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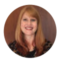

Lauri Bishop
Columbia University

Yuchen Xiao
Northeastern University

On the Feasibility of Wearable Exotendon Networks for Whole-Hand Movement Patterns in Stroke Patients

Sangwoo Park[1], Lauri Bishop[2], Tara Post[2], Yuchen Xiao[1], Joel Stein[2,3] and Matei Ciocarlie[1,3]

***Abstract*— Fully wearable hand rehabilitation and assistive devices could extend training and improve quality of life for patients affected by hand impairments. However, such devices must deliver meaningful manipulation capabilities in a small and lightweight package. In this context, this paper investigates the capability of single-actuator devices to assist whole-hand movement patterns through a network of exotendons. Our prototypes combine a single linear actuator (mounted on a forearm splint) with a network of exotendons (routed on the surface of a soft glove). We investigated two possible tendon network configurations: one that produces full finger extension (overcoming flexor spasticity), and one that combines proximal flexion with distal extension at each finger. In experiments with stroke survivors, we measured the force levels needed to overcome various levels of spasticity and open the hand for grasping using the first of these configurations, and qualitatively demonstrated the ability to execute fingertip grasps using the second. Our results support the feasibility of developing future wearable devices able to assist a range of manipulation tasks.**

I. INTRODUCTION

Wearable devices have established themselves as an important area of focus for research in robotic rehabilitation. Traditional robot-assisted therapy, based on desktop-sized (or larger) machines, can mainly be provided in clinical settings. In contrast, wearable devices promise to enable use outside the hospital, providing the larger number of repetitions that is generally considered key to effective rehabilitation [1]. Beyond rehabilitation, wearable devices could also act as functional orthoses, providing assistance with Activities of Daily Living and increasing independence.

In this paper, we focus on wearable assistive devices for the hand. This is a particularly challenging context: the human hand is highly dexterous, often modeled as having as many as 20 individual joints. This high dimensionality of the joint position space gives rise to an enormous set of possible configurations.

A key tenet of our approach is that a hand orthosis can provide meaningful assistance with daily manipulation tasks even when using a number of actuators far smaller than the number of joints in the hand. Even though the human hand is highly dexterous, previous research suggests that numerous

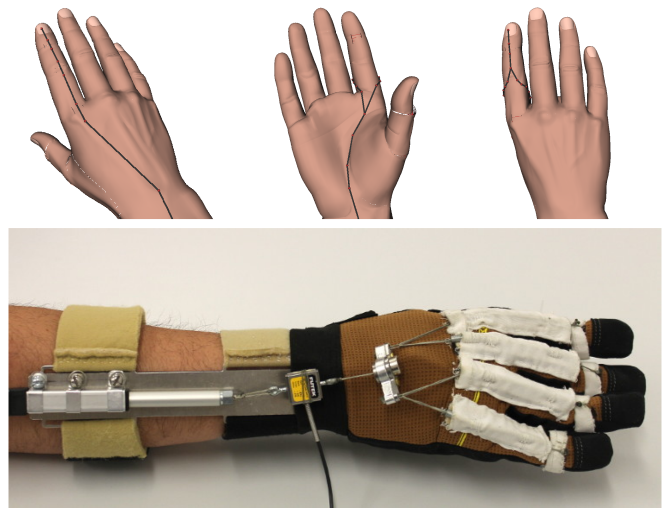

Fig. 1. Example exotendon routes for achieving different movement patterns illustrated for index finger (top) and whole-hand movement pattern implemented with single-actuator exotendon network (bottom).

manipulation tasks are dominated by a smaller number of effective degrees of freedom [2], [3], [4]. Previous work has shown that this result translates to artificial hands as well [5], where is it often implemented using the key principles of underactuation and passive compliance. In recent work, In et al. [6] have shown how underactuation can also be applied to our area of interest, namely tendon-driven assistive devices for the human hand. Overall, it seems likely that using a relatively small number of motors will be key in achieving a compact and lightweight wearable device.

To implement these principles, we used a network of exotendons, or tendons routed on the surface of the hand, used to initiate and assist movement. The tendons form a network providing both intra- and inter-finger underactuation; a subset of them are connected to actuators mounted on the forearm (Fig. 1). However, before such devices become practical, key questions still need to be addressed. *First, can a device using few and relatively small motors reach the force levels needed for meaningful assistance?* This is a particularly important question given that a common stroke aftereffect is hand spasticity, with permanent involuntary flexion. *Second, can we hope to achieve the dexterity levels needed to enable varied and useful manipulation*, across a wide range of patients exhibiting different impairment patterns?

In the study presented here, we implemented and tested devices that assist with two movement patterns (full hand extension and fingertip pinch). These aim to address some

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[1]Department of Mechanical Engineering, Columbia University, New York, NY 10027, USA. {sp3287, yx2281, matei.ciocarlie}@columbia.edu

[2]Department of Rehabilitation and Regenerative Medicine, Columbia University, New York, NY 10027, USA. {tp2213, lb2413, js1165}@cumc.columbia.edu

[3]Co-Principal Investigators

of the hand impairment types most commonly encountered as stroke aftereffects. Each pattern assists with movement of multiple fingers (four and five, respectively) through the use of a single actuator. Overall, the main contributions include the following:

- We investigate the feasibility of providing assistance for whole-hand movement patterns using a single actuator and a network of exotendons, and report here on prototype designs that achieve this functionality.
- We quantitatively assess the combined actuation force needed for assisting a multi-digit hand movement pattern (hand extension) in stroke patients. It is, to the best of our knowledge, the first time that exotendon force needed to overcome spasticity has been measured and reported. We believe this data will prove highly significant as we make progress towards dexterous, yet compact and wearable assistive devices for the hand.
- We correlate our results with the spasticity level observed in stroke patients, measured using the Modified Ashworth Scale, commonly employed in patient assessment for rehabilitation. This type of data will help identify patient populations most suited for using wearable assistive devices for the hand. We also characterize the resistance to movement provided by spastic muscles through the assisted range of motion, further informing future designs.
- We provide qualitative results indicating the feasibility of single-actuator assistance for a second movement pattern (fingertip pinch).

II. RELATED WORK

Wearable assistive devices for the hand have been proposed in the literature using various actuation methods (e.g. electric, pneumatic, etc.) and transmission mechanisms (e.g. linkages, tendons, etc.). While linkage driven systems exhibit efficient power transmission and support bidirectional actuation, this type of devices often faces the additional challenge of rotational axes misalignment. Several methods have been proposed to address this, such as direct matching of joint centers in HANDEXOS [7] and HEXORR [8], remote center of motion mechanism in EHI [9], and serial links chain connected to distal phalanges in HEXOSYS [10]. While effective for rehabilitation exercises, complex linkages also increase size and thus reduce applicability in constrained, cluttered environments typical of daily living. We note that wearable linkages can also take the form of a supernumerary robotic finger [11], a different way of providing assistance without interfering with the natural kinematics of the hand.

In contrast, wearable hand orthoses comprising only soft structures produce more compact systems, since soft devices do not require appropriate alignment with the biological joints of the user [12]. Fabrics can provide robust structure while keeping the device adjustable and affordable [13]. Easy customization is important, as it allows one device to be used with multiple users.

Hand rehabilitation devices using soft pneumatic actuators [13], [14] keep the advantages of completely soft, wearable robots, but pneumatic actuators require an additional air compressor. Our approach combines soft gloves with guided tendons driven by linear electric actuators. The tendon-driven design allows us to mount actuators at locations proximal to the joints they are driving, thus making the device easier to wear. A tendon-based approach also simplifies the construction of underactuated kinematics, as tendons can cross multiple joints for intra-finger coupling and bifurcate for inter-finger coupling. A number of existing hand and arm rehabilitation devices are also tendon driven [15], [16], [17], [18]. However, aiming towards fully wearable solutions, our device is fully self-contained and includes lightweight, portable actuators.

A research effort closely related to our approach resulted in the development of the BiomHED prototype [19]. This exotendon-driven device uses 7 motors attached to a tendon network that mimics the geometry of hand muscle-tendon units. Experiments established the ability of the device to generate fingertip motion and increase finger workspace in stroke survivors, highly encouraging for the area of active hand orthoses. However, the BiomHED prototype used one actuator per finger, and implemented a single movement pattern. Here, we investigate multiple whole-hand movement patterns each driven by a single actuator, aiming to reduce the number of actuators needed by future, more dexterous devices.

In terms of quantitative assessment of actuation forces for hand movemebt, Iqbal et al. [10] conducted a series of experiments to measure the forces applied on each finger by a hand exoskeleton device, showing a maximum force of up to 45N. In et al. [20] showed that a soft robot hand with jointless structure can apply effective joint forces for grasping. Recently, pinch and enveloping grasp force by a soft hand orthosis with a tendon routing system, the Exo-Glove [6], were measured on a healthy subject, with EMG signals confirming that the subject did not exert additional voluntary force. Our results are based on studies with stroke survivors, and are additionally correlated with spasticity levels, which can significantly affect manipulation abilities. Finally, a comprehensive review of additional hand exoskeletons for rehabilitation and assistance can be found in the study by Heo et al. [21].

III. MOVEMENT PATTERNS AND TENDON NETWORKS

Stroke survivors experience a broad range of hand impairments, ranging from barely perceptible slowing of fine finger movements to complete loss of all voluntary movement. It is unlikely, for now, that a single device can effectively address all these impairment types. We have thus chosen to focus on certain patterns of impairments that are particularly common and challenging from a rehabilitation perspective, selected based on the clinical experience of our team. We describe these below, noting again that there are a wide range of other motor and functional impairments that affect stroke survivors.

Fig. 2. Hand exotendon configurations for eliciting desired movement patterns. Left: tendon configuration 1 (hand extension), dorsal view. Right: tendon configuration 2 (MCP flexion / IP extension), lateral and palmar views.

- Pattern A: These individuals are able to form a gross grasp with the hand moving all digits in synergy, but lack sufficient finger extension to actively open the hand after grasping. This pattern is particularly challenging as it commonly includes spasticity, where the hand is in a persistently flexed pose and digit extensors are unable to overcome ongoing involuntary contraction of the flexors. These individuals also typically lack individuated finger movements.
- Pattern B: Another common pattern is the ability to move all digits of the hand, but to have limited individuation, and for the movements to be slow, lacking in dexterity, and of diminished force. Such an individual may be able to oppose the thumb to each of the other digits in sequence, but only slowly and with considerable effort. The ability to manipulate objects is limited.

Here, we report on two exotendon network configurations informed by these patterns. Each of these configurations is designed to be driven by a single actuator, with multiple joints moving in synergy. For initial study and assessment, we have implemented each configuration separately, in a dedicated prototype. However, combined versions able to produce multiple movement patterns with few actuators will be a promising direction for future research. Both configurations are illustrated in Fig. 2.

Tendon configuration 1: hand extension. In this configuration, one motor assists extension for all digits. From a clinical perspective, this configuration addresses Pattern A described earlier, where a person lacks sufficient finger extension to overcome spasticity and actively open the hand. Combined finger extension is amenable to direct implementation through a single motor, since a tendon can be routed on the dorsal side of all joints all the way to the phalanges. These routes also allow the tendons to be neutral with regard to abduction/adduction motion of the fingers. Simulations carried out using the human hand model included with the *GraspIt!* simulator for robotic grasping [22] have shown that complete range of motion of all the joints of the index finger requires 57mm of travel of the tendon. This matches the specifications of the off-the-shelf linear actuators we use, noting that functional use of the hand for common tasks is unlikely to require full simultaneous extension of all joints.

The implementation we report on in this study addresses all digits except for the thumb. The trapeziometacarpal joint is significantly more complex than finger carpometacarpal joints; *GraspIt!* simulations based on the common model with two non-perpendicular axes of rotation indicate that most extensor exotendon routes will also have a limited but non-zero effect on thumb abduction. We are currently investigating this effect and plan to include the thumb in future prototypes developed for functional testing.

Tendon configuration 2: metacarpophalangeal (MCP) flexion / interphalangeal (IP) extension. This pattern assumes opposite motion at the MCP joints versus the IP joints for each finger. Functionally, this pattern can allow transition between enveloping postures and fingertip opposition postures. For stroke patients exhibiting pattern B described earlier, this could increase the range of grasps that can be executed. From an implementation perspective, it is achieved through a single tendon for each finger, routed on the palmar side of the MCP joint then wrapping around the finger to the dorsal side of the proximal and distal IP joints. The tendon bifurcates to wrap around both sides of the finger in order to obtain a neutral effect on finger adduction. Our implementation of this pattern addresses all digits, including the thumb, where the role of MCP flexion is instead played by adduction.

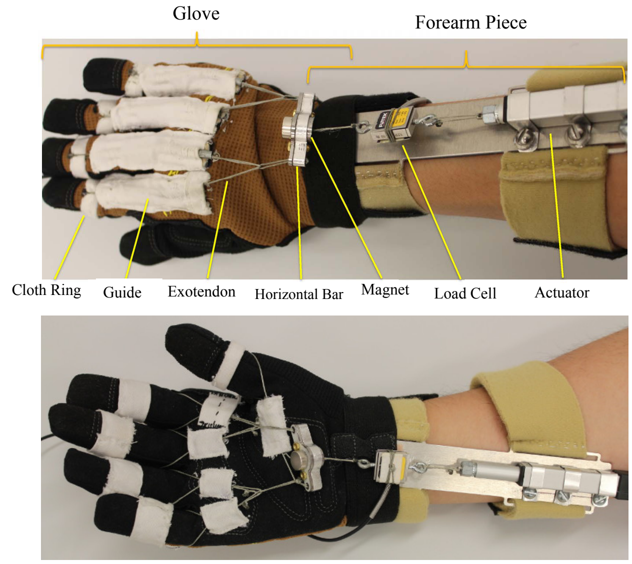


Fig. 3. Prototype hand orthotic devices. Top: tendon configuration 1. Bottom: tendon configuration 2. Both devices comprise a forearm splint with a mounted actuator and a glove implementing the desired tendon network.

IV. PROTOTYPE DESIGN AND FABRICATION

Our overall design is illustrated in Fig. 3. To facilitate donning the device, we split it into two modules: a forearm piece with actuation, and a glove with the tendon network. The two components are connected via mechanical features that automatically detach before potentially dangerous forces

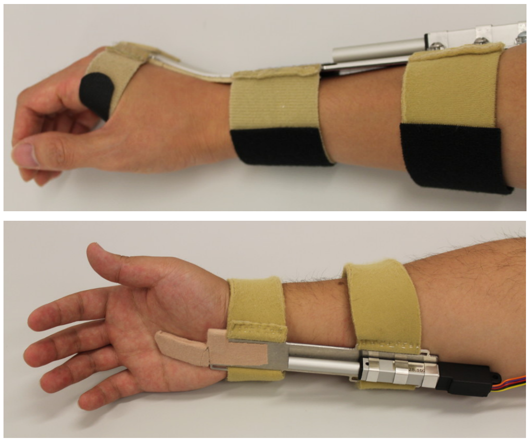


Fig. 4. Forearm splint components for devices with tendon configuration 1 (top) and tendon configuration 2 (bottom).

Fig. 5. Tendon guides with increased moment arms via raised pathways.

are reached. This mechanical coupling includes a permanent magnet connecting the motor and exotendons. We currently use permanent magnets capable of a pull force of either 34N (D73, KJ Magnetics Inc.) or 41N (D73-N52, KJ Magnetics Inc.), both cylindrical with a diameter of 11 mm and thickness of 4.7 mm. Connector pieces with different tendon lenghts allow us to adjust the device to the subject, such that, with all digits fully flexed and the actuator in the fully extended position, we remove all tendon slack up to a few millimeters.

A linear actuator with a 50 mm stroke length, a 5 mm/s maximum speed of travel, and a 50 N peak force (Firgelli, L12-P-50-210-12) is mounted on the forearm piece. A 50mm stroke length suffices for the expected range of motion, and 5mm/s as maximum speed is slow enough to prevent any hazardous circumstances. The peak force of 50N is above that of the breakaway magnetic coupling, so it was never reached in our experiments.

One of the main roles of the forearm piece is to constrain the wrist joint (Fig 4). Splinting the wrist is important in our mechanism as it helps extend the fingers without hyperextending the wrist. Furthermore, the splint is designed to maintain a wrist extension angle of 30°, considered a functional wrist pose [23]. This design also reduces distal migration, or the phenomenon where an entire orthotic device slowly slides towards the distal end of the arm while in use. To reduce pressure, which might cause pain on the hand, soft materials, such as moleskin, are attached underneath the splint.

The tendon networks described in the previous section are implemented on the glove component of the device. In each case, one tendon connected to the actuator bifurcates into a network that actuates each finger. All bifurcation points are rigid, with no differential mechanism installed to distribute loads. A number of existing cable-driven soft wearable hand devices have tendon attachment points on the fingertip of the glove [12], [18]. We have found that this design can produce finger hyperextension at the DIP joint. To alleviate this problem, the tendons attach on each finger to a cloth ring on the middle phalanx. Through IP joint coupling, this produces both PIP and DIP extention, without causing hyperextension.

On the dorsal side of each finger, raised tendon guides sitting on top of multiple layers of fabric are used to increase the moment arm of the extensor tendons around the joints. The increased moment arms allow us to reduce the linear forces applied to the tendons. For the index finger (and representative for the other fingers), the raised pathways have height of 8.5mm above the MCP joint and 7.5mm above the PIP joint; the cloth ring only protrudes 1.5mm above skin (Fig 5). For tendons on the palmar side of the joints, we have found that such increased moment arms are not necessary.

A load cell (Futek, FSH00097) is installed between the actuator and the magnet piece to measure the tension of the actuated tendon. The sensor has been calibrated to have a resolution of 0.196N and can measure up to 50N.

V. EXPERIMENT DESIGN

Our experiments were designed to provide initial validation of the approach with the intended target population of stroke patients. In particular, we aimed to verify the capability of the device to produce the expected patterns and ranges of motion, and to characterize the forces encountered, especially when assisting patients exhibiting various levels of spasticity.

Testing was performed with five stroke survivors, three female and two male. All testing was approved by the Columbia University Internal Review Board, and performed in a clinical setting under the supervision of Physical and/or Occupational Therapists. All subjects displayed right side hemiparesis following a stroke event; in all cases, experiments took place more than 6 months after the stroke. Subjects also exhibited different spasticity levels, ranging between 1 and 3 on the Modified Ashworth Scale (MAS).

The first step in the experimental procedure consisted in measuring the patient's range of motion in all digits as well as the wrist, and assessing the spasticity level on the MAS. The next step consisted of donning the orthotic device, consisting of the forearm splint and the exotendon glove. After donning, the motor on the forearm splint was connected to the tendon network via a breakaway magnetic mechanism as described earlier.

Starting with the linear actuator at full extension, we define one trial as one excursion of the actuator to the completely retracted position. Depending on the tendon network being used (tendon configurations 1 or 2 described above), this

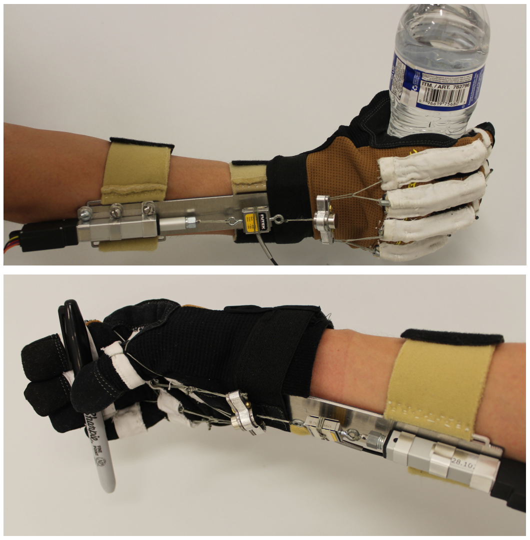


Fig. 6. Illustrations of functional experiments with tendon configuration 1 (top) and tendon configuration 2 (bottom).

produced a given movement pattern of the subject's hand. Throughout each trial, we recorded both the actuator position and the tendon force levels reported by the load cell; both measurements were taken at a frequency of 100 Hz. When tendon forces exceeded the maximum load supported by the magnet, the breakaway mechanism disengaged and the actuator retraction completed without exerting any forces to the subject.

With each subject, we performed the following set of trials:

- 1 trial where we asked the subject to relax their hand and not apply any voluntary forces;
- 2-3 trials where we asked the subject to voluntarily assist the device in producing the intended movement pattern, to the best of their abilities;
- (for Configuration 1) 2-3 trials where the subject attempted to grasp an object (soda can). Starting from the subject's rest pose, the exotendon was engaged by retracting the linear actuator, providing finger extension. Once functional extension was achieved, the hand was positioned around the object and the exotendon was released allowing the subject to flex the fingers (illustrated by an able-bodied user in Fig. 6). If needed, the subject was assisted by the experimenter in positioning the arm such that the hand would be able to execute the grasp.
- (for Configuration 2) 2-3 trials where the subject attempted to execute a pinch grasp of an object (highlighter pen). Starting from the subject's rest pose, the exotendon was engaged by retracting the linear actuator, placing the hand in a pose appropriate for fingertip grasping a given object (illustrated by an able-bodied in Fig. 6). If needed, the object was positioned by the experimenter such that the hand would be able to execute the grasp.

After the completion of the procedure, subjects were asked to describe their impressions of wearing the device, any discomfort or pain produced by it, and any suggestions for improvement.

VI. RESULTS

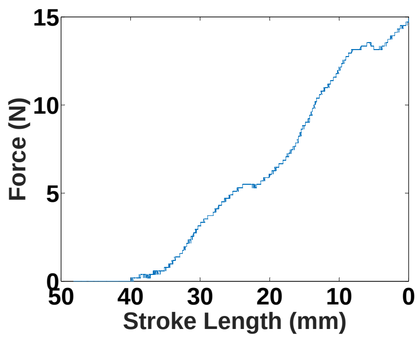
One of the main objectives of our set of experiments was to determine the actuation forces needed to achieve functional hand extension in stroke patients exhibiting various levels of spasticity. Fig. 7 summarizes our results measuring actuation forces during trials with five stroke patients using tendon configuration 1 (full extension). We present one representative trial per subject; surprisingly, we found very little variation between trials were the subject was asked to relax and trials where the subject was asked to actively assist the device or to attempt a grasp. Throughout the trials, we recorded the applied force levels as a function of the position of the actuator. Hand opening in response to the device was observed by the experimenter and rated as functional (sufficient to grasp an object of approximately 55mm in diameter) or not; however, quantitative data for joint angles was not recorded.

The assistive hand device was able to achieve functional hand extension for 4/5 patients. In 2/5 cases the force level led to the breakaway mechanism disengaging; however, in one of those cases this occurred after functional hand extension was achieved. Overall, we were able to achieve functional hand extension for all patients with MAS spasticity levels of 1 and 2. Breakaway occurred after achieving functional extension for one patient with MAS spasticity at level 2, and without achieving functional extension for one patient with MAS spasticity at level 3. In all cases, the subject was able to complete an enveloping grasp of the target object, as described in the previous section.

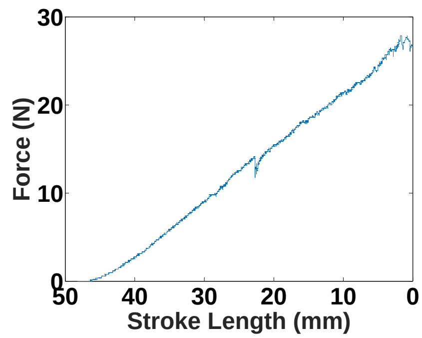
The maximum level of recorded force varied between subjects: between 15-20 N for Subjects 1 and 3, between 25-30 N for Subject 2, and exceeding 35 N (and thus leading to breakaway) for Subjects 4 and 5. These results suggest that an exotendon assistive glove with a single actuator able to apply up to 40 N to a tendon network similar to the one used here will succeed in generating functional hand extension for most patients with spasticity levels 1 and 2, but will not be strong enough to be used by patients with spasticity level 3.

An interesting finding concerns the observed relationship between force and position, used here as a proxy for hand pose. In all observed cases, the relationship was highly linear. To quantify this phenomenon, we first normalized the data as follows. First, as each trial generally begins with a small amount of slack in the tendon that is picked up as the actuator retracts, we removed all data points until the force first first reached a threshold of 3N. For cases where the trial ended by a disconnect of the breakaway mechanism, we also removed data points starting at the breakaway moment (observed as a sudden drop in force levels all the way to 0). Finally, we normalized remaining force and position values by dividing with the maximum observed value, and measured the correlation coefficient between the resulting data series.

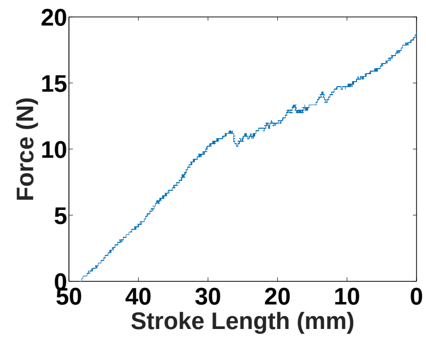
For all the trials shown in Fig. 7, we obtained correlation coefficients ranging between 0.97 (Subject #2) and 1.00



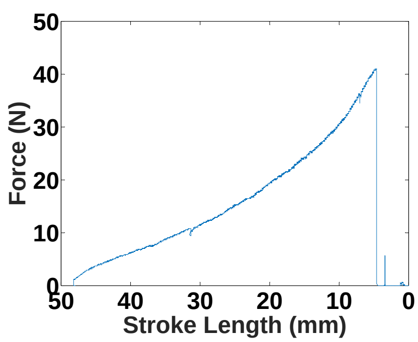
Subject #1. Functional extension was achieved. Spasticity level: 2.



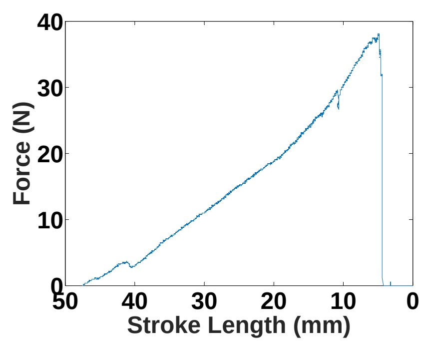
Subject #2. Functional extension was achieved. Spasticity level: 1.



Subject #3. Functional extension was achieved. Spasticity level: 1 (except for index finger, rated at 2).

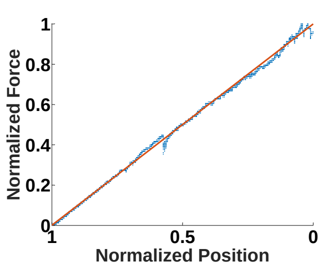


Subject #4. Functional extension was not achieved. Spasticity level: 3.



Subject #5. Functional extension was achieved. Spasticity level: 2.

Fig. 7. Characterization of hand extension trials: force vs. position data. Each plot shows, for one trial, the relationship between the measured force in the actuated tendon and the linear position of the actuator. Note that each trial begins with the actuator fully elongated (50 mm actuator position) and slack tendon network (0N force). As the actuator retracts (left-to-right movement on the plots), we measure the force applied to the tendon network. If the force exceeds the maximum load supported by the magnet, the mechanism disengages producing a sudden drop in the force profile. This plot shows one representative trial from each of the 5 subjects tested using this movement pattern. For each trial, we also indicate whether functional extension (defined as sufficient hand opening to grasp an object of approximately 55mm in diameter) was achieved before the mechanism achieved maximum retraction or disengaged.



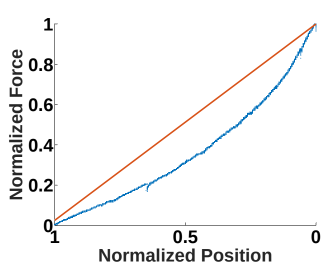


Fig. 8. Normalized force vs. position data (blue) and superimposed linear fit (red) for trials exhibiting the highest (left, 1.00) and lowest (right, 0.97) correlation coefficient between these two variables.

(Subject #4). Fig. 8 shows the normalized data, along with the linear fit, for the trials with the highest and lowest correlation coefficient. These results suggest that the spastic muscle does not oppose movement with a fixed force level. Rather, it behaves in spring-like fashion, with resistance increasing linearly along with elongation.

We also carried out experiments with two stroke patients using tendon configuration 2 (MCP flexion / IP extension). Force vs. position data for these experiments is less relevant, since, in these cases the assistive device does not need to overcome involuntary forces in the opposite direction. Rather, we were interested in the functional aspect: does the assistive device in this configuration enable stable fingertip grasping. This was quantified as the ability to hold the object using such a grasp without external support while the assistive device was engaged and applying tendon forces. One of the subjects displayed this ability without the use of an assistive device; however, both subjects were able to perform this task with the use of the device.

Throughout the experiments, none of the subjects reported any pain or discomfort from using the device. However, subjective feedback repeatedly included suggestions to make doning the glove component of the device easier. We plan to take more steps in this direction for further iterations.

VII. DISCUSSION AND CONCLUSIONS

Based on our results, we draw the following conclusions, which we believe can be informative for research and development for next generation wearable assistive devices for the hand:

- A single linear actuator applying a total force below 40 N can overcome hand spasticity and produced desired

movement patterns for stroke survivors with spasticity levels 1 and 2. This suggests that lightweight wearable devices (we used an actuator with a total weight of 40 g) can be effective, from a force generation perspective, for a significant range of the population affected by hand impairments as a result of stroke.
- Multiple functional whole-hand movement patterns can be produced using a single actuator for each. In particular, we demonstrated two such patterns: full extension (which combines with voluntary flexion to produce enveloping grasps) and MCP flexion / IP extension (which produces fingertip grasps). These results suggest that a single device with a small number of actuators can combine multiple such patterns, producing a wider range of manipulation capabilities.
- Our results also suggest that spastic muscles oppose movement in a spring-like fashion, with forces increasing linearly with elongation. In turn, this suggests that selection of actuators (and implicitly force levels) for assistive devices must take into consideration how applied forces will vary throughout the expected range of motion.

Overall, by illustrating the fact that multiple movement patterns are possible using few and portable actuators, this study provides data to support the feasibility of building assistive devices for the hand that will be both wearable and dexterous. Such devices could help with the manipulation component of activities of daily living, enable functional training on real-world manipulation tasks, extend training beyond the small number of sessions performed in a clinical setting, and provide distributed training during the course of daily activities rather than block training in designated therapeutic sessions.

Our current study also revealed a number of limitations. While hand movement was observed by the experimenter and functionally tested by the ability to execute a grasp (enveloping or fingertip), digit movement was not measured or recorded. As such, based on this data, we can not study the relationship between joint angles and actuator position or force. When performing grasps, we did not measure the resultant forces applied to the object or numerically quantify the stability of the resulting grasp. Finally, the study was exploratory in nature, covering stroke patients with multiple levels of spasticity and hand impairment types, but without a sufficient population to examine the statistical significance of the findings. We plan to address these limitations in future work.

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