A Hybrid Rigid-Soft Hand Exoskeleton to Assist Functional Dexterity

Chad G. Rose and Marcia K. O'Malley

***Abstract*—A hybrid hand exoskeleton, leveraging rigid and soft elements, has been designed to serve as an assistive device to return the ability to perform activities of daily living (ADLs) and improve quality of life (QOL) for a broad population with hand impairment. This glove-like exoskeleton, the SeptaPose Assistive and Rehabilitative (SPAR) Glove, is underactuated, enabling seven hand poses which support most ADLs. The device resides on the spectrum between traditional rigid devices and the latest soft robotic designs. It includes novel ergonomic elements for power transmission and additional features to enable self-donning and doffing. Embedded sensors enable pose estimation and intent detection for intuitive control of the glove. In this paper, we summarize the overall design of the glove, and present details of the novel rigid palm bar and hyperextension prevention elements. We characterize the grasp force and range of motion (ROM) of the glove, and present initial feedback from an end-user. The SPAR Glove meets or exceeds the functional requirements of ADLs for both ROM and grasp force. Additionally, the glove exceeds the grasp force capabilities of comparable devices, while simultaneously offering the highest number of poses. In addition to its role as an assistive device, the SPAR Glove exoskeleton has the potential to provide "hands-in" rehabilitation centered on performing functional tasks. In the near term, the glove is a highly capable prototype for exploring hybrid assistive device design, intent detection, and user interface research.**

***Index Terms*—Physically Assistive Devices, Wearable Robots, Rehabilitation Robotics, Prosthetics and Exoskeletons**

I. INTRODUCTION

A significant population has reduced upper extremity motor function as a result of neuromuscular injury or disorder. Many of the 6.6 million Americans with stroke [1] and the 5.3 million with traumatic brain injury (TBI) [2] have hand impairment that prevents unaided completion of ADLs. Other populations, such as those with ataxia [3] or certain classifications of dystonia [4], can have similar debilitating impairments. More than half of the 17,000 annual incidences of spinal cord injury (SCI) in the United States are at the cervical level [5] and result in severe arm and hand disabilities. Restoration of this lost hand function is the highest priority for over half of the individuals with tetraplegia due to SCI [6], underscoring the clear, critical need for specialized interventions and the outsized impact they can have on post-injury QOL and life expectancy.

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Fig. 1. Devices fall along the rigid-soft spectrum, with most, such as the Cybergrasp [10] and the glove by Polygerinos *et al.* [11], residing at the ends. In the hybrid middle of the spectrum, we propose the SPAR Glove, a novel device which leverages the strengths of each end of the spectrum to serve as a technology framework for investigating impacts of assistive devices, developing novel intent detection schemes, and creating softgoods (fabric and other flexible material-based) designs to promote wearability.

To significantly impact therapeutic outcomes and recovery of hand functions, therapy must occur outside of the clinic, and interventions must target the distal degrees of freedom (DOF) of the upper limb [7], [8]. These interventions should include devices that both assist in completing ADLs and support recovery of motor coordination by overcoming learned non-use of the impaired limb [9].

A robotic intervention that supports ADLs and encourages recovery of motor function outside of the clinic, will have to overcome the limitations of current designs (reviewed by Bos *et al.* [12]). These devices typically reside at the extremes of a rigid-soft spectrum, shown in Fig. 1. Most rigid hand rehabilitation systems either offer limited functionality in terms of movement or exhibit significant weight and bulk, limiting their wearability as an assistive device, as detailed by Yun *et al.* [13]. For example, the Cybergrasp [10], while exhibiting high precision torque and position control, is large, heavy, and expensive. As a result, rigid devices are relegated to clinical environments.

Towards the soft end of the spectrum are tendon-driven devices, which typically leverage Bowden cable transmissions and remote actuation to assist grasps. Most of these tendon-driven devices, such as the Exo-Glove [14] and the glove proposed by Xiloyannis *et al.* [15], support only a single three finger grasp and nearly meet force requirements for ADL, with the Exo-Glove providing 40 N for cylindrical grasps [14]. However, the soft construction of these devices limits their force output and cannot prevent hyperextension. Devices such as the Graspy Glove [16] are promising in their support of multiple poses, but distal location of actuators can reduce their wearability. All of these devices rely on a single DOF thumb which cannot support lateral pinch grasps. Very soft devices often have performance limitations stemming from their actuation strategies, such as the limited torque and bandwidth available to pneumatic devices such as the glove proposed by Polygerinos *et al.* [11] and refined by Cappello *et al.* [17], [18].

Few devices for the hand reside in the middle of the spectrum. Hybrid designs, such as Armstrong [19], a rigid-soft exoskeletal garment for proximal upper limb rehabilitation, and the Exo-Glove PM [20], a device combining soft pneumatic actuators with rigid connections, have potential as assistive devices. With rigid elements enabling power transmission, mechanically-programmed safety features, and soft interfaces enhancing wearability, hybrid designs have the potential to support and train ADLs in ways not achievable with fully soft or fully rigid systems.

To this end, we designed the SeptaPose Assistive and Rehabilitative (SPAR) Glove, and update the first presentation [21] with more specific design guidelines described in Section II. Section III provides new details concerning the design of the softgoods, power transmission, and compliant sensing integral to the SPAR Glove. We then present new performance characterization and comparison to other assistive devices in Section IV. The results of this characterization are discussed in Section V, and the novel contributions are summarized in Section VI.

II. Design Approach

By bridging the gap between fully rigid and fully compliant hand-based devices, it is possible to achieve both assitance in ADLs and functional training with a semi-portable, self-donnable device. We propose the SPAR Glove to support ADLs and simultaneously promote functional use of the impaired limb, a capability known to have great cognitive importance [22]. To this end, we prioritize multiple DOF, sufficient ROM, and torque output to achieve a majority of ADLs, while also striving for practical safety features, ease of maintenance, and reasonable weight.

A. Achieving Functional Grasps

Neither complete grasp taxonomies proposed in the robotic manipulator field [23], [24] nor single DOF taxonomies [14] are suitable targets for supporting ADLs, since complete taxonomies require fully actuated, complex devices, and single DOF taxonomies omit grasps such as the lateral pinch crucial to ADLs and assessments such as the Fugl-Meyer [25]. A subset within the Cutkosky Grasp Taxonomy proposed by Dalley *et al.* for myoelectric prosthetic control [26], shown in Fig. 10, comprises an estimated 85% of the grasps needed for ADLs. Given the broad range of achievable grasps with these basic poses, we have defined this set (opposition, reposition, hook, point, lateral pinch, pinch, and cylinder) as our design objective.

B. Finger Joint Range of Motion

The active ROM of healthy fingers is large, with flexion ranges for metacarpalphalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints measured to be 100°, 105°, and 85°, respectively [27]. Our design goal is the functional ROM, which averages 61°, 60°, and 39° for MCP, PIP, and DIP respectively [27].

C. Grasp Forces

While healthy users can provide maximal forces of 95.6 N and 400 N in precision and power grasps [28], we define the design targets to be the requirements for ADLs, with the maximum required forces around 15 lbf (66.7 N) [29], and 75% of ADLs requiring less than 10.5 N [30].

III. The SPAR Glove

The SPAR Glove, shown in Fig. 2, is a novel design integrating rigid and soft elements to overcome design limitations of fully rigid or fully soft devices. The key contributions of this design can be organized into the design of softgoods, power transmission, and compliant sensing. The softgoods design had three goals: first, provide a compliant fit to promote comfort and safety; second, enable donning and doffing by impaired individuals; and third, integrate rigid elements for safety and power transmission (Section III-A). The power transmission, building off the rigid elements embedded in softgoods, provides torque through a flexible Bowden cable transmission and ensures safety through the judicious placement of rigid elements, while promoting wearability through the remote placement of motors and implementation hardware (Section III-B). Connecting the softgoods and power transmission are compliant sensors used to estimate finger pose and detect the wearer's intent (Section III-C). Key features of all of these contributions are summarized in Fig. 3.

Fig. 2. The SPAR Glove combines a novel glove-based exoskeleton with intent detection at the wrist, EMG at the forearm, and proximally located actuation to create a powerful, wearable system for hand assistance and functional task based training. Motors can be packaged in a wide range of configurations on the arm or in a backpack.

A. Softgoods Design

The softgoods design was based on a commercially available glove to leverage low-cost, refined designs and materials where practical. The glove base is made out of a combination of lycra elastic materials and simulated microsuede for comfort and grip.

1) Enabling Donning and Doffing: The seam on the ulnar side of the glove was opened from the wrist to the small finger MCP joint, creating room for donning and doffing with slightly flexed fingers. Nylon loops (2" long) were added to the base (wrist) of the glove which enabled

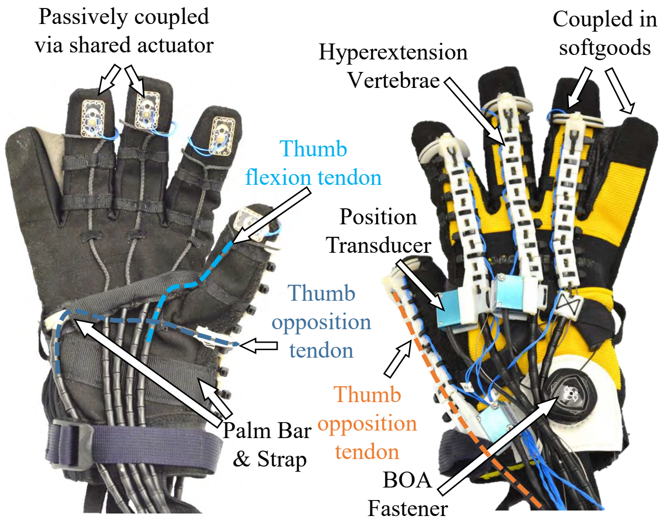


Fig. 3. Key features of the device are called out, highlighting key features of the actuation strategy, softgoods designs for ease of donning and doffing, and rigid elements integrated into softgoods.

quick donning by an individual with hand muscle tone and limited function when combined with 'shoehorn'-like devices such as the Glove Pilot [31]. To close the glove, the wearer tightens the palm strap and the optional wrist strap.

2) Palm Strap as Anchor: The palm strap, similar to how a boxer wraps their hand before sparring, serves as the main method of fastening the softgoods to the hand of the wearer. The strap is confined to a path around the hand, crossing on either side of the thumb, and is gathered on the dorsal side of the hand, seen in Fig. 3. The strap is tightened with a BOA fastener, a commercially-available ratcheting closure device found on equipment such as snowboots, where the user has reduced dexterity from wearing gloves. By removing the need for Velcro, buckles, or other fastening mechanisms, this glove can be securely fastened and unfastened to the hand by users with limited hand function, Tand reviewed positively by the participant, detailed further in Section IV-A.

B. Power Transmission

To date, most wearable systems involve remote actuation, either through pneumatic actuation or via Bowden cable transmissions. The key difficulty is transmitting power accurately and comfortably without deforming the device, and this difficulty is the reason many wearable systems have limited torque application.

1) Palm Strap Integration: The hybrid design of the SPAR Glove, which integrates a rigid palm bar into the palm strap softgoods, is a novel step towards overcoming this limitation. The glove features a Bowden cable transmission that terminates in the palm strap, reducing the fit and stiffness requirements on the softgoods and ensuring a strong and comfortable interface with the wearer. Instead of requiring the glove to distribute the conduit reaction loads, an ergonomically curved bar, shown in Fig. 4, is sewn into a sleeve in the palm strap using holes located at the ends of the palm bar. The shape is based on the retaining bar used to prevent spacesuit gloves from deforming when pressurized [32], [33], and has been scaled to small, medium, and large sizes This palm bar was refined through testing with the medium size detailed in Section IV-A and optimized to fit hands with muscle atrophy. The palm bar was 3D printed out of 316 stainless steel using selective laser sintering (SLS) to facilitate greater resolution in sizing and accommodate curved tendon paths for the thumb DOF. Inside the palm bar, the tendon paths for the index, middle, and ring fingers are straight, whereas the thumb flexion and opposition tendon paths each follow a custom spline trajectory. The tendon paths and hole locations were placed manually with the following guidelines: 1) have a large factor of safety (>20) in finite element analysis simulations and minimize stress concentrations (to account for imperfections in the SLS manufacturing process) 2) locate as many conduits as possible on the ulnar side of the palm, away from the thumb and 3) minimize the curvature of the tendon path from the conduit to the respective fingers, especially at the boundaries between the palm bar and the glove, and the axially-aligned paths along the finger and the palm. Finite element analysis suggests that the factor of safety of the current palm bar design is approximately 100, with the conduit dimensions and tendon path shape driving the shape more than material strength concerns.

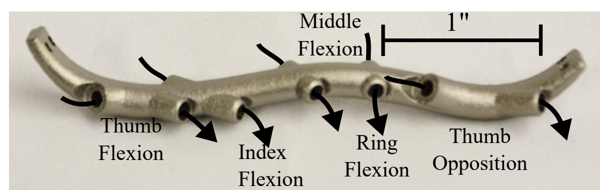


Fig. 4. Ergonomically shaped palm bar serves as the grounding termination for the Bowden cable conduit, and is integrated into the strap which anchors the glove to the wearer's hand. Figure shows a right-handed, size medium palm bar in the configuration of the viewer's right hand with the palm facing downwards, along with representative tendon paths.

2) Hyperextension Vertebrae: The bases of a series of vertebrae-like links (each 0.5" L x 0.4" W x 0.25" H) designed to prevent finger hyperextension are also anchored to the palm strap, and serve as the termination point for the Bowden cable transmission. Interstitial elements are sewn or connected directly to the glove and surround the tendon with cut outs to prevent pinches at the interface between vertebrae. The vertebrae are strung along a thin steel wire on either side of the tendon, as seen in Fig. 5 preventing off-axis rotation. These elements prevent hyperextension and provide the added benefit of increasing extension torque. For the fingers with position transducers, one of the steel cables is replaced by the string potentiometer.

3) Bowden Cable Transmission: The Armstrong [19] identified Jagwire as an lower cost alternative to custom square profile springs used in RG and SSRG [34], [32]. This segmented conduit resists movement under load, a desirable trait for conduit in a wearable garment. Jagwire elements are strung on 0.110" teflon tubing. Tendons consist of 1 mm braided kevlar (Spear-It) terminated in brummel splices.

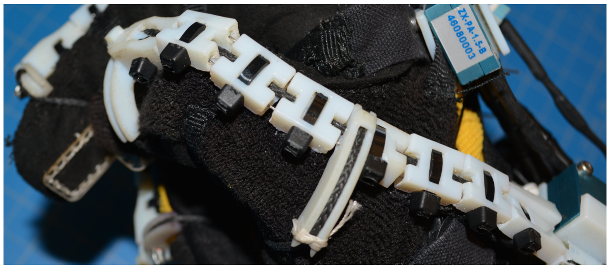


Fig. 5. Hyperextension vertebrae are segmented links, connected to the glove with either a whipstitch or zip tie (zip tie pictured here for the thumb). The vertebrae are 0.5" long and 0.4" and use a thin steel cable routed alongside the kevlar tendon to maintain alignment.

Extension tendons terminate on the dorsal side of the hand in the distal hyperextension vertebrae located on the intermediate phalange. The thumb opposition tendon terminates in a similar manner after crossing the thumb metacarpal bone. Flexion tendons terminate in a loop which goes around the intermediate phalanges, which are protected by saddles integrated into the distal vertebrae.

Since the secondary fingers (small, ring) are coupled in softgoods, they can be coupled with the middle via the Bowden cable transmission. The index finger and thumb are actuated individually, with the latter having three tendons, one for flexion, one for opposition, and a third for a combination extension/reposition, as seen in Fig. 3.

A common failure mode for wearable Bowden cable transmissions is for the tendonto bind and pull the teflon liner out of the assembly at conduit termination. This would require non-trivial downtime to perform the requisite maintenance and assembly tasks. By placing a flat termination area perpendicular to the conduit liner path at termination (seen on the left hand side of the palm bar in Fig. 4, the pull-out force was increased by 24% over an arbitrary ellipse (6.7 lbf vs. 5.4 lbf), as measured by an IMADA DS2-220 digital force gauge during quasi-static load tests.

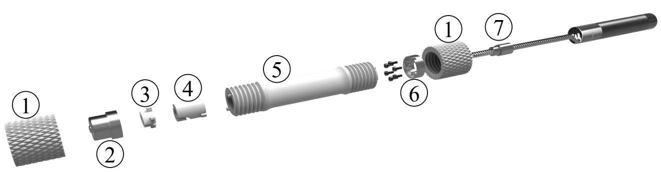


Fig. 6. SPAR Glove actuators include improvements over prior actuator designs [34], [32], by reducing complexity, cost, and maintenance difficulty while increasing performance. Figure shows a rendering of the actuator used for the thumb and index finger. Component 1 is a 7/8-9 threaded fastener, capturing components 2 and 6, which act as hard stops and interfaces to the Bowden cable transmission and motor subassembly, respectively. Component 3 is used to keep the tendon loop separated and reduce the likelihood of binding. Component 4 is the tendon hook which pulls the tendon for flexion or extension, and has an internal threaded connection to the ball screw carriage (component 7) and has rotation lock features (small tabs at the base, seen at the right of the part) which slide along internal channels to component 5, the ball screw housing tube. Components 1, 3, 4, and 5 were 3D printed, whereas components 2 and 6 were milled out of 7000 series aluminum. Note that component 2 is modified for the two actuators used for the secondary fingers to have two Bowden cable interfaces, and component 3 is therefore not required.

4) Actuator Subsystem: The device uses seven brushless DC motors (Maxon P/N 405794), coupled to a combination planetary gear (4.4:1 reduction) and ball screw transmission (2 mm pitch, Maxon P/N 424222) with an approximate 3.2" stroke length. The design of the actuator subsystem reduces the need for specialized tools whenever possible, relying on large knurled nuts to connect the conduit and ball screw guides to the actuator, as shown in Fig. 6. Printed parts (Objet RGD 450) are used where possible cost. Implementation hardware consists of a Quanser Q8-USB DAQ and Acellus Panel (ASP-055-18) motor drivers.

C. Compliant Sensing

The goals for the compliant sensors are to augment the actuator-side knowledge of position to better estimate finger pose and detect user intent in an intuitive manner.

1) Grasp Pose Sensing: There are three sensors which capture information about grasp pose. First, motor encoders (Maxon P/N 201940, 512 counts per revolution, quadrature) capture actuator-side knowledge about tendon position with a backlash-limited (1.4°) resolution of 0.007 mm. Second, linear position transducers (Unimeasure ZX-PA-1.5B) with a 1.5" stroke cross the MCP and PIP joints through the hyperextension vertebrae (seen in Fig. 3), enabling distal sensing of finger pose. Finally, low-profile buttons (LilyPad button board, Sparkfun) are used to gain fingertip contact information during grasping.

2) Intent Detection: Complementing these pose information sensors are two sensors aimed at detecting user intent for pose and grasp aperture. Intent detection is crucial in maximizing the value of therapeutic interventions and in developing intuitive shared control of wearable devices [35], [36]. The SPAR Glove detects user intent via bend sensors at the wrist and electromyography (EMG) activity in the upper extremity with a Myo armband. Surface EMG has been shown to be a useful signal for controlling upper extremity exoskeletons worn by individuals with SCI, even with limited volitional motion resulting from the activation [37]. The tenodesis grasp is an intuitive target for controlling grasp aperture with intact motion at the wrist, and has seen successful prior implementation [14]. Impaired individuals with residual control of the wrist flexion extension can regain some hand movement by leveraging the biomechanical coupling of wrist flexion and extension to passively move the coupled joints of the finger [38]. By locating flex sensors (Flexpoint, 2" polyester overlaminate) on a wrist sleeve, the grasp aperture can be intuitively controlled in the same manner as the familiar tenodesis grasp.

Fig. 7. The intent detection subsystem of the SPAR Glove consists of flexible resistors (1) located at the wrist for measuring the tenodesis grasp, and the Myo armband (2) for EMG detection.

IV. Characterization of Grasp Capabilities

We validated the capabilities of the glove's rigid and softgoods subsystems in isolation and the performance of the prototype system as a whole for the application of functional grasp assistance. Specifically, we incorporated user feedback into the design loop, determined the ability of the palm bar strap integration to reduce unintended deformation of the glove, and quantified the maximum grasp force capabilities of the device. Then, the SPAR Glove performance is benchmarked against comparable devices.

A. User Feedback

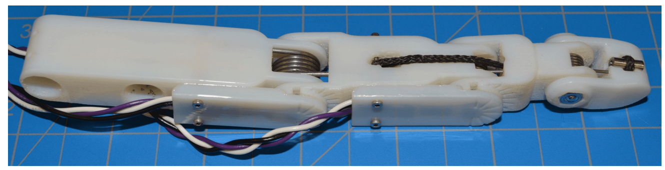
End-users have invaluable insights for the design of assistive devices which are not always available or taken into consideration [39]. The first rounds of user feedback were to determine the efficacy of the palm bar design and features for ease of solo donning and doffing. The preliminary design feedback from the intended population consisted of two sessions with one participant (C5-C6 iSCI, ASIA Score D) who provided informed consent to participate in device evaluation (IRB protocol 882515-1) and validated the actuation design and don/doff considerations made in the design of the device. The ergonomic and don/doff considerations were centered around using BOA fasteners, seen in Fig. 3, to both secure the softgoods interface, and integrate the ergonomically designed Bowden cable transmission terminal design with the palm. The participant was able to use the BOA fastener, and indicated that this would be preferable to velcro. Additional feedback from the participant stressed the importance of the lateral pinch pose, which they relied on for many ADLs, and a desire to use the glove for barbell/weight lifting exercises, which would require robust designs and large force outputs. Lastly, the wrist strap was requested by the wearer, who felt that the extra fastener would improve comfort and feel, even if it was not a key to bearing loads from the power transmission.

Most anthropometric data available does not correlate well with the hands of individuals with SCI which have changes in hand shape and size caused by muscle atrophy. After these tests, the curvature of the palm bar was reduced by approximately 20% to better fit atrophied hands. Also, user feedback was crucial in developing the softgoods designs for donning and doffing. The subject indicated a preference for more rigid designs, which could be used with the Glove Pilot and pull loops. This was counterintuitive to some designs which could be donned one finger at a time. This is likely the difference between gloves that are intended to be donned alone versus donned by a caregiver.

B. Palm Bar Validation

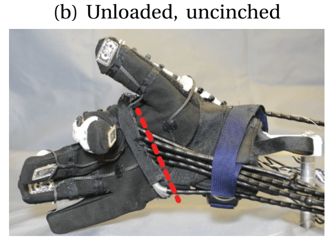
Testing with the Roboglove [34] identified the poor fit in Bowden cable actuated glove exoskeletons causing travel of the conduit termination resulting in large PIP and minimal MCP flexion. This travel results in a grasp which is unusable for cylindrical, pinch, lateral pinch, and hook grasps. An ergonomically shaped palm bar should have much less deformation, which should better distribute Bowden cable tendon travel across MCP and PIP joints, resulting in a more even and useful grasp to meet ADLs requirements.

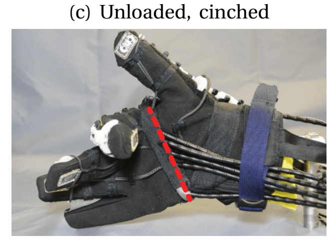
To validate the palm bar softgoods' reduction of conduit termination travel, an instrumented finger was developed [40], shown in Fig. 8a. Adding to the open-source designs originally presented by Yun *et al.* [41], this modular finger is compatible with soft or semi-soft hand devices such as the glove-based prototype presented here, and similar designs have been used for validation previously [42]. With anthropometric dimensions, two KMA210 linear angle sensors from NXP Semiconductors and neodymium ring magnets are embedded in the finger to approximate MCP and PIP joint angles. The PIP and DIP joints are coupled with a tendon, to mimic the coupling seen in human fingers.

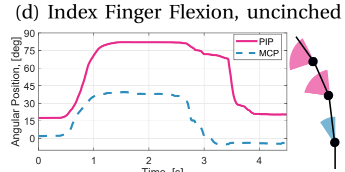

(a) Instrumented Finger


(b) Unloaded, uncinched

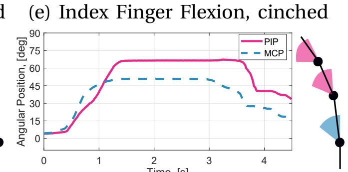

(c) Unloaded, cinched


(d) Index Finger Flexion, uncinched


(e) Index Finger Flexion, cinched



(f) Joint positions, uncinched



(g) Joint positions, cinched

Fig. 8. A glove-compatible instrumented finger, based on the design by Yun et al. [41] was used to estimate finger position for the case with and without the palm bar fixed in softgoods. In all figures, the red dashed line is fixed relative to the glove's thumb position, in order to separate the effects of the entire glove sliding along the instrumented finger system, and the palm bar's travel. As suggested by Fig. 8e, when the palm bar is cinched to a simulated palm, the bar travels less and the tendon's travel is more equally shared across the coupled MCP/PIP joints.

MCP and PIP joint positions were measured with and without the palm bar affixed to a simulated foam palm, shown in Fig. 8b-e, with the glove following a sinusoidal trajectory via PD control. The figures highlight the travel of the palm bar relative to the thumb and show that the palm bar shape and attachment mechanism greatly reduces deformation of the glove without relying on strong connections to the wrist or curved palm surface. Fig. 8g shows that the integrated palm bar is able to distribute Bowden cable transmission reaction loads, resulting in more evenly distributed flexion across the PIP and MCP joints through the palm bar interface and better matches the functional requirements set out in Section II-B.

C. Grasp Performance

Initial validation of the SPAR Glove's ability to support and train ADLs are the maximum cylindrical grasp force, the finger joint ROM, and its ability to achieve each pose of the proposed taxonomy (Fig. 10).

1) Max Cylindrical Grasping Force: To determine the glove's maximum force output in the cylindrical power grasp, the glove was commanded to follow a sinusoidal position input via PD control which would generate an estimated 150 N in tendon tension 12 times with the Lafayette hand dynamometer (model 78010, 3 cm grip distance). The wearer was instructed to remain passive for the duration of the motion, and did not participate in modulating the grip force. The average (83 N) exceeds and the minimum (59 N) nearly meets the requirements for ADLs (66.7 N).

2) Index ROM: To validate the range of motion beyond the single trial presented in Section IV-B, the instrumented finger was placed in the index finger of the glove with the palm bar affixed. The SPAR Glove index flexion and extension motors were then commanded to follow a sinusoidal trajectory encompassing their full range of motion. Figure 9 shows the joint angles recorded by the instrumented finger over 12 periods of this sinusoidal motion. Since the MCP joint of the index finger is closer to the palm bar than the MCP of the middle or ring finger, we expect the effect of palm bar travel to have the greatest impact on index MCP. The initial joint positions for the MCP and PIP were 0° and 9°, respectively, and achieved maximum positions of 72° for MCP and 66° for the coupled PIP/DIP joints, respectively. The large standard deviation of values for PIP extension show areas for improving extension performance as well as changing the constructions of the instrumented finger to capture glove movement. Still, this ROM meets the functional ADLs requirements established in Section II.

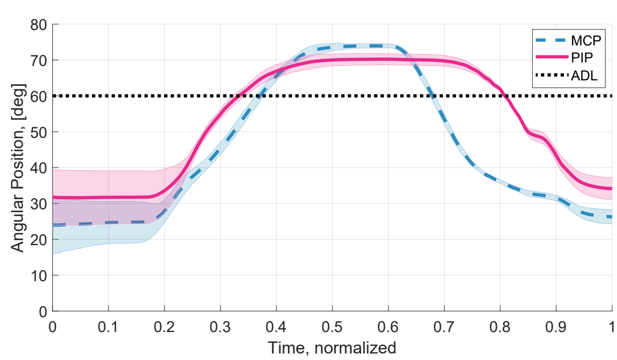


Fig. 9. Index range of motion, with the average presented as a dark line, and one standard deviation shaded. Max flexion angles for this trial with the instrumented finger and simulated foam palm were consistently above 60°. High variability of PIP joint during extension likely caused by friction, both internal to and caused by a snug fit of the instrumented finger.

3) Poses: The proposed exoskeleton supports the entire taxonomy, with proof-of-concept shown in Fig. 10 accomplished through manually-tuned tendon position control.

D. Comparison to State-of-the-Art Systems

An interesting metric, proposed by Popov, *et al.* [16], seeks to compare a selection of devices based on their performance, scored as a percentage of requirements for ADLs. The metric is averages scores on six characteristics: pinch force, glove weight, total weight, number of fingers, bidirectionality, and unconstrained wrist. Pinch force is scaled by the maximum force found in the presentation of the metric (40 N). The weight metrics were scaled according to the formula $W = {}^{100}/_{e^x}$, where x is the weight in kilograms, and the metric has a lower bound of 20%. Number of fingers scaled linearly with 20% added to that individual score for each finger the device actuated. Bidirectionality and wrist constraints are either 100% or 20% for bidirectional and unconstrained wrist, or unidirectional and constrained wrist, respectively. By this metric, the proposed glove scored a 83.4%. The parameters were defined as follows:

- Pinch force is estimated at 40N (half max. grasp) to avoid re-scaling previous scores (100%).
- Glove weight is 0.220 kg, (80.25%).
- Total weight (including benchtop implementation hardware) is 16 kg (20%).
- All fingers are supported (coupled secondaries, 100%).
- The glove is bidirectional (100%).
- The wrist is unconstrained (100%).

These scores, along with other relevant measures, are summarized in Table I. Note that the number of poses for ADLs was estimated to be 9, which successfully categorized 96.7% of studied grasps used in ADLs [43]. The grasp force of the Graspy Glove [16] was estimated to be double the max pinch force (16N from finger and thumb only, estimated 16N additional from middle and ring).

TABLE I
PERFORMANCE COMPARISON OF ASSISTIVE HAND DEVICES

	MCP/PIP ROM	Grasp Force	Poses	Popov Metric [16]
ADLs [27], [29], [43]	61°, 60°	66.7 N	9	100%
Graspy Glove [16]	45°, 75°	32 N	4	80.2%
Exo-Glove [14]	46°, 48°	40 N	2	70.4%
Cappello *et al.* [11], [17]	85 °, 90°	15 N	4	75.9%
Roboglove [34]	-, -	89 N	2	68.8%
SPAR Glove	72°, 66°	83 N	7	83.4%

V. DISCUSSION

The initial characterization of the proposed exoskeleton supports the device's use in assisting ADLs. The ROM meets or exceeds the functional requirements of ADLs, and the max continuous grasp force exceeds all other comparable devices (Table I). This high performance is available across more poses than other comparable gloves, due in large part to the design of the multi-DOF thumb. The metric proposed by Popov *et al.* [16] suggests that overall, the SPAR

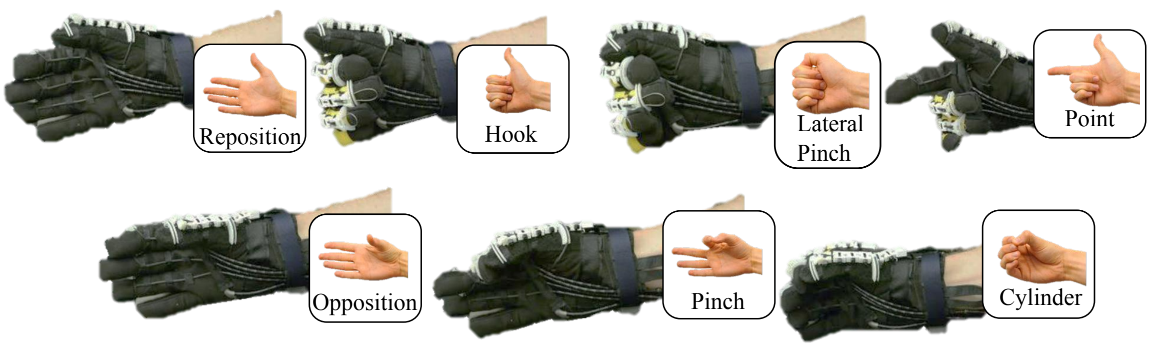


Fig. 10. Glove can support motion to all seven poses of the proposed taxonomy (Section II-A). Reposition relies on only the reposition+extension thumb tendon, Hook utilizes index and secondary flexion tendons as well as reposition+extension thumb tendon. Lateral pinch requires index and thumb flexion tendons only. Point only requires the index extension tendon, but could be augmented with secondary flexion as needed. Opposition relies only on the opposition thumb tendon. Pinch requires index flexion, thumb flexion, and thumb opposition tendon actuation. Lastly, Cylinder requires index, secondary, and thumb flexion combined with thumb opposition tendon actuation.

Glove offers comparable or improved performance to the state of the art, but identifies marked underperformance in terms of total system weight. This weight can be reduced by replacing benchtop implementation hardware with portable designs. Improvements to the descriptive power of this useful metric could include straightforward measures such as ROM, bandwidth, and number of poses as well as more subjective measures such as ease of donning and doffing or ergonomic concerns such as comfort.Currently, the metric places a large emphasis on weight, with equal values to glove weight and overall weight of the system, which reflects a set of priorities which may not align with users in wheelchairs, for example.

The iterative design process identified several unexpected features important to wearers, such as the more rigid design and desire to augment functional ADLs based training with weight lifting exercises. These features are highly complementary to the hybrid design language of the SPAR Glove.

The limitations to the hybrid approach to wearable device design present themselves at the connection between the rigid and soft elements, such as the tendon liner interface failure. Designing robust interfaces which can tolerate and distribute the loads is a challenge for softgoods design, and final prototypes do require some maintenance and repair.

Assessments identified shortcomings in the methods and the glove itself. The instrumented finger, while enabling high resolution analysis of the performance of the proposed exoskeleton, does have drawbacks which limit its utility, such as the lack of a palm or wrist, friction in the tendon coupling, and size. The maximum grasp forces are limited by two factors. First, the residual compliance of the palm bar softgoods interface presents upper limits on the quality of the grasp on the dynamometer under high loads. Second, the weakest point of the actuator relies only on the pressfit of the ball screw shaft into the gearbox, limiting the feed force to 176 N intermittent and 64 N continuous, which is sufficient for ADLs (as shown here) but below what the rest of the actuator subassembly can accomplish.

Extension, in particular the thumb (Fig. 10) and the MCP joints (Fig. 9) was a key performance limitation of the glove. This is likely the result of friction and unintended locking of the hyperextension vertebrae, and will be addressed in future designs. If the prototype assistive device is to transition to the clinic and to the home, future work must include the demonstration of safe and effective use with multiple participants, iteration of the design to improve efficacy, and investigation of the changes in upper extremity function correlated with the use of an assistive glove device. The first step towards these goals will be the development of robust intent detection methods and control algorithms for grasping beyond the position control in this manuscript. In addition to the benefits of increased use, the flex cuff intent mechanism presents the opportunity to pursue therapeutic goals of reducing reliance on tenodesis, by including training which relies on the inverse (wrist extension for finger flexion) inputs. Any long-term study should also investigate the effect of fit and travel of the palm bar on comfort, wearability, and grasp stability.

VI. Conclusion

To meet the critical need of hand assistance for individuals with neuromuscular impairment and overcome limitations of fully soft and fully rigid device designs, a novel hybrid device has been proposed. The SPAR Glove fills an identified need in assistance and rehabilitation and exploits a gap in the rigid-soft device spectrum. This hybrid device leverages the strengths of both rigid and soft devices, and has the potential to improve individuals with hand functional impairment quality of life and independence. The initial validation results of grasp force output, range motion, and initial feedback from intended users supports the use of the device as a testbed for future studies on intent detection, wearable sensors, ergonomic softgoods design, and assistive technologies.

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