Implanted Miniature Engineering Mechanisms in Tendon-Transfer Surgery Improve Robustness of Post-Surgery Hand Function

Ravi Balasubramanian*, J. Montgomery*, K. L. Mardula*, and C. H. Allan+
Oregon State University and University of Washington+*
ravi.balasubramanian@oregonstate.edu

INTRODUCTION

Upper-extremity tendon transfer surgeries have been routinely performed since the 1970s for conditions such as stroke, paralysis, spinal muscle atrophy, nerve or muscle trauma, and congenital disorders. The surgery involves re-routing one or more tendons from an non-functioning muscle and directly suturing it to a functioning donor muscle in order to partially restore hand function [3, 4].

However, a fundamental aspect of tendon-transfer surgery has gone unaddressed. Oftentimes, a single donor muscle is directly sutured to multiple recipient tendons in order to actuate multiple joints. For example, take the case of tendon-transfer surgery for high median-ulnar palsy, a severe condition that disables the flexor digitorum profundus (FDP) muscle bellies and results in an inability to fully close the fingers, leading to weak grasps.

In order to restore finger flexion capability, the current surgical procedure is to directly suture the FDP tendons of all four fingers to a functioning donor muscle, such as the extensor carpi radialis longus (ECRL) (see Figs. 1a and 1b). While the direct suture is a simple method of attachment, it results in directly coupling the movement of the distal joints of all four fingers. As a result, the direct suture method prevents the fingers from adapting independently during physical interaction tasks such as grasping an object, fundamentally impeding post-surgery hand function. Specifically, when the hand closes in on an object during the grasping process, if one finger makes contact and stops, all the other fingers will stop before making contact since the motion of all the fingers is coupled (see Fig. 1b). Thus, the direct-suture attachment method results in poor multi-finger power/enveloping grasping ability and may require the patient to use unnatural wrist and arm movements to complete the grasp. This is a significant issue since the ability to perform power grasps is fundamental to the activities of daily living, such as when holding objects to feed oneself [2].

In order to address this fundamental issue in tendon-transfer surgery, our group is exploring the use of implanted passive miniature *differential* mechanisms[1] called "adaptive coupling mechanisms" to attach the donor muscle to the recipient tendons (see Figs. 1c, 1d, and 1e). Inspired by the application of these adaptive coupling mechanisms in underactuated robotic hands [1], the key idea is that these adaptive coupling mechanisms, such as a hierarchical pulley system or seesaw mechanism, will enable each digit to continue to travel even if another digit actuated by the same donor muscle is stopped when it makes contact with an external object, thanks to the rotation of the pulleys or the seesaw mechanisms. Initial cadaver experiments and simulation studies we have conducted show that the implanted mechanisms enable the finger joints to adapt to the shape of the object during grasping and make complete contact [6, 7].

In this paper, we present results from a simulation study that show that the adaptive coupling mechanisms are able to accommodate for uncertainty that is typical in surgery and is typical in a grasping task. Specifically in the case of tendon transfer for high ulnar-median palsy, surgeons need to accurately choose the tendon lengths when attaching the donor muscle to the recipient tendons. If the tendon lengths are short by even 5% in the conventional procedure, some fingers would make contact prematurely during the grasping process, exacerbating the weak-grasp problem highlighted earlier. Also, since there is always uncertainty in each tendon's moment arm (or the mechanical advantage the tendon has over a joint) since it slides on top of the bone, any small variation in the moment arm would also result in premature closing after a conventional tendon-transfer surgery. Finally, there will always be some error when placing the hand relative to the object to be grasped. Small deviations from the object center would also result in incomplete or weak grasps after the conventional tendon-transfer procedure. For each of the three cases, we present results from simulation that show that the proposed procedure using adaptive coupling mechanisms is able to accommodate such uncertainties. To our knowledge, this is the first time that the robustness of post-surgery grasping capability has been studied for tendon-transfer surgery.

MATERIALS AND METHODS

An open-source biomechanics simulation platform OpenSim [5] was used to evaluate how the proposed modification to the high ulnar-median palsy tendon-transfer surgery improved the robustness of post-surgery hand function. The study focussed on the effect of replacing the FDP muscle with the ECRL muscle on the flexion of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints following the conventional and proposed tendon-transfer procedures.

The conventional four-tailed procedure was studied by adding a weightless body with full freedom of movement to the forearm to act as the interface between the ECRL muscle and the FDP tendons. The proposed procedure was studied by using a seesaw mechanism to attach the tendons to ECRL (see Fig. 1e). Three weightless bodies

[1] A common application of the differential mechanism is in the automobile transmission, where the mechanism enables all four wheels to be driven by the same drive shaft and still allow each wheel to rotate at differing speeds when accommodating a turn.

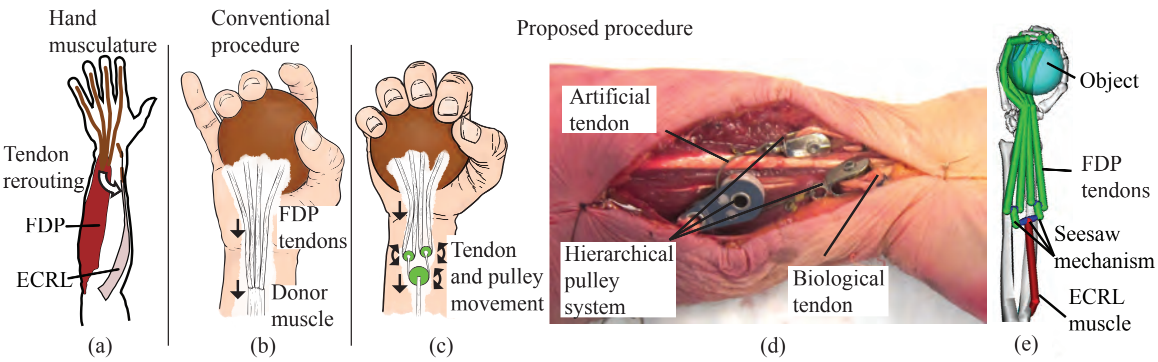

Fig. 1: (a) Schematic representation of the hand anatomy showing the muscles and the rerouting that occurs in tendon-transfer for high ulnar-median palsy. (b) Schematic representation of the conventional procedure. The fingers do not close in completely on the object because of coupled finger movement. (c) Schematic representation of the proposed procedure with the hierarchical pulley system. The fingers close in completely around the object due to adaptive movement enabled by the pulley system (Subfigures (a), (b), and (c) are reproduced from [6]). (d) A hierarchical pulley system constructed with off-the-shelf components and implanted in a cadaver forearm. (e) An OpenSim biomechanical model of the proposed procedure using seesaw mechanisms.

were added to the forearm; one was given full freedom of movement, while the others were attached to the first body and allowed free rotation about the Z axis. The ECRL was attached to the first bodys center, and the four FDP tendons were attached to the sides of the other two bodies.

A large sphere was placed near the hand center to simulate the grasping of a ball. Soft spheres were added to the fingertips to model the compliant contact between the ball and the fingertips using the Hunt-Crossley model. A forward dynamics simulation of a ball grasp was run using each model, providing a two-second linear ramp-and-hold excitation profile to the ECRL. The joint angles of each digit were measured.

Three tests were conducted in order to measure the grasping robustness of the post-surgery hand to the uncertainty in the surgical process (in both the conventional and proposed procedure) and in the grasping task: 1) The tendons that inserted into the four fingers were shortened by 5%; 2) The moment arms of each of the tendons were varied by 5%; 3) The objects position was varied by 2 cm in three random directions. The goal was to see how these variations affected the total flexion of the MCP and PIP joints in a grasping task and observe if the hand was able to still make full contact with the target object.

RESULTS

Fig. 2 shows that after the proposed procedure there is little variation in the total flexion even if the tendon lengths are short or if there is moment arm variation. In contrast, there is large variation in the total flexion after the conventional procedure for the same conditions. While not shown in Fig. 2, it was noticed that even with variation in the object's relative position with respect to the hand and variation in moment arms and the tendon lengths, the fingers made full contact with the object after the proposed procedure. In contrast, after the conventional procedure, only one finger made contact for the same conditions, resulting in incomplete grasps.

DISCUSSION

The results indicate that the conventional procedure is highly sensitive to uncertainty in the surgical process and

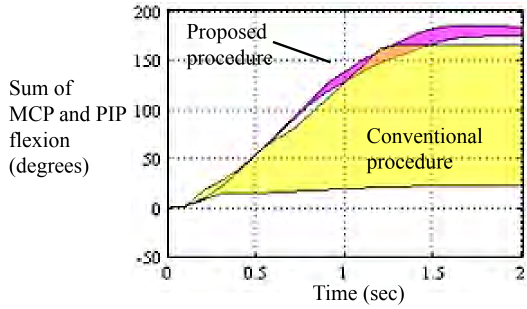

Fig. 2: Variation in total flexion angle at the MCP and PIP joints of all four fingers measured during a grasping process.

uncertainty in grasping tasks. In each simulation, it was noticed that a hand that underwent the conventional procedure was unable to create full multifinger power grasps, an important aspect of daily living. In contrast, the proposed procedure enabled the fingers to accommodate the uncertainty in tendon lengths, moment arms, and object location and create secure multifinger grasps. The finger forces during the grasping process is being investigated.

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