simultaneously by the same tendon, that slides to adjust the flexion angle of each as required [6] [7].

The most common example of a traditional manmade differential mechanism is the differential transmission employed in automobiles to allow wheels to rotate at different rates during turning to retain traction [5]. Man-made adaptive coupling mechanisms can also take various other forms, such as seesaw and moving pulley systems (Figure 1).

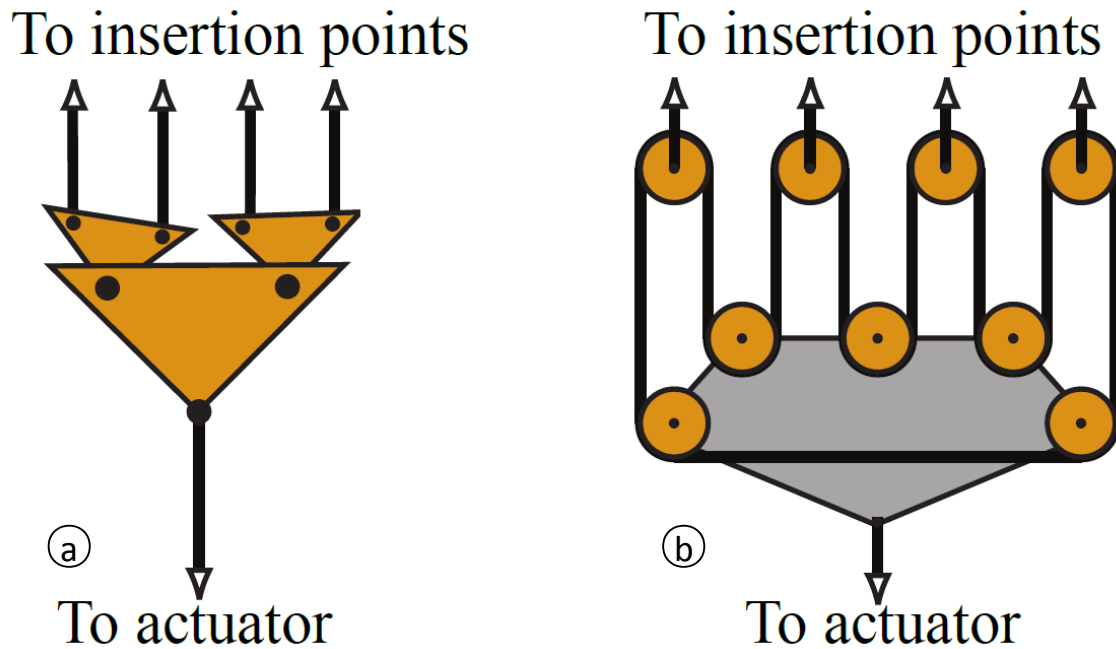


Figure 1: Passive adaptive mechanisms used in robotic hands come in several different designs, like the a) seesaw and b) pulley designs for underactuation [8].

ADAPTIVE MECHANISMS IN THE DESIGN OF UNDER-ACTUATED ROBOTIC HANDS

In the field of robotics, under-actuation refers to a mechanism containing fewer actuators than degrees of freedom (DOF). Under-actuation is often applied to robotic hands simply because it is easier to grasp objects using a simple control rather than having to command and coordinate several different actuators. An under-actuated robotic hand (Figure 2) contains adaptive coupling mechanisms, reducing the amount of required actuators and allowing the hand to adapt passively to the shape of an object being grasped (Figure 3). It is not uncommon for an under-actuated robotic hand to use only a single actuator for grasping [9] [10] [11].

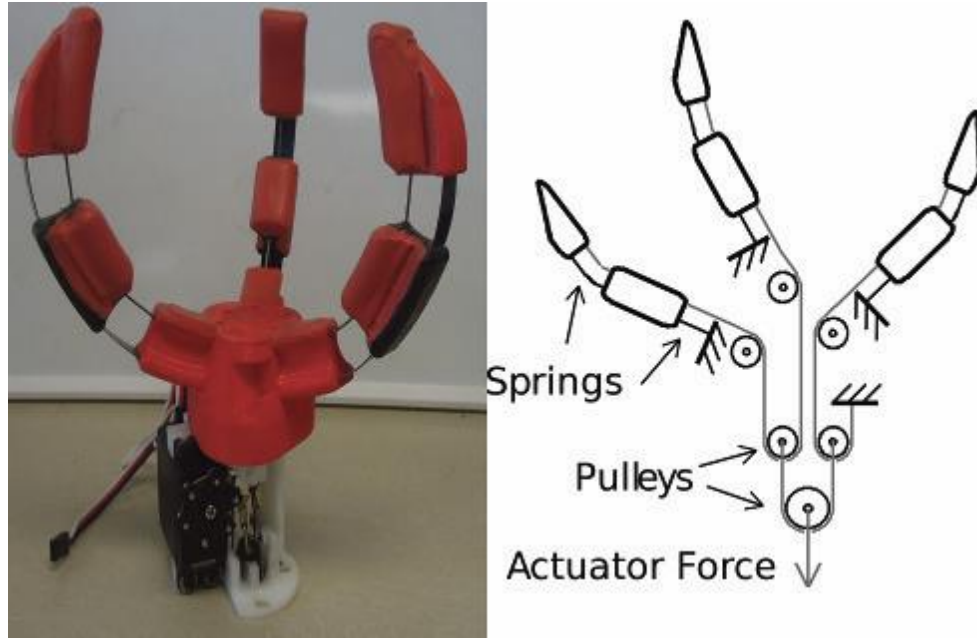


Figure 2: The OSU agricultural robotic hand that uses adaptive coupling mechanisms to route power from one motor across six joints.

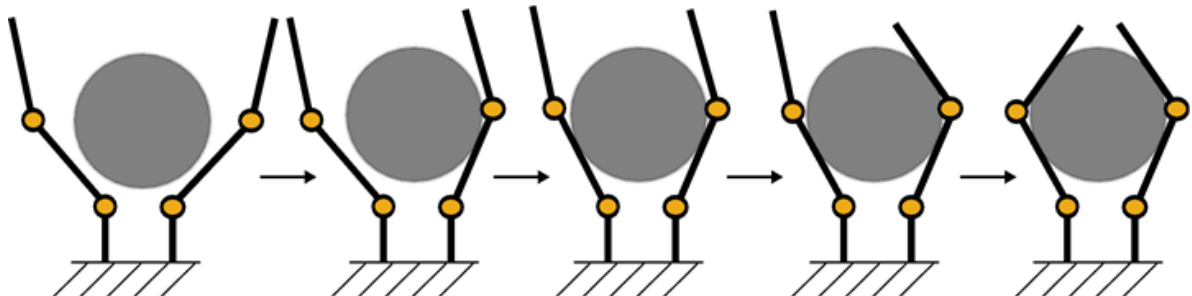


Figure 3: The adaptive grasping process exhibited by the OSU agricultural robotics hand. Each finger link passively adjusts to the contact of the ball to form a tight, secure grasp [8].

APPLYING ADAPTIVE ENGINEERING MECHANISMS TO TENDON TRANSFER SURGERIES

Applying the concepts of under-actuated robotic hands to tendon transfer surgeries, this paper proposes to rectify the constraints of current multiple tendon tendon-transfer procedures (Figure 4) by using adaptive coupling mechanisms to interface between the donor muscle and

the recipient tendons. The proposed tendon-transfer surgical procedure for high median-ulnar nerve palsy will use a hierarchical seesaw mechanism to interface between the ECRL muscle and the FDP tendons (Figure 5) while retaining all other aspects of the Brand procedure. As the ECRL muscle contracts, the entire seesaw mechanism will translate. But as each finger makes contact, each seesaw mechanism will rotate to allow continued flexion of the other fingers.

This paper hypothesizes that adaptive coupling mechanisms, when utilized in tendon transfer surgeries, will 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, while still being actuated by a single donor muscle.

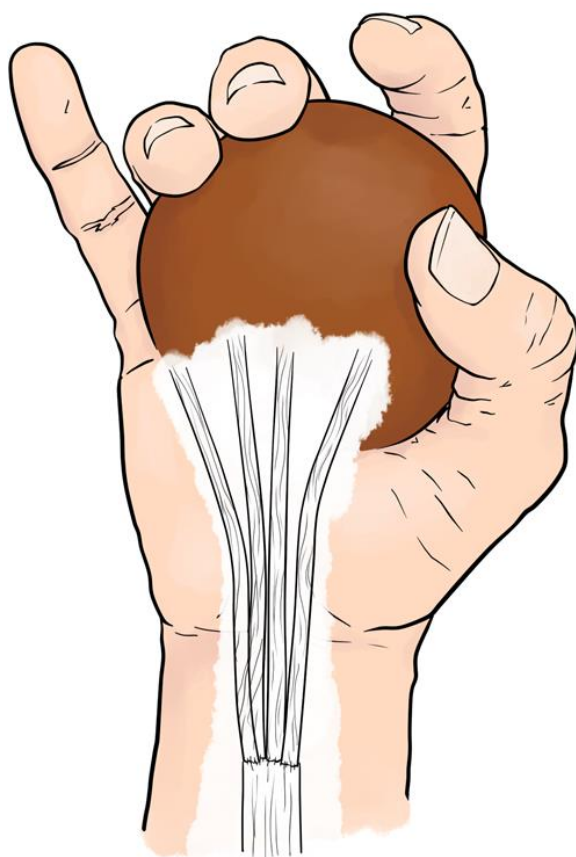


Figure 4: Schematic representation of the conventional modified Brand tendon transfer procedure and associated non-normative grasp.

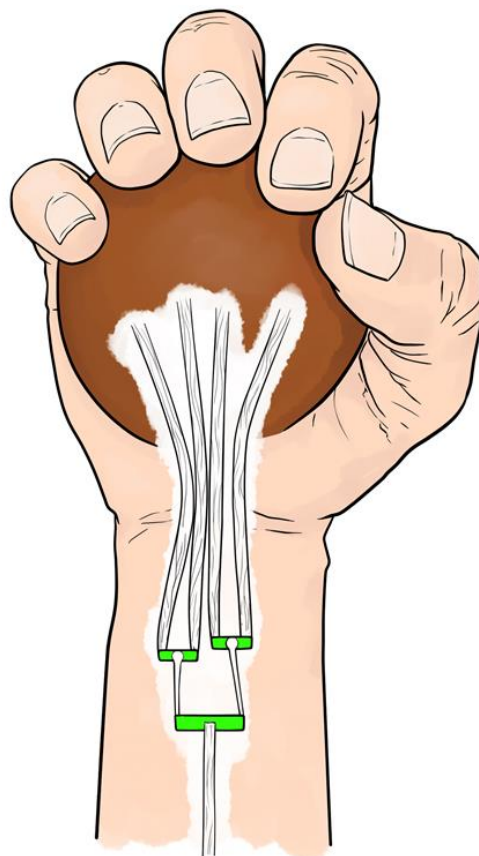


Figure 5: Schematic representation of the proposed alteration to the modified Brand tendon transfer procedure with inserted seesaw mechanism and associated improved grasp.

METHODS

MODEL CREATION

A biomechanical simulation of the forearm and hand was built in OpenSim, an open-source biomechanics software platform [12]. The Stanford VA Upper Extremity Model [13], 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] [14] [15] [16] [17]. 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 6a), 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 adaptive coupling mechanism (Figure 6b), 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.

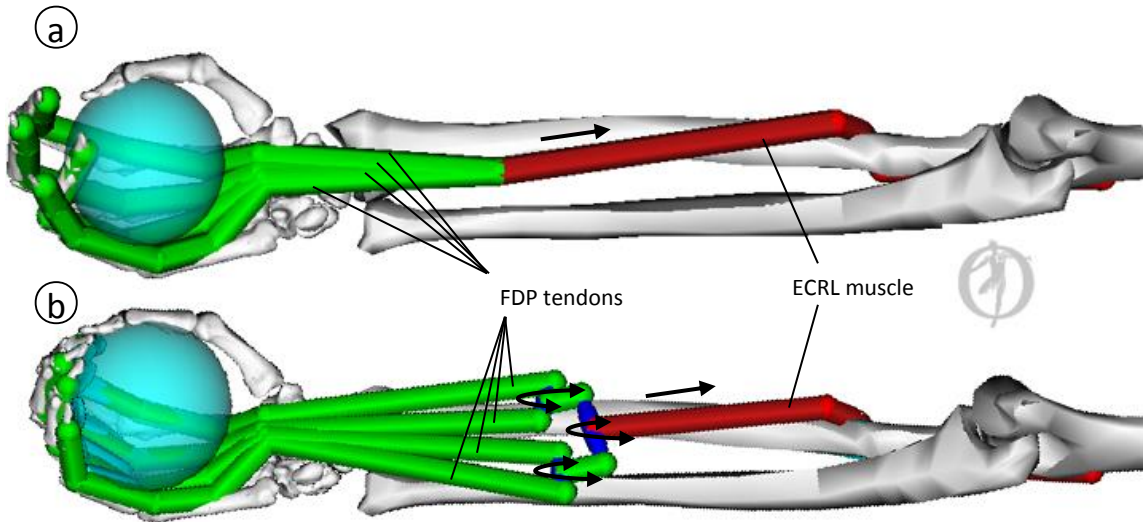


Figure 6: Graphic representations of the Opensim models utilized in this paper: a) the conventional procedure model; b) the proposed modified procedure model. Arrows indicate freedom of movement.

GRASP SIMULATION

CONTACT FORCE MODELING

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 distal phalanges to model the contact between the ball and the fingertips. Contact was only considered for the fingertips for model simplicity. Contact parameters were defined using the Hunt-Crossley model [12], with a large stiffness constant k (1500000), small dissipation constant (0.1), and a high Coulumbic friction coefficient ($\mu=100$).

FORWARD DYNAMICS SIMULATION

The forward dynamics simulation in Opensim uses an excitation profile for the muscles, initial state, weight and inertial properties, and defined force set of the model to determine the movement of the model over a period of time.

A forward dynamics simulation of a ball grasp was run using each model, driven by an excitation profile supplied to the ECRL (Figure 7). A period of minimal muscle activation was utilized before flexion began, in order to ensure model equilibrium before beginning movement.

The Force Reporter analysis in Opensim was enabled for each simulation.

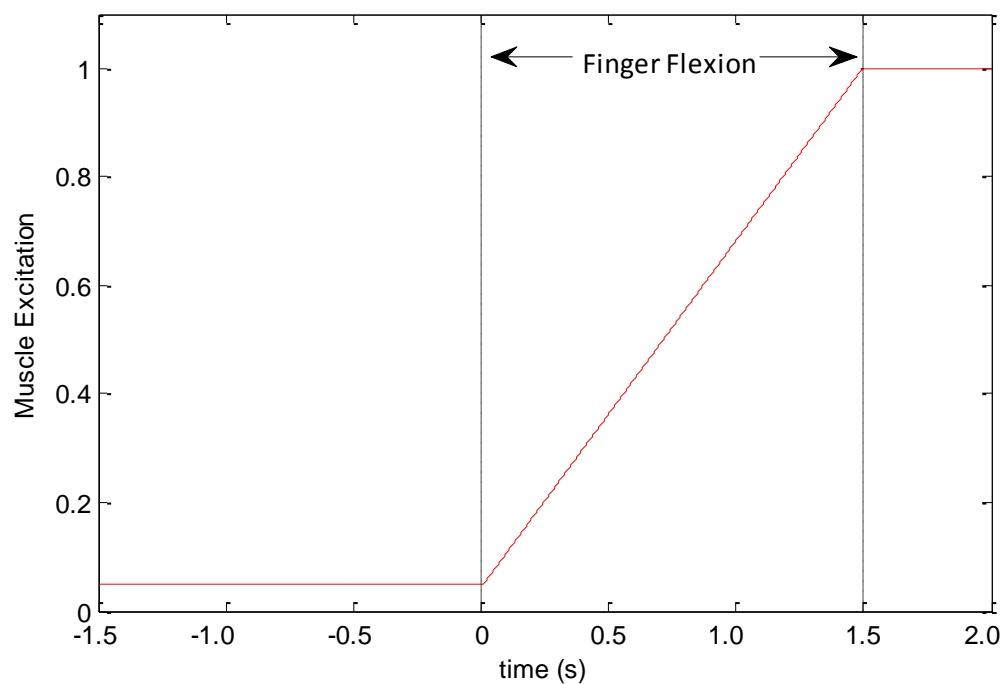


Figure 7: Excitation profile supplied to the ECRL during the forward dynamics simulations. An excitation value of 1.0 is 100% muscle excitation while a value of 0.05 is considered 0% muscle activation for the purposes of this study.

EXPERIMENTAL VARIATION

To allow for a more thorough analysis of the results between models and to simulate the natural variation of human hands, several different variations of the base model were created and tested. In the first set, the tendons of each finger were varied by $\pm 5\%$ to simulate surgeon error during surgery. In the second variation set, the moment arms of the fingers were varied by altering the position of the MCP joint in the Y direction by $\pm 5\%$. To keep the total length of the finger constant in the second set, the DIP joint positions were increased or decreased by the appropriate amount. The PIP joint positions were kept constant in relation to the MCP joint positions.

ANALYSIS

FLEXION

The flexion angles of the MCP and PIP joints at each time step were measured through the states degrees OpenSim output file. The sum of the MCP and PIP joint flexion angles for each individual finger (total finger flexion) was used to compare the flexion performance of each finger in the model. The sum of the total finger flexion for all four fingers in the model (total combined finger flexion) was taken to compare across model variation.

CONTACT FORCES

Contact forces in the XYZ directions for each individual contact sphere were extracted from the Opensim Force Reporter output file. The total force as well as the direction of that force was

analyzed. In an ideal grasp, the four fingers direct force on an object towards the thumb and the thumb balances that force. Grasps were judged both on the maximum force strength exerted and the directional control of that force.

RESULTS

FLEXION

The modified procedure model enabled all the fingers to travel through larger angles and close in on the object independently (Figure 8) [18]. In contrast, finger movement after the conventional 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 makes contact at 0.9 seconds. In the proposed procedure, the index finger struck first at 0.8 seconds. Then the seesaw mechanism swung to allow contact of the little finger at 1.0 seconds, the middle finger at 1.3 seconds, and finally the ring finger at 1.5 seconds.

The introduction of variation into the model also revealed the superior adaptability of the modified model (Figure 9) [19]. When surgical error was introduced into the system, the modified model demonstrated passive adjustment to these new conditions with minimal overall effect on finger flexion.

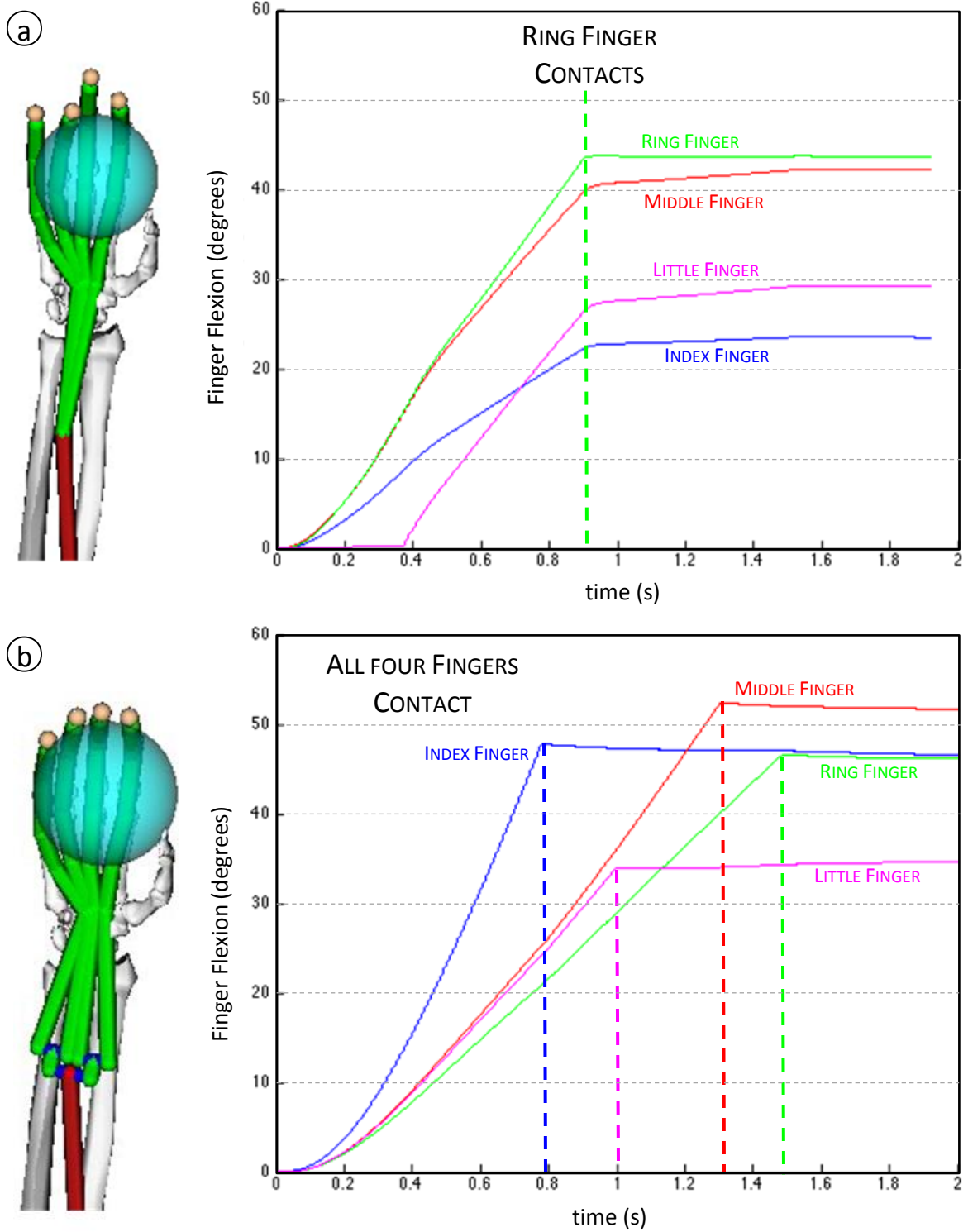


Figure 8: Simulation results of finger flexion over time for a) the conventional model and b) the modified model with inserted seesaw mechanism [18].

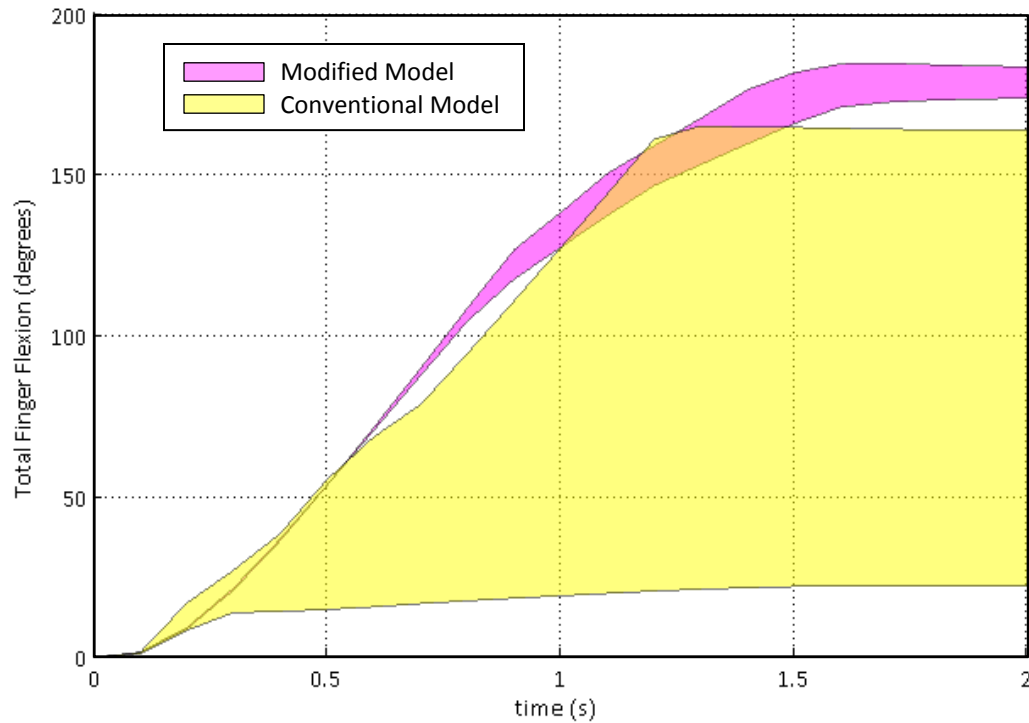


Figure 9: The range of total flexion angle of all fingers when variation was introduced between the modified and conventional models. The modified procedure model demonstrated a high adaptability to variation and retained its superior performance over the conventional model when error was introduced into tendon length and moment arm length [19].

GRASP FORCE

TOTAL CONTACT FORCE

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 (Figure 10). 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.

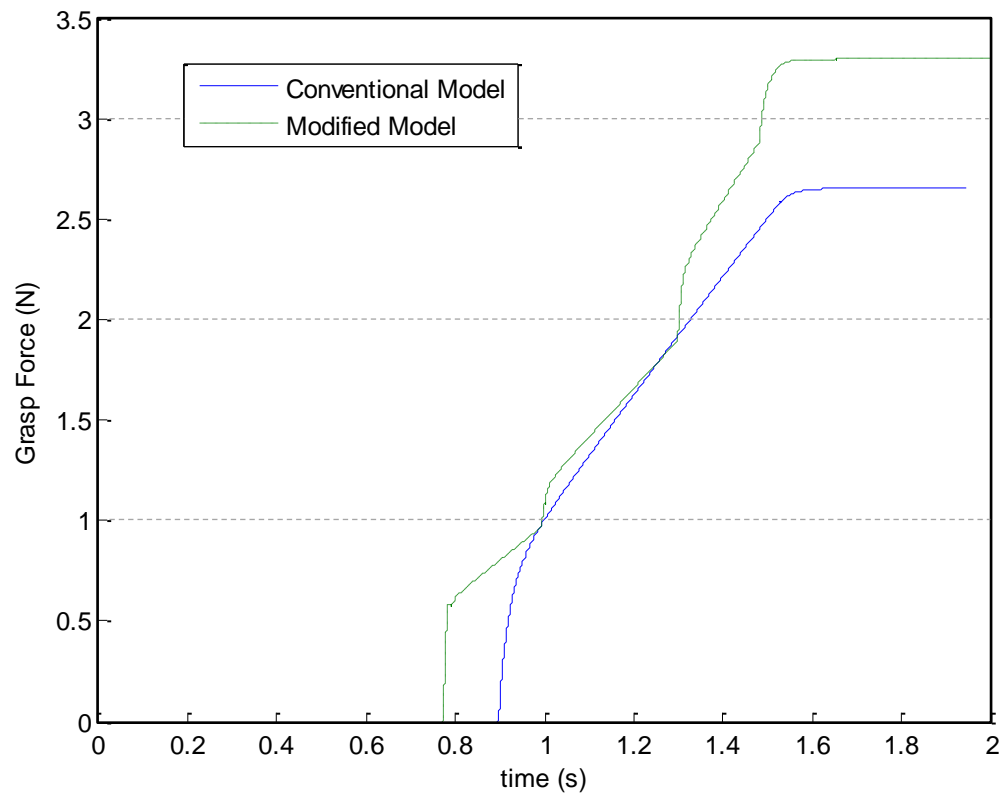


Figure 10: The total grasping force exerted on the object by the fingers in the modified model is greater than that of the conventional model.

GRASP FORCE DIRECTION

Since only a single finger makes contact in the conventional model, the overall direction of force was entirely dependent upon which fingertip made contact first. This resulted in extremely poor force direction control in the conventional model (Figure 11a).

The modified model, with four points of contact, had much better overall control of force direction (Figure 11b). Force was generally directed towards the thumb, but changed exact direction with each additional contact point (Figure 11c).

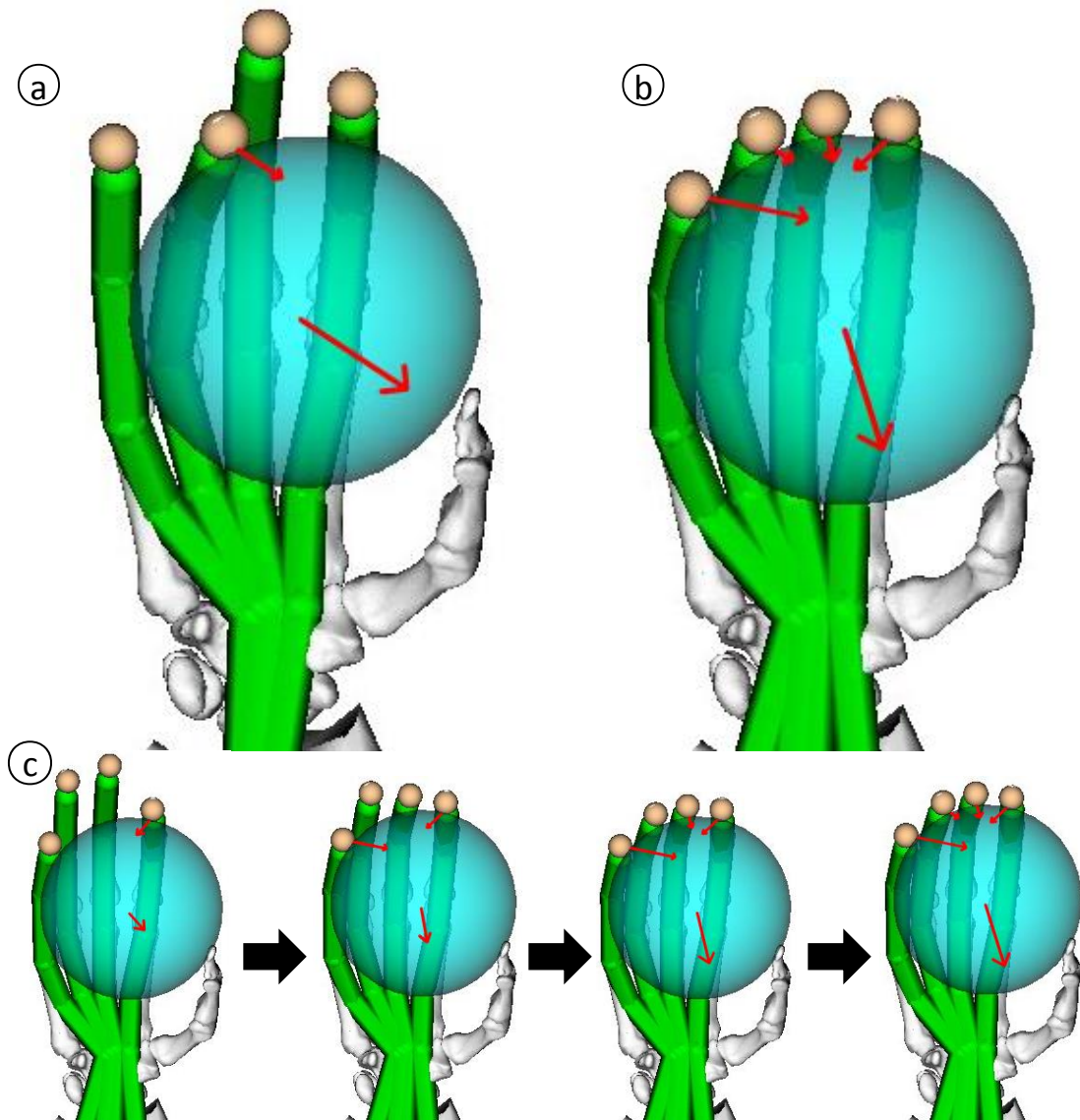


Figure 11: Final grasp force direction plots of the a) conventional model and b) modified model, as well as c) the force direction change with increasing finger contacts in the modified model.

CONCLUSIONS

The simulations showed that hand function after the proposed tendon transfer procedure using an adaptive coupling mechanism performed better than the conventional procedure in terms of independent and greater finger movement as well as force production. Most importantly, hand function after the proposed procedure more closely fit ideal surgical outcomes related to grasping capability 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.

In conclusion, our modified tendon transfer procedure allows the fingers to adapt to object shape, accounts for surgical error, allows a better grasping force and direction of that force, all while retaining the benefits of the conventional procedure.

FUTURE WORK

Future work will focus on cadaver studies and refinement of the biomechanical model.

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