Design of Spiral-Cable Forearm Exoskeleton to Provide Supination Adjustment for Hemiparetic Stroke Subjects

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Abstract—We present the development of a cable-based passive forearm exoskeleton, designed to assist supination for hemiparetic stroke survivors, that uniquely provides torque sufficient for counteracting spasticity within a below-elbow apparatus. The underactuated mechanism consists of a spiral single-tendon routing embedded in a rigid forearm brace and terminated at the hand and upper-forearm. A spool with an internal releasable-ratchet mechanism allows the user to manually retract the tendon and rotate the hand to counteract involuntary pronation synergies due to stroke. We performed device characterization with two healthy subjects, and conducted a feasibility test of the forearm mechanism in maintaining a neutral hand position with a single chronic stroke subject having no voluntary supination capacity. Our preliminary assessment on an impaired subject suggests comparative performance in supination assistance between our implementation and a commercial passive splint, and shows promise in improving capabilities of existing robotic exoskeletons for stroke.

I. INTRODUCTION

Wearable assistive devices have established themselves as promising tools for supplementing an impaired hand’s function and encouraging its use in everyday life [1]. But many bimanual, day-to-day tasks for which stroke survivors would elect to use their impaired hand require maintaining a neutral hand position to grasp vertically-oriented objects. In previous work with wearable robotic exoskeletons for hemiparetic stroke subjects [2], [3], [4], we observed that many subjects would attempt to grasp cups or bottles from a pronated hand position and had difficulty supinating the forearm enough to reliably grasp and use these objects. Flexor synergies from squeezing objects in the hand or lifting the arm further exacerbated unwanted pronation. We further noted from patient feedback that, because the impaired limb fatigues easily from weakness due to stroke and lack of regular use, our existing orthosis was already near tolerable limits for weight and bulk. Although this patient population stands to benefit from both assisted hand-opening and assisted forearm rotation, few if any existing devices accommodate the constraints of their impairment. These patient-driven observations motivated the development of a lightweight exoskeleton specifically designed to assist supination that featured a small footprint feasible for integration in existing below-elbow exoskeletons.

Although there exist many instrumented benchtop devices [5], [6], [7] and workstation-mounted exoskeletons [8], [9], [10] designed to provide rehabilitative therapy in supination, few devices exist that provide rotational assistance in a fully-wearable form. SpringWear, developed by Chen and Lum [11], uses an open C-shaped forearm cuff mounted to a shoulder-anchored linkage crossing the elbow. Gasser et al. [12], implemented forearm rotation adjustment with a lockable ball-detent mechanism as part of a rigid elbow-joint module within a hand-arm orthosis. Myomo’s MyoPro Motion G is a commercial device that combines these concepts by using a ball-detent system within a C-shaped cuff at the wrist [13]. But these all require precise positioning about several joints; in particular, obstruction of shoulder and elbow movement for many stroke survivors encourages maladaptive compensation from the trunk to perform reaching movements and manage hand pose [14]. Elastic spiral-supinator bands exist on the market that anchor around the bicep and thumb to provide constant passive resistance against pronation, with minimal constraint to elbow flexion, but these cannot be adjusted when worn underneath a hand orthosis. Soft-actuator versions of this concept [15], including one contained within a below-elbow sleeve [16], use spiral inflatable bladders encompassing the entire surface of the forearm that similarly make integration difficult.

This work was supported in part by the National Institute of Neurological Disorders and Stroke under grant R01NS115652

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This article describes the design of a forearm exoskeleton and embedded spiral cable route that converts torque about a hand-turned dial to supination torque about the forearm, enabling adjustment of forearm rotation angle. The dial incorporates a ratcheting mechanism to lock the device at the desired position; tension in the cable counteracts spasticity and stroke-imposed flexor synergies. Our device is specifically intended for individuals with unidirectional deficit in supination; thus, we focus on providing unidirectional assistance and use a release mechanism to enable unrestricted, body-powered pronation.

To our knowledge, we are the first to present a physical wearable device featuring a cable-based mechanism for adjusting forearm rotation. This implementation is uniquely able to leave the elbow unencumbered, instead using differential rotation along the length of the forearm to apply supination torque. Our device is able to provide repositioning from pronated to near-neutral hand position in an easily adjustable, unobtrusive package that can be integrated in a robotic hand orthosis. We characterize device angle and force–torque metrics with benchtop and self-driven testing, then conduct a preliminary feasibility test of the device’s potential to assist maintenance of a neutral arm position in a case study with one chronic stroke subject lacking volitional supination ability.

II. SUPINATION FOREARM MECHANISM

The robotic hand exoskeleton shown in Fig. 1 consists of two independent, integrated mechanisms mounted to a rigid, aluminum forearm splint: a two-actuator finger-thumb extension device connected to 3D-printed components strapped to the distal links of the digits, and a manually-adjustable supination device strapped around the hand and forearm (shown alone in Fig. 1, Top). Design of the digit extension device used in this study was previously described in [2], [3], [4] whereas the supination exoskeleton has not been previously described. For our hemiparetic population of interest, lack of supination function is usually accompanied by hand impairment; thus, our supination exoskeleton assumes usage in conjunction with passive or robotic hand orthoses that typically feature straps encircling the forearm but confine equipment to the dorsal side.

A. Spiral-cable Actuation Principle

Our design is inspired by the supinator (supinator brevis) muscle, which occupies the posterior compartment of the forearm and curves around the upper third of the radius to connect to the ulna. Muscle contraction rotates the radius laterally, turning the arm about its longitudinal axis. The exoskeleton likewise rotates the wrist in supination by contracting a cable wrapped around the forearm, shown in Fig. 2 and anchored at the hand and at the posterior area of the forearm. This design relies on the hand-wrist component of the exoskeleton having sufficient rotation relative to the proximal region of the forearm.

Because the wrist is rigidly splinted, the hand-arm system acts similarly to a cantilever beam in torsion. When the arm is subjected to an axial moment, each cross-section twists about its torsional center. The angle of twist decays as axial distance from the applied torque increases, as illustrated in Fig. 3. We maximize effective distance by placing the cable’s distal termination point at the base of the index finger, taking advantage of integration with the hand orthosis apparatus to extend past the wrist and connect to an existing 3D-printed structure bolted to the splint.

Any external twist will impose substantial shear and warping stresses at the surface of a torsional beam. To prevent potential discomfort or torque losses from cable constriction, the exoskeletal housing for the cable must be sufficiently rigid in compression to prevent transmitting undesired pressures to the soft tissue. Additionally, the exoskeleton must prevent collapse of the spiral routing when tension is applied to the cable. We accomplish these criteria by routing the cable through a sheath embedded within a rigid thermoplastic brace.

The supination exotendon’s proximal termination point is mounted to a mechanism strapped to the bulk soft tissue of the forearm, which is a compliant structure that will deform with cable contraction. We note that our design requirement for sufficient relative rotation between hand and forearm can accommodate twisting losses due to soft tissue deformation so long as the proximal anchor does not slip against the skin.
B. Forearm Brace Design

Practical considerations for the design of an exoskeleton to house a cable tightly wrapped around the arm include preventing the cable from constricting around soft tissue, mitigating risk of the cable chafing against skin, and aiding ease of donning/doffing while transmitting sufficient torques.

The proposed solution is a two-part brace (Fig. 4, Top), for which one part is a mid-forearm open-C brace secured with fabric straps shared with the hand-opening orthosis and the other part is an armband strapped around the proximal forearm. The supination cable exits a spool mounted dorsally on the armband, is guided circumferentially along the forearm over a plastic skid plate, then crosses an elevated gap above the forearm to enter the spiral teflon sheath embedded within the distal brace. Both components of the supination brace are made from self-bonding thermoplastic (Rolyan 1/8” Polyform) molded to match the shape of the forearm.

Soft high-density foam padding (Rolyan-16271) is positioned in the interior of the brace and underneath the armband’s skid plate to elevate the exoskeleton where the cable crosses the open gap between components, mitigating risk of the plastic plates pinching against the skin when the cable is retracted. A fabric pad attached around the cable at this gap serves to further minimize risk of skin pinching or chafing, although during normal usage the cable does not contact the skin even at full retraction. We also use foam padding to cushion the bony prominences at the wrist, so that we can more tightly secure the brace around the arm.

We remove much of the material at the underside of the brace, creating an H-shaped structure with wings for attaching straps and with a reinforced-thickness strip surrounding the tendon route at the center. In addition to minimizing mass and improving ventilation, the open space confers some flexibility to the brace that allows it to better conform to the shape of the arm. Altogether, the entire supination exoskeleton has a mass of 161.1 g, for a total mass of 445.7 g when integrated with the hand-opening orthosis.

The fabric strap securing the armband to the forearm includes a layer of high-friction Dycem fabric sewn on the underside, such that the device moves with the skin instead of slipping. The armband is positioned on the user at the posterior compartment immediately below the elbow, but exact positioning is not required for function of the device.

C. Locking Winch Design

The cable retraction assembly, shown in Fig. 5, consists of a captive spool with a 3D-printed internal releasable ratchet mechanism. Twisting a dial located at the top of the device directly turns the spool to wind the cable and rotate the arm (Fig. 6). The user can release the cable by pressing a button at the center of the dial to disengage the ratchet mechanism, allowing the wrist to freely rotate in pronation.

Asymmetric gear teeth at the inner diameter of the spool engage against a pawl to prevent backward rotation and force one-way progress capture of cable retraction. The tooth profile uses a gentler slope than with traditional ratchet geometries in order to allow the release button to displace the pawl, which is preloaded against the spool with a torsional spring.

III. DEVICE CHARACTERIZATION AND FEASIBILITY TESTING

We conducted a series of experiments to characterize how our device withstands applied forces from the cable transmission and its ability to assist a user in keeping the hand in a neutral orientation, starting with load testing of the winch assembly and culminating in a set of proof-of-concept tests with one stroke subject having no volitional supination. Finally, we guided the stroke subject through a preliminary functional grasping exercise to check that the device can assist arm rotation without interfering with the hand-opening function of the integrated orthosis.
A. Benchtop Mechanical Tests

We first characterized the ratcheting winch assembly in isolation to obtain the relationship between dial operation and cable contraction. We fixed the mechanism in a vise to measure ratchet backlash, dial repeatability, and compression forces required for button release. Then, we conducted tensile testing to determine ultimate strength of the mechanism.

Under minimal load (just enough to remove cable slack), we advanced the ratchet by one click and marked the cable, then pulled on the cable and measured the resulting displacement before the pawl jammed against the next gear tooth (n = 10). Mean cable backlash was (5.34 ± 1.14) mm. We then measured cable retraction per dial rotation for the full extent of the cable length, then released the cable and repeated the process once (n = 2, 17 total rotations). Mean retraction length was (110.34 ± 6.62) mm per dial rotation.

To measure forces required to release the device with ratchet locked, we manually applied approximately 15–20 N tension on the cable then pressed a handheld force gauge (Omega DFG31-200) against the button until the cable was released (n = 4). Mean compression force was (8.3 ± 1.5) N. We then fixed both force gauge and winch mechanism to the table, and slowly wound the cable to increase tension until we were unable to turn the 45mm–diameter dial by hand. Hand-rotation of the dial (healthy investigator) maxed out at 40 N, with mechanism left intact.

Finally, we conducted a tensile test to determine ultimate holding strength of the winch assembly. Using the force gauge, we progressively increased cable tension until device failure then disassembled the winch to determine cause (n = 3). Ultimate tensile force was (115.3 ± 4.0) N, for which in all three cases the pawl’s jamming surface was the point of failure. With estimated 50-percentile male and female arm sizes [17] and distal cable insertion angle of 30°, we expect maximum holding torque to be about 4.5–5.0 Nm, or 60% of maximum biological pronation torque [18].

B. System-level Characterization

Because evaluating the prototype requires studying the device in conjunction with body-powered movements, we obtained the relationships between cable contraction force and exoskeleton resistive torques and forearm angles by trying on the device ourselves. We note that even healthy subjects display wide variance in hand-arm sizes and strengths, muscle tone, skin tightness, joint flexibility, and user comfort levels. Here, we were primarily interested in proof-of-concept validation of our distributed-rotation supination method given the inherent compliance of soft-tissue, without additional complexity due to spasticity or impaired motor-synergies. We conducted two tests with two subjects: 1) we determined whether finger-torques on the dial or soft-tissue compliance is the main limiting factor for overall range of assistive rotation, and 2) we overpowered the device in pronation to obtain an estimate of maximum holding torque.

To determine device limitations during normal operation, we instructed the user to first rotate their arm into full pronation with the cable disengaged, then to apply a constant user-defined “moderate” amount of resistance while slowly turning the adjustment dial until the arm was supinated as far as comfortably possible. During this test, we logged cable tension with a load cell (Futek LSB200-FSH00097, sampling rate 10Hz) mounted inline with the supination cable and measured end-effector orientation angle with a handheld inclinometer, which consisted of a smartphone running a tilt app (Sylos Apps, “Simple Inclinometer”) inserted in a plastic tube. We compared the measured range of motion (ROM) of hand end-effector rotation with the subject’s total baseline ROM when wearing the device with the mechanism disengaged. With the device, we achieved a total rotation of 126° and 105°, respectively, achieving an average 89% of pronation–neutral ROM (53% of total ROM) with 16 N cable tension (n = 2). We found rotational displacement of the proximal armband component to come from soft-tissue compliance, but not from device slippage against the skin.

Second, we attempted to overpower the device. We engaged the device and fixed the arm in a neutral position, then instructed the user to exert their maximum strength to pronate the arm. Beyond about 12 N cable tension (approx. 0.4 Nm supination), overall compliance in the exoskeleton’s straps begins to allow the user’s arm to rotate within the brace and bypass the cable mechanism. Comparing the two methods, we found that cable forces recorded while rotating the arm in supination, without having the device slip, were greater in magnitude than forces recorded when trying to overpower the device; we believe that sudden activation of arm flexors.
and pronators during the second test likely changed forearm shape more than with constant exertion during the first test.

C. Feasibility Testing with Hemiparetic Stroke Subject

We evaluated the device on a subject with right-sided hemiparesis and moderate spasticity in hand and arm; specifically, scores of 2 for finger/elbow flexors and 1+ for forearm pronators on the Modified Ashworth Scale. The subject had no ability to actively move the arm into supination. He was able to actively rotate his forearm about 15° out of a fully-pronated position, and had sufficient arm strength to lift the hand to touch the face or extend the elbow. This subject was a participant in our previous studies with the hand-opening orthosis; however, his pronation when lifting the arm prevented him from completing many of the functional tasks requiring grasping cylindrical objects with a neutral hand pose. We first determine the subject’s forearm pronation–supination (PS) ROM, validating our inclinometer method with standardized goniometer measurements. We then qualitatively evaluated the subject’s functional ability to grasp and maneuver cylindrical objects with and without exoskeletal assistance. Our final set of tasks focused on evaluating the ability to assist maintaining the hand in a neutral orientation when reaching. Preliminary testing was conducted over the course of three 45-minute sessions under the guidance of an occupational therapist. The subject provided informed consent to participate in this study in accordance with the protocol approved by the Columbia University Medical Center Institutional Review Board.

1) Forearm PS, elbow bent: To study forearm rotation in isolation, we instruct the subject to sit with his shoulder adducted and elbow flexed at 90°. He places the inclinometer in his hand with the arm resting on the chair’s armrest, then slightly lifts the arm above the armrest while attempting to keep the inclinometer in a vertical position. The subject performed this task without wearing the exoskeleton (baseline condition), while wearing the exoskeleton but without engaging the supination mechanism, and after fully retracting the mechanism (assisted condition). To measure active pronation, we asked the subject to simply pronate as much as comfortably possible. This task mimics the standard clinical procedure for measuring forearm PS ROM; we validated inclinometer readings by also taking goniometer measurements, which all agreed within 5°. The subject was able to rotate the arm closer to a neutral position with assistance, but remained slightly pronated (Table I).

2) Hand Orientation, elbow extended: The following set of reaching tasks focuses on tracking orientation of the hand, instead of strictly measuring forearm PS rotation, since end-effector pose is most relevant for functional grasping. We note that hand orientation involves forearm PS as well as shoulder rotation, which we do not assist; however, we are interested in studying whether forearm PS compensation alone can enhance arm function. Overall, we expect the hand to turn downwards when the subject reaches forward due to shoulder abduction and internal rotation, along with lack of supination. We attempt to limit effects of shoulder movement on hand orientation during these tasks by asking the subject to consciously keep his elbow tucked in during forward reach. This reduces habitual abduction and internal rotation of the shoulder.

We first qualitatively compared reaching forward while wearing a commercial elastic supinator band (McKie Supination Strap and thumb splint) and while wearing our device, shown in Fig. 7. Although we do not assist shoulder rotation, we find the resulting hand orientation angles to be visually similar to those with a device that does cross the elbow to anchor around the bicep.

We then conducted a guided exercise of grasping a bottle and maneuvering it around the table surface, with and without the exoskeleton, to qualitatively evaluate ease of reach-to-grasp along with smoothness of arm motion (Fig. 8). Videos of the subject performing the bottle-maneuvering exercise are included in the supplemental material associated with

| Measurement (deg) | Baseline | Assisted |
|-------------------|----------|----------|
| Passive-ROM pronation | 0 – 60 | —        |
| Passive-ROM supination | 0 – 35 | —        |
| Total Active-ROM | 45 – 60 (pronated) | 25 – 50 (pronated) |

Fig. 7. Photos of stroke subject reaching forward while wearing a commercial supinator strap device (Left) and while wearing the proposed device (Right). The subject is asked to reach forward, keeping the elbow tucked in to avoid shoulder abduction and internal rotation; this motion is repeated while the subject attempts to maintain a neutral hand orientation.

Fig. 8. Photos of stroke subject reaching for (Top) and grasping (Bottom) a plastic bottle both without (Left) and with device assistance (Right) during the on-table maneuvering task.
this article. Without device assistance, the subject could only grasp the top of the bottle from a pronated position. By using the device, the subject could grasp the bottle from the side and could lift it to his face as if to drink.

We quantitatively evaluated device assistance by measuring end-effector angle while the subject attempted to reach forward while maintaining the inclinometer in a vertical orientation. Like the elbow-bent assessments, this test begins with the subject’s arm placed on the armrest with his elbow bent and tucked next to the body. He slowly lifts his arm and reaches forward, extending the elbow. When the arm is fully straightened, the subject is instructed to attempt to keep the inclinometer oriented vertically for about 30 seconds. The full attempt was recorded on video (about 1 minute total duration), and angle results for the straightened-arm portion of the exercise are shown in Fig. 9.

Fig. 9 shows the maximum and minimum extents of inclinometer readings recorded when the subject attempts to keep the hand in a vertical orientation after reaching forward. Although the subject’s arm can be passively rotated into supination, the subject lacks the volitional ability to rotate out of a horizontal hand pose. Overall, most angle deviations occur from the whole arm moving in space as the subject experiences difficulty in both stabilizing the inclinometer and keeping his arm up. When wearing the device, the rigid brace provides a slight bias towards vertical hand orientation; although the range of angles between No Device and Device Unlocked are similar, the latter is shifted about 15° more vertical. Without using the cable mechanism to physically rotate the hand, end-effector orientation is still largely horizontal. Fully engaging the supination mechanism not only rotates the hand to about 60° above horizontal, but also reduces effort required to maintain this angle. The range of end-effector angles recorded with the device fully-engaged is narrower than with the other conditions, partially because cable tension resists forearm pronation and partially because the elbow shook less during the attempt. The subject provided feedback that the exoskeleton made this task easier; one possibility is that the device allows him to only exert the minimal effort required to lift his arm, minimizing spasticity.

These results are only for a single subject, but indicate that for this individual, the hand exoskeleton was comfortable and able to effectively supinate the forearm in order to achieve and maintain a near-neutral hand position. For this individual, our device visually matches performance of a commercial passive splint while avoiding encroachment above the elbow. Although we do not achieve a truly neutral hand orientation, we do find that this device provides a noticeable assistive impact for some functional tasks.

IV. Conclusions

In this paper, we present a novel cable-based exoskeleton to assist supination for hemiparetic stroke. We demonstrate feasibility of an approach that leaves the elbow unencumbered; characterization tests suggest that the device can withstand the torques required to adjust forearm rotation even given soft-tissue compliance. Here, we successfully integrate our proposed supination exoskeleton with an existing robotic orthosis and demonstrate that our device does not interfere with hand-opening. Preliminary testing on a stroke subject having no volitional supination suggests functional utility. Positioning the forearm in a more neutral position enables stroke survivors to approach vertically oriented objects with a more functional hand position during forward reach. This has the potential to increase ease of performance during common bimanual tasks such as grasping a bottle to open it, holding a cup when pouring, or opening the refrigerator to retrieve food. Although internal rotation of the shoulder also contributes to downward orientation of the palm during forward reach for stroke survivors, this novel device has demonstrated the potential to address part of the problem.
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