Thumb Assistance Via Active and Passive Exotendons in a Robotic Hand Orthosis for Stroke

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Abstract—We present a tendon-driven, active-extension thumb exoskeleton adding opposition/reposition capabilities to a robotic hand orthosis designed for individuals with chronic upper-limb hemiparesis after stroke. The orthosis uses two actuators to assist hand-opening, with one tendon network controlling simultaneous four-finger extension and one separately driving thumb extension. When combined with a passive palmar abduction constraint, the thumb network can counteract spasticity and provide stable thumb opposition for manipulating objects in a range of sizes. We performed a preliminary assessment with five chronic stroke survivors presenting with arm-hand motor deficits and increased muscle tone (spasticity). Experiments consisted of unimanual resistive-pull tasks and bimanual twisting tasks with simulated real-world objects; these explored the effects of thumb assistance on grasp stability and functional range of motion. We specifically compare functional performance of actuation against static thumb-splinting and against no device. The addition of active-extension to the thumb improves positioning ability when reaching for objects, and improves consistency and duration of maintaining stable grasps.

I. INTRODUCTION

Hand impairment due to loss of volitional control of the digits is a common contributor to chronic disability following a stroke [1]. Inability to achieve finger and thumb extension is strongly associated with severity of motor impairment, but is the slowest and least likely movement to recover even following targeted rehabilitation techniques [2]. Recent developments in wearable robotics to assist hand-opening show promise in providing functional support for activities of daily living (ADLs) and encouraging use of the impaired limb outside the clinic [3], [4], [5]; we have established that such support can be accomplished using lightweight, underactuated designs [6], [7], [8]. But the vast majority of robotic orthoses, including our previous work, focus on finger actuation while splinting the thumb in a position of general opposition. Devices that actively assist thumb motion have typically actuated a subset of degrees of freedom contributing to overall opposition/reposition [9], [10], [11], [12], [13], but these devices do not consider whether their methods add value to functional manipulation beyond that provided by a passive thumb splint [14].

Thumb placement, and its effects on hand configuration, plays a vital role in how humans interact with the environment around them [15]. Intuitively, expanding the thumb’s active range of motion (AROM) generally increases the hand’s ability to open and grasp a greater range of object sizes. However, involuntary synergies and spasticity after stroke often cause asymmetric, abnormal motor coupling between fingers and thumb such that overall hand aperture can decrease with applied extension to a digit [16]; we have informally observed such thumb-flexion reflexes in multiple subjects. Robotic interventions intended to support ADLs for a stroke population must overcome additional challenges to maintain grasp stability against external and stroke-derived perturbations in order to perform better than baseline compensatory techniques.

In this study, we assist thumb motion using two tendons: one active and one passive. We build on our previous work leveraging the stereotypical asymmetry of stroke impairment to reduce device complexity by strictly assisting extension while using body-powered movements for flexion. Our two-tendon routing uniquely affords per-user, per-session customization to accommodate variance in spasticity. The active thumb tendon both physically moves the thumb into a wider grasp and helps to counteract stroke-synergistic flexion about the metacarpophalangeal (MP) and interphalangeal (IP) joints, and helps to resist spastic adduction about the carpometacarpal (CMC) joint. We add an adjustable passive tendon to set thumb abduction position and to provide support about the MP and CMC; the combined tendon network enables active opposition/reposition motions without

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requiring precise alignment of joint centers. Finally, we compare functional efficacy of this actuation approach against a statically-splinted thumb and against no device.

To our knowledge, we are the first to introduce a thumb actuation method that provides beneficial effects to both grasp AROM and stability when compared to static splinting, doing so with a single actuator. Indeed, no existing robotic hand orthosis has presented a concurrent, comparative assessment of its actuation method against a passive version on an impaired population. We are also the first exoskeleton study to demonstrate a quantitative link between assisting thumb AROM and functional improvement in grasping ability within an impaired population, where we show that thumb actuation increases ability for stroke subjects to generate and maintain grasp forces for a range of object sizes. Here, we show what the rehabilitative community has long intuited—that stroke-impaired thumb opposition benefits from stabilization about a combination of axes, and that increased ability to position the thumb also increases ability to keep objects in the hand to complete more prolonged tasks.

II. MECHANICAL DESIGN

The thumb mechanism presented here is used in conjunction with an existing hand orthosis, shown together in Fig. 1, because our interest in studying effects of thumb assistance on hand function cannot be performed without also assisting the other digits. Design of the hand orthosis was previously described in detail in our previous work [6], [7], [8], but we include below a brief description of its most relevant aspects for ease of reference. We expand on our work with tendon-driven systems to develop an actuation system for the thumb, shown in Fig. 2 that enables motion while stabilizing against individualized presentations of motor coupling and spasticity.

A. Exotendon-driven Hand Orthosis

The hand orthosis is a modular device that supports interchangeable mounting of individually-customized 3D-printed hand components to an aluminum splint that fixes the wrist at a neutral angle. Velcro straps around the hand and arm secure and locate the device. The forearm splint houses an actuated winch mechanism that connects to an exotendon network routed through cable guides at the MP knuckles and anchored to 3D-printed fingertip components. Motorized retraction of the exotendons transmits finger-extension torques to the IP and MP joints, opening the hand.

The design of the knuckle-mounted cable guides and fingertip components preferentially transmits extension torques about the proximal IP joint while minimizing hyperextension about the MP. Dimensions of the fingertip components are specific to the individual finger lengths of each subject; these components splint the distal IP joint and are secured to the fingers with Velcro straps. Foam padding and non-slip fabric straps enable these components to be tightly secured to the fingers while minimizing discomfort and migration.

Subjects press a button to switch between “open” and “closed” position setpoints, which are calibrated for each individual. Hand-actuator extension or retraction takes approximately 1.8 seconds, and the thumb actuator engages after a 1–3 second delay based on spasticity level or user preference. Actuation uses integrated encoders for closed-loop PID motor control. For this prototype, motor drivers and power supply are located external to the device.

B. Active-Extension, Passive-Abduction Thumb Module

Our proposed thumb mechanism uses one actuated tendon and one passive tendon that work together to stabilize the thumb in an opposition/reposition motion, as shown in Fig. 3. As with the fingertip components, the thumb component rigidly splints the distal joint to prevent hyperextension and features a raised outrigger feature to increase leverage; this scheme drives motion about the MP and CMC joints.

The actuated tendon is connected between the radial side of the forearm splint and the dorsal side of the thumb, crossing the splinted wrist, and is attached to a 3D-printed component splinting the IP joint. This tendon anchors to an outrigger feature on the dorsal side of the thumb splint, which enhances force transmission by increasing the moment arm about the MP joint. A linear actuator (Actuonix-PQ12-P) attaches to the rear of the forearm splint such that it is suspended at the radial side of the forearm, in-line with the thumb’s path of extension. The actuator provides 20mm
retraction when fully engaged—about 15° to 30° in extension depending on hand size.

The passive tendon is anchored to the ulnar side of the forearm splint, loosely located near the styloid process, and routes around the palmar side of the hand to secure the thumb’s proximal link with a fabric hammock. Specifically, this tendon holds the thumb in varying degrees of abduction; pure extension without an abduction constraint pulls the thumb away from optimal opposition, as shown in Fig. 4.

The combination of active extension and passive abduction defines the trajectory space of thumb opposition, as illustrated in Fig. 5. The degree of abduction constraint can be manually set by lengthening or shortening an adjustable grip-hitch knot securing the hammock to the abduction-tendon. Tension maintained between the two tendons throughout the thumb’s motion counteracts reflexive flexion and adduction of the thumb when the digits are extended by the device. Within this study, we chose one general abduction-tendon setting per subject that encourages index-thumb pinch grasps while still facilitating whole-hand power grasps.

III. Experiments

Of the numerous functional grasp patterns afforded by hand anatomy, most healthy human subjects rely on pinch and power grasps that use the thumb extensively; stroke survivors lacking thumb function instead often rake the four fingers against an object to drag it along a surface, or tuck the thumb away against the backs of the fingers in order to squeeze an object between fingers and palm [17]. Our orthosis, like any exoskeleton with rigid elements spanning the hand, limits the ability to perform compensatory grasps that avoid thumb involvement. Our objective in designing an assessment to test thumb assistance is two-fold: 1) observe any improvement in orthosis performance due to thumb actuation, but 2) determine whether stroke subjects gained functional improvement compared to not wearing a device at all.

Initial evaluation of the active thumb mechanism tested the users’ ability to maintain stable grasps against disturbances for a range of object sizes. Primary assessments included: 1) grasping and pulling a tethered object as hard as possible without letting the object slip out of the hand, and 2) stabilizing cylindrical objects while exerting twisting torques. We conducted experiments over the course of two 90-minute sessions both with and without exoskeleton assistance of the impaired arm, and both with thumb actuation and the thumb splinted in gross opposition. The order of assistive conditions, and of tasks within each condition, were randomized to minimize effects of practice or fatigue. We allowed patients a few minutes at the start of each session to familiarize themselves with the open/close button, and allowed one practice trial with the object before each task.

A. Participants

Five community-dwelling stroke survivors with chronic hemiparesis and limited upper-limb motor function volunteered to participate in the study. Eligible participants met the following inclusion criteria: (1) at least 18 years of age; (2) at least 6 months post-stroke; (3) muscle tone and spasticity scoring ≤ 2 on the Modified Ashworth Scale in digits, wrist, and elbow; (4) passive range of motion of digits and wrist within functional limits; (5) unable to extend fingers fully without assistance; (6) sufficient active flexion in digits, elbow, and shoulder to form a closed fist and lift the arm above table height; (7) intact cognition to provide informed consent and follow complex commands.

Subjects S1 and S2 had prior experience with early prototypes of the actuated-thumb exoskeleton, but not with the tasks described in this protocol. Each subject provided informed consent to participate in this study in accordance with the protocol approved by the Columbia University Medical Center Institutional Review Board. Participants were primarily recruited from a voluntary research registry of stroke survivors or referred from within NewYork-Presbyterian Hospital. All experiments were performed under supervision of an occupational therapist.

B. Unimanual Pull Task

We evaluated subjects’ ability to grasp an object, lift it clear from the table, then maintain the grasp while pulling as hard as possible against the object’s tether without letting
it slip out of the hand. The three 3D-printed objects were intended to be lightweight but in a range of sizes: a large cube (6cm side length), small cube (2.5cm side length), and thin rectangular prism (1.5cm width). The test apparatus consisted of the object tethered to a load cell (Futek LSB200-FSH00097, sampling rate 10Hz), which was clamped to the table. An in-series pulley and stiff extension-spring mounted between object and load cell allowed subjects to freely pull without imposing jerk or off-axis loads on the sensor. We allowed for any type of grasp in which 1) the object was lifted clear of the table and 2) neither tether nor cable tension were involved in keeping the object in the hand (i.e. “hook” grasps were disallowed). Invalid trials were repeated.

Subjects were instructed to pull the object as hard as they could without letting the object slip from the hand; each trial concluded when the object was dropped or after the subject maintained a constant arm position and accompanying tether tension for approximately five seconds. Participants repeated the task three times per object. Fig. 6A shows a subject performing the unimanual-pull test with the large cube.

C. Bimanual Twist

We evaluated subjects’ ability to “open” cylindrical objects using a bimanual palmar grasp-torque test. This experiment used three simulated real-world objects: a water bottle (6.5cm diameter), pill bottle (4cm diameter), and marker (1.5cm diameter). These objects were modified to attach to a digital torque meter (MXITA 0.3–30 Nm) along with a 3D-printed set of object-specific caps. Subjects were instructed to use the weaker hand to stabilize the object as if they were to open it, then have the stronger hand twist the cap as hard as possible to achieve a peak-torque measurement; the cap does not experience angular displacement with this apparatus. Participants were allowed to use their other arm to aid with object placement during the task, which was repeated three times per object. Fig. 6B shows a subject performing the bimanual-twist task with the water bottle.

IV. RESULTS

Detailed results for the unimanual-pull experiment are plotted separately for each subject, along with a summary of sustained forces across objects and subjects, in Fig. 7. Aggregate results across the five subjects for peak pulling force, along with time for object to slip after achieving peak force, are shown in Fig. 8. Aggregate peak torques for the bimanual-twist experiment, along with elapsed time before achieving a two-handed grasp to begin twisting, are shown in Figs. 9 and 10. For all figures, left-right organization is unassisted (blue), then assisted-finger/static-thumb (red), finally assisted-finger/active-thumb (yellow). Differences in medians were tested for significance using a one-sided Wilcoxon rank sum test, with hypothesis threshold of 0.1 to reflect small-sample size. All unmarked differences in the figures between actuated thumb and unassisted (i.e., no device) cases with non-zero active-thumb results were found to be significant with \( p < 0.1 \) except for subject S4 durations (all \( p = 1.0 \)); all differences between active- and static-thumb cases with non-zero active-thumb results are noted in the figures with the exception of pairs having \( p = 1.0 \) insignificance, which are left blank.

A. Unimanual-Pull Stability

Fig. 7 shows a detailed view of results for the unimanual-pull test. Specifically, Fig. 7 depicts median unimanual stabilization capability for subjects S1 through S5, respectively, for each of the three objects and three assistive conditions. Collective results for all subjects are plotted at the far right. The rows within the figure organize results into force and time components, depicting mean-averaged magnitudes and total durations for a sustained pull, which we define as the longest consecutive sequence of force readings above 1.0 N. The sustained-pull contains the peak force, but reflects a measure of how well the subject approached competing instructions to “pull as hard as possible” while “without letting the object slip.” Trials for which subjects were unable to grasp the object were marked as zero for force and duration. After video inspection of the set of trials in which the object never slipped, each was assigned the 10-second within-category average duration for comparative purposes.

Across grasp cases, active thumb assistance on average increased sustained-pull forces when compared to static thumb assistance by a factor of 1.4 and 1.2 for subjects S2 and S5, respectively, and increased pull duration by a factor of 3.7 and 1. Thumb actuation decreased force for subject S1 by a factor of 0.8 when compared to the static case, but increased duration by a factor of 1.1. When compared to no device, active thumb assistance enables subjects S1, S2, and S5 to more consistently grasp objects and pull on them harder.
for longer durations. Subject S3 was unable to consistently grasp and maintain the object in-hand to pull on the tether, achieving non-zero median force and duration only for the active-thumb, large-cube case. Subject S4 was able to retain a stable grip on nearly every object, only dropping the large cube once during a static-thumb trial, and is an outlier in achieving a factor of 1.5 higher non-assisted pull forces than those while wearing the exoskeleton. Median sustained-pull force across subjects and objects was 0 N with no device, 6.9 N for the static thumb, and 8.6 N for the active thumb with an active-static increase by a factor of 1.2 (not significant, $p = 0.4$). Median sustained-pull duration was 0 seconds for no device, 1.6 seconds for static thumb, and 3.2 seconds for active thumb with an active-static improvement by a factor of 2. Active-static duration difference in aggregate results neared significance with $p = 0.1$.

Fig. 7 shows aggregate results for peak forces and time-to-slip, across all subjects and objects, as a broader comparison between assistive conditions. Again, trials concluding without the object slipping were post hoc assigned 10-second durations. The difference in aggregate peak force between active-thumb and unassisted conditions was statistically significant with a 13.3 N increase (from 0 N) with $p < 6e-03$, and in aggregate time-to-slip with 1.6 seconds improvement (from 0 seconds) and $p < 2e-04$. Aggregate difference in active-static peak force was not statistically significant with $p = 0.34$, but was significant in time with a 1.0 second improvement (factor of 2.7) and $p < 4e-03$.

B. Bimanual Twist

Our method for collecting bimanual torque data records a single peak measurement per trial; therefore, we report only aggregated results across subjects and objects in Figs. 9 and 10. Specifically, Fig. 9 shows collective peak torques along with elapsed time to achieve a stable grasp, defined as time between when the subject initiates the task by picking up the object and when the subject deems the grasp stable enough to begin twisting the cap. Elapsed time measurements were determined through post hoc observations of video data; trials for which clear elapsed-time indications could not be determined were excluded from time results (6 unassisted, 4 static, 3 active trials excluded). For computational purposes, trials in which the subject could not achieve a torque measurement were assigned post hoc elapsed-time scores of 30 seconds. Because most subjects were unable to exert
torques on the marker in any grasp condition whereas subject S4 could apply similar torques with and without assistance, Fig. 10 shows results for water-bottle and pill-bottle only.

Active thumb assistance was not found to significantly affect torque generation when compared to either baseline or static conditions, but did reduce time to position the object in the hand to begin grasping. Across all grasp cases (marker included), the aggregate difference in elapsed-time was a 2.4 second improvement between unassisted and active-thumb (factor of 1.3) and a 3.4 second decrease from static to active-thumb (factor of 1.4). Excluding the marker yields an elapsed-time difference of 3.1 seconds between unassisted and active-thumb conditions (factor of 1.4), and yields a 1.2 second decrease from static to active-thumb (factor of 1.2).

V. DISCUSSION AND CONCLUSIONS

Our overall results find active-extension thumb assistance to improve consistency in generating and maintaining grasp forces for a range of object sizes. In particular, thumb actuation has a comparative advantage over passive splinting when precise positioning and pre-shaping of the hand is required for manipulation. When comparing between unimanual and bimanual performance, we see that thumb actuation has a much greater effect in reducing likelihood of dropping an object when the impaired hand must reach for it; when the hand simply needs to open and accept an object as part of a bimanual task, differences in force generation become negligible. We also confirm that assisted-opening of the hand can help with grasping larger objects without necessarily having to sacrifice performance for smaller objects.

A limitation of our study was that, because we do not assist finger flexion, our smallest objects could either be grasped in all cases or none depending on the individual. We also chose objects expecting the static condition to fail outside of a narrow range of sizes, which was not the case. Further exploration with a larger set of patients and objects is needed to enhance our understanding of functional thumb assistance.

In future work, we would like to further explore the temporal aspects of grasp stability. Our study challenged participants to exert high arm-flexor effort to pull and twist objects, triggering spastic motor synergies and increased muscle tone—a modified set of tasks that tracked how quickly the hand could release objects after successful task completion would complement our work on finger-thumb extension. We hope our work inspires others to also consider grasp-durations when conducting device evaluations; this would bring the field more in-line with the rehabilitative needs of this stroke population.

In this paper, we present a two-tendon actuation method to assist thumb opposition/reposition for a hand orthosis. We demonstrate functional efficacy of our exoskeleton in actively assisting thumb extension to improve grasp stability, for which we examined both the magnitude of disturbance forces resisted to keep an object from slipping and the amount of time the user was able to maintain adequate contact forces. We uniquely evaluated our actuation approach not only against a baseline condition with no device assistance, but also against a device configuration that provides passive assistance. Our experiments considered both a unimanual use case, in which a user must position the orthosis in an adequate pose for grasping, and a bimanual use case, in which the other hand may help with positioning but the user must determine whether a grip is stable or not. We performed these evaluations with stroke survivors having spasticity and limited hand function in order to study real-life applicability.

Finally, we continue working towards our main goal: developing a wearable orthosis that can assist stroke survivors in everyday activities outside of a structured research environment. Numerous challenges must still be overcome to realize this vision, both in effectiveness (improved function over a wider range of metrics) and usability (more intuitive and streamlined design). We believe that further research on wearable robots, when conducted in partnership with stroke survivors, can help with grasping larger objects without necessarily having to sacrifice performance for smaller objects.

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