Accepted article. 42nd Annual International Conferences of the IEEE Engineering in Medicine and Biology Society.

Motor-Augmented Wrist-Driven Orthosis: Flexible Grasp Assistance for People with Spinal Cord Injury

Andrew I. W. McPherson[1]*, Vatsal V. Patel[2], Phillip R. Downey[3], Ahmed Abbas Alvi[4], Michael E. Abbott[1] and Hannah S. Stuart[1]

***Abstract*— This paper presents the design of a motor-augmented wrist-driven orthosis (MWDO) for improved grasp articulation for people with C6-C7 spinal cord injuries. Based on the traditional passive, wrist-driven orthotic (WDO) mechanism, the MWDO allows for both body-powered and motorized actuation of the grasping output thus enabling more flexible and dexterous operation. Here, the associated control scheme enables active decoupling of wrist and finger articulation, which can be useful during certain phases of manipulation tasks. An additional modification to the traditional WDO is the integration of a magnetic latch at the Distal Interphalangeal (DIP) joint allowing for improved pinching. These abilities are demonstrated with common activities of daily living (ADL).**

Fig. 1: (Left) The MWDO is worn the same way as a traditional WDO, but has an additional motor located at the proximal end of the device for adjusting hand behavior in parallel to the user's wrist motions. The fingertips are straight in the neutral pose in order to enable finer pinching motions. (Right) A tenodesis grasp demonstration shows how wrist extension closes the fingers, while wrist flexion allows the fingers to open.

I. Introduction

Approximately 291,000 people live with spinal cord injury (SCI) in the United States today [1]. A common level of cervical SCI, which occurs at the C6-C7 vertebrae, causes tetraplegia with severely diminished hand function [2]. This dramatically impacts common activities, such as manipulating and grasping objects in the home, leading to loss of independence. In fact, restoring hand and arm function is reported to be the top priority for people with tetraplegia [3]. Individuals with C6-C7 SCI develop ways to maintain dexterity in the face of these challenges. For example, they often learn to use tenodesis grasping [4], the passive coupling between wrist extension and finger flexion, demonstrated in Fig. 1. This work introduces a new device, also shown in Fig. 1, used to study the augmentation of this existing capability.

A. *Related works*

The human hand is typically capable of performing a variety of grasp types, e.g., non-prehensile pushing, prehensile power wrap grasping, precision prismatic pinching, referring to the taxonomy by Cutkosky 1989 [5]. Yet, a large portion (>60%) of human grasps can be described by a single motion synergy, which involves the opening and closing of the fingers and thumb in opposition [6]. A number of devices prioritize re-enabling and strengthening this single grasp motion using one degree-of-freedom (DOF) linkages. One such solution is a passive, wrist-driven orthosis (WDO) that uses a mechanical linkage to amplify the grip force due to tenodesis grasping, as in [7]–[9]. This is a completely passive mechanism and, as such, can be lightweight, physically resilient, insensitive to moisture, and low cost. However, it has ultimately seen a decrease in therapist prescriptions given the low longitudinal use by patients [10].

WDOs couple finger and wrist motion, which can be problematic for individuals who use a wheelchair and must contort their arms and trunk at times in order to perform a grasp via wrist flexion. An initial assessment metric for the ability of a person to reach a target hand pose and close the hand when constrained by coupled hand-wrist kinematics, introduced in [11], illustrates this major limitation of a purely passive wrist-driven device. It should be noted that some WDO devices add extra locks or ratchets, that are either manually or electronically triggered, e.g., [12], as a way to compensate for this issue. There are a host of powered grasp-assist devices that can be actuated in any number of different ways (e.g., pneumatic bladders, tendons, etc.) such as in [13]–[16]. However, these articulated solutions generally do not assist grasping when unpowered.

We seek to selectively decouple wrist and finger motions in a way that is useful for decreasing arm contortions for individuals with SCI using a WDO while also increasing overall functionality. A *motor-augmented bionic* – defined here as a machine whose output can be controlled by an electromechanical motor and body-power simultaneously in parallel – may act as a platform for intuitive operator embodiment and flexible control capabilities necessary to accomplish this goal while maintaining the mechanical simplicity and unpowered function of prior WDOs.

[1]University of California Berkeley, Dept. of Mechanical Engineering, Embodied Dexterity Group, Berkeley, USA
[2]Yale University, Dept. of Mechanical Engineering & Material Science, New Haven, USA
[3]Manufacturing Engineer, SpaceX, Hawthorne, CA 90250
[4]University of Hong Kong, Dept. of Mechanical Engineering, Pokfulam, Hong Kong
*Direct correspondence to drewmcpherson25@berkeley.edu or 2521 Hearst Ave, Etcheverry Hall Rm 2112, Berkeley, CA 94709.

B. Overview

Section II provides a description of the kinematic design of the MWDO device and Sec. III describes the implementation of the prototype hardware and control. Preliminary bench-top tests are presented in Section IV, where use of the devices is demonstrated for tasks of daily living, such as grasping a pen, turning a key, and opening a door with a round doorknob, highlighting the diversity of tasks that this hybrid device is able to perform. The results indicate that the MWDO device can assist with simple, lightweight grasping activities, discussed in Section IV. Section V, conclusion and future work, highlights the need to perform a set of human subject trials to investigate the development of adaptive algorithms for real-world adoption of this technology in the home.

II. Kinematics

The MWDO uses an underactuated linkage, consisting of two four-bar linkages in series, as shown in Fig. 2. The point W is located along the axis of the wrist's center of rotation while the M and D points are located near the metacarpophalangeal (MCP) and distal interphalangeal (DIP) joints respectively. Point D is constrained by hardstops and a preload force, such that the distal four-bar linkage remains rigid in free motion of the device. However, if a force is applied, pictured here as an object that the device is wrapping around, the preload may be overcome and the whole hand will wrap around the object. This adaptive design concept is similar to a number of robot hands reviewed in [17], such as [18]. This linkage will tend to first provide a motion with straight fingers for pinching, then later transition into a wrap grasp. Shown in Fig. 3, the thumb is moved by a linkage whose motion is fully coupled to the linkage in Fig. 2.

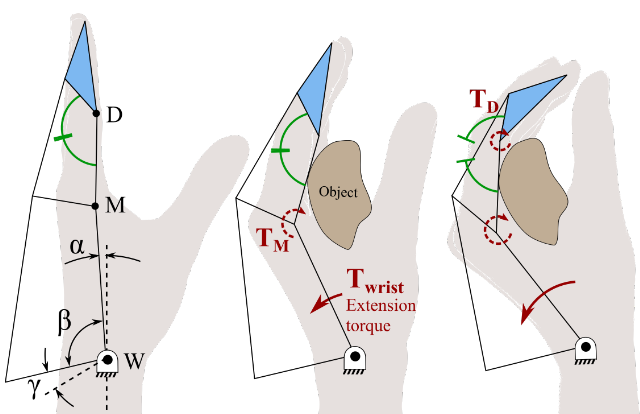

Fig. 2: The device is made up of two consecutive four-bar linkages. The blue triangle is the most distal rigid phalanx link. The most proximal four-bar linkage can be actuated with both wrist extension α and motor actuation γ, which change the angle β. Since β is set by both wrist and motor motion, the hand can be closed/opened with either one or both working in parallel. In this diagram, only wrist pose is changed to close the hand around an object, denoted as extension torque T_{wrist}. This body-powered actuation produces torques about M and D points, T_M and T_D. A magnetic hard-stop (shown in green) provides preload at the distal point D, maintaining rigidity in the distal linkage until T_D exceeds this preload. This creates a staged grasping motion; here, a contact force occurs on the middle phalanx before wrap grasping initiates.

The device is actuated by two inputs: α, defined as the angle of the wrist in extension, and γ, defined as the actuated angle of the motor. The hand can be opened or closed by motor actuation alone, wrist motion alone, or a simultaneous combination of both. The angle between the link actuated by the wrist $\overline{WM}$ and the link actuated by the motor, or β, provides a single measure of how open or closed the hand is at any given wrist angle. Fig. 4 demonstrates how a small value of β corresponds to a closed hand and a large value of β corresponds to an open hand. The horizontal axis in Fig. 4 represents a gain of $G = \partial\gamma/\partial\alpha$, where $G = 0$ is passive tenodesis (a↔c). As G increases, the motor will increasingly augment the opening or closing of the hand during wrist flexion. The hand can be opened and closed with no motion of the wrist as well (b↔d).

III. Implementation

A. Mechanism

As shown in Fig. 1 and Fig. 5, the MWDO is made of a combination of 3D printed plastic and cut 6061 aluminum parts with the goal of producing a lightweight yet stiff device. The size of the device and initial prototypes were based on the open-source, fully passive WDO presented in [7]. The device is attached to the body at multiple points – two loops around the pointer and middle fingers, a support around the palm, a loop on the thumb, and two straps around the forearm

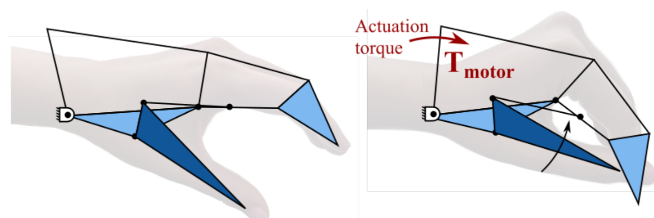

Fig. 3: The thumb motion (the thumb link is represented as a dark blue triangle) is fully coupled with the motion of the linkage for closing the fingers. The fingers and thumb move in opposition to perform a strong grasp. This effect is pronounced in this diagram for clarity, showing approximate motion of a hand shadow given motor actuation alone (no wrist movement).

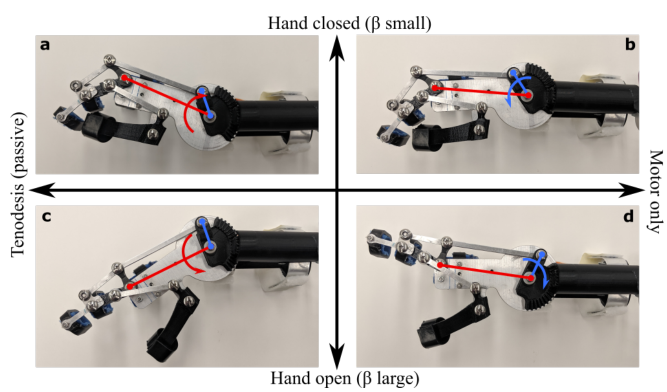

Fig. 4: A range of grasping behaviors are enabled by allowing for both wrist and motor actuation. Passive tenodesis grasping is possible when the motor is stationary. The hand can also be opened and closed with the motor alone, when the wrist is stationary. Simultaneous combinations of both wrist and motor actuation are also possible. The angle β dictates the degree to which the fingers are open or closed.

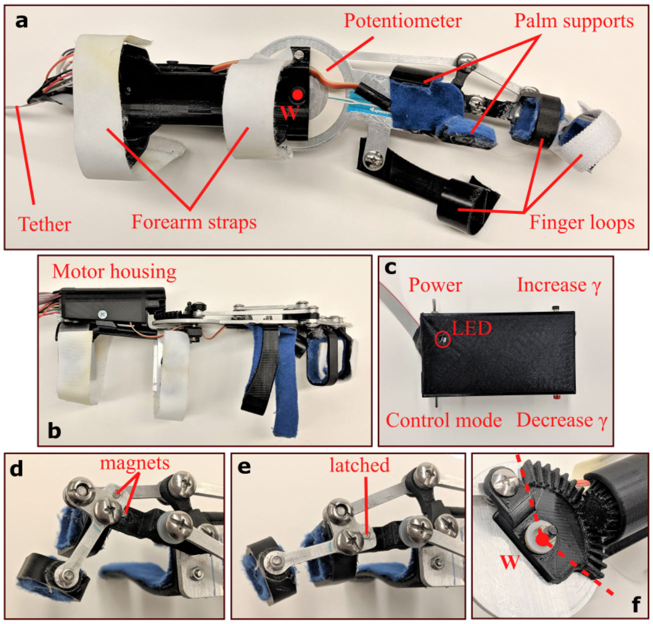

Fig. 5: The MWDO has a number of straps and loops for attachement on the hand and arm, as well as a wrist position potentiometer sensor and a tether for wires (a). The motor is housed at the forearm (b) and the tether leads to a control box (c) with two toggle switches, two momentary buttons and an indicator LED. A set of magnets at the distal end of the linkage (d) latch the distal four-bar linkage when aligned (e). The bevel gear drive (f) rotates around point W with limited angles of 50° in extension and 70° in flexion; beyond this range of rotation angles the motor will disengage to avoid injury.

– and felt cloth is used to increase comfort at these locations Fig. 5 (a). A rotary thin film soft potentiometer (Spectra Symbol SP-R-0046-353-103-3%-RH) is used as an encoder for measuring α located at the wrist joint W. This particular potentiometer helps to mechanically stabilize the wrist joint as well with the off axis, spring-loaded delrin wiper.

A motor with incremental encoder for measuring γ (12V brushed DC motor with 156:1 metal gearbox) is located at the forearm, and is contained inside a protective cover (b). Motor actuation is transmitted through a set of bevel gears that give a 3:1 advantage (f). The output gear has a limited range of engagement to only allow a healthy range of motion in the wrist of 50 degrees in extension and 75 degrees in flexion from a neutral wrist posture, as defined in [19], to avoid injury – the gears will disengage if the motor drives too far in either direction.

The linkage joint at point D is constrained by two aligned magnets (d-e) that separate by shearing apart when linkage $\overline{MD}$ movement is inhibited. A return spring is not typically required to pull back the distal linkage magnets into alignment. When the device is opened by wrist flexion, as with passive tenodesis, the fingers will naturally open, resulting in realignment. When the device is opened by the motor (T_{motor}), the distal phalanges are opened first before overcoming the resistance to a change in wrist position, α, provided by the weight of the hand, friction at joint M, or any residual stiffness in the user's hand. For individuals with significant contractures, when the fingers will be most difficult to open; motor torque will first extend the wrist until the limit of α before opening the fingers and finger range of motion will be limited.

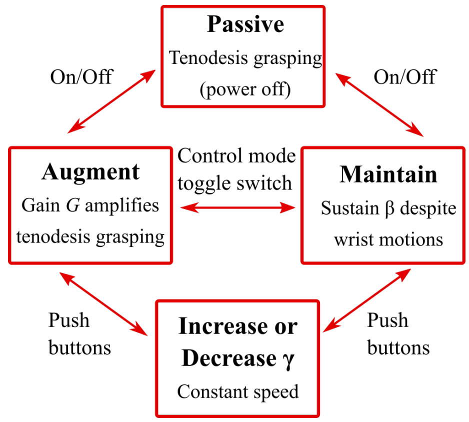

Fig. 6: The device starts as a passive WDO. Power-on yields either Augment or Maintain state based on position of toggle switch – this active mode can be switched at any time. Directly increasing or decreasing motor angle is possible by pressing the open/close push buttons.

A wire tether (a) exits the device at the proximal end of the forearm brace; this tether connects to an operator controller box (c). The current implementation positions the toggle switch and momentary buttons far apart on the control box for ease of use by people with limited dexterity due to SCI.

B. Control

With two degree of freedom, the MWDO has the potential to enable a flexible set of behaviors. In this initial work, we demonstrate three particular example functions, outlined in the State Transition Diagram in Fig. 6. Passive State is when the motor stays at a fixed position, and the device performs passive tenodesis. This occurs when the device is powered off. Active Augment State is when G is at a value such that a small extension in the wrist will yield a larger relative grasp motion of the fingers. Active Maintain State is when β is maintained regardless of changes in wrist pose α – the motor tracks the motion of the wrist using the potentiometer. The operator can switch between these two active modes with a toggle switch. Both active states are implemented by position feedback control, requiring accurate measurements from the motor and wrist encoders. A simple PI (Proportional and Integral) control scheme is used. It should be noted that grasping often benefits from force, rather than position, control of the fingers; due to the parallel nature of motor and body actuation in this device, the person can directly and rapidly modulate squeeze forces despite position control at the motor in the Passive and Augment modes. Implementing force control during the Maintain state will be explored in future work.

In either active state, the operator can use momentary push-buttons on the controller to manually change γ. This functionality becomes most useful when space or comfort

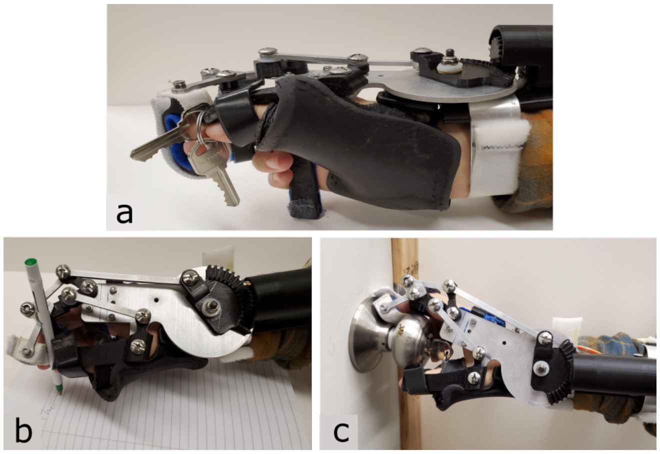

Fig. 7: The author demonstrates wearing the MWDO in Augment mode, grasping objects encountered in a typical day: a) keys, b) pen, c) round doorknob.

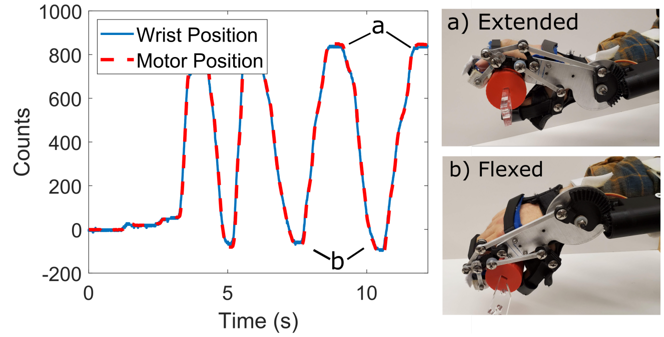

Fig. 8: The wrist was repeatedly extended (a) and flexed (b) to test the controller while grasping a cylindrical object. The motor and wrist position (measured in counts by the incremental encoder and potentiometer, respectvely) were recorded and plotted over time. The controller produced a constant angle between motor and wrist position, which allowed the user to maintain their grasp on the object. Without this mode, the flexed position would result in releasing the object.

constraints the range of motion of the user's wrist. Additionally, users with a C6 spinal cord injury are unable to flex their wrist (only extend). This is a primary limitation of existing WDO devices as the user must utilize gravity to open their hand. Here, the push button may also be used to open the hand to grasp larger objects than the user could otherwise manipulate due to contractures of the fingers.

IV. Performance Evaluation

The two active modes of operation, described in Section III-B, were demonstrated by an author (no human subjects were recruited). First, a round door knob, a set of keys (as in [20]) and a pen were successfully grasped and manipulated using the Augment mode of operation, shown in Fig. 7. An author wearing the device also maintained a steady grasp on a cylindrical test object with relaxed fingers and varying wrist positions using the Maintain mode, with results shown in Fig. 8. In this state, the user did not need to continually extend the wrist in order to continue grasping an object, a property that may enable the execution of more complex bilateral manipulation tasks.

Current research suggests that a device must meet a minimum set of design criteria to even be considered by an end-user [21]. To this end, the design criteria selected seek to enable independently donning and doffing of the device, grasping forces capable of holding a coffee cup, beer or small bag with a speed to close/open the hand completely in under two seconds and overall device mass of less than 500 g [21]. The palm of the user was also left exposed for manual wheelchair manipulation and tactile sensation. Initial bench-top testing indicates that all of these specifications are met (see Table I for a summary).

TABLE I: Summary of design characteristic meeting all minimum functional requirements as previously set forth.

Characteristic	Achieved
Don/Doff	yes
Grasp Force >10 N	10.8 N
Mass <500 g	330 g
Speed Grasp in <2 s	yes
Open Palm	yes
Grasp Augment	yes
Grasp Maintain	yes

In the current implementation, the maximum motor-actuated grasp force did not exceed 11N. This was tested by holding α constant (i.e. anchoring the link $\overline{WM}$ and the forearm brace to a table) while measuring fingertip load with an electronic force scale (ES-PS01) during motor actuation. Because of the parallel nature of wrist and motor actuation, functional grasp strength will be limited by the weaker of the two (motor or wrist) when worn by an operator (i.e. α is not immobilized). Therefore, someone with weaker wrist extension may not reach the full 11N of grasp strength. In this case, when the users hand has closed as far as it can and the motor force exceeds the strength of the operator, the wrist will be forced to flex until the motor is stopped or the end of bevel gear is reached.

V. Conclusion

The motor-augmented wrist driven orthosis (MWDO) is introduced as a method to enable more flexible operation for functional grasp, demonstrated by preliminary tests during common activities of daily living. Other desirable characteristics, such as low weight, high strength, responsive speed and easy donning, additionally indicate that this type of device may prove to be useful for the C6-C7 SCI population.

A. Future work

Future work will involve the testing of this device with human subjects, specifically including people with spinal cord injuries to determine the MWDO's efficacy relative to a traditional WDO; these tests will employ quantitative clinical scoring evaluations. We have assumed that wrist extension is an intuitive way to command grasping, particularly in subjects with SCI who already use tenodesis, but this is yet to be proven for this device. The performance of the device may also be improved by including a brake at the wrist joint to increase maximum grasp force, not limited by muscle activation (an issue described in Sec. IV). Eventually, this device could enable studies in the home to explore the benefits and limitations of this device in daily use. In particular, we will address how people switch seamlessly between operation modes during ADL, for example through gesture control, and how device behaviour can be personalized to an individual's preferences.

ACKNOWLEDGEMENT

This material is based upon work supported by the University of California at Berkeley and a National Science Foundation Graduate Research Fellowship under Grant No. DGE 1752814. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] National Spinal Cord Injury Statistical Center. Spinal Cord Injury Facts and Figures at a Glance 2019. https://www.nscisc.uab.edu. Accessed: 2019-08-24.

[2] L. Harvey, J. Batty, *et al.*, "Hand function of c6 and c7 tetraplegics 1–16 years following injury," *Spinal Cord*, vol. 39, no. 1, p. 37, 2001.

[3] K. D. Anderson, "Targeting recovery: priorities of the spinal cord-injured population," *Journal of neurotrauma*, vol. 21, no. 10, pp. 1371–1383, 2004.

[4] S. Mateo, P. Revol, *et al.*, "Kinematic characteristics of tenodesis grasp in c6 quadriplegia," *Spinal cord*, vol. 51, no. 2, p. 144, 2013.

[5] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Trans. on Robotics and Automation*, vol. 5, no. 3, pp. 269–279, 1989.

[6] M. Santello, M. Flanders, and J. F. Soechting, "Postural hand synergies for tool use," *Journal of Neuroscience*, vol. 18, no. 23, pp. 10 105–10 115, 1998.

[7] A. A. Portnova, G. Mukherjee, *et al.*, "Design of a 3d-printed, open-source wrist-driven orthosis for individuals with spinal cord injury," *PloS one*, vol. 13, no. 2, p. e0193106, 2018.

[8] Y.-S. Kang, Y.-G. Park, *et al.*, "Biomechanical evaluation of wrist-driven flexor hinge orthosis in persons with spinal cord injury," *Journal of Rehabilitation Research and Development*, vol. 50, no. 8, pp. 1129–1138, 2013.

[9] Becker Orthopedic. U-17: Wrist Driven Wrist Hand Orthosis. https://www.beckerorthopedic.com. Accessed: 17 Jan 2020.

[10] C. Shepherd and S. Ruzicka, "Tenodesis brace use by persons with spinal cord injuries." *American Journal of Occupational Therapy*, vol. 45, no. 1, pp. 81 – 83, 1991.

[11] D. Kaneishi, R. P. Matthew, *et al.*, "Hybrid control interface of a semi-soft assistive glove for people with spinal cord injuries," in *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, 2019.

[12] S. Ates, C. J. Haarman, and A. H. Stienen, "Script passive orthosis: design of interactive hand and wrist exoskeleton for rehabilitation at home after stroke," *Autonomous Robots*, vol. 41, no. 3, pp. 711–723, 2017.

[13] D. Kaneishi, J. E. S. Leu, *et al.*, "Design and preliminary assessment of a semi-soft assistive glove for people with spinal cord injuries," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2019.

[14] S.-S. Yun, B. B. Kang, and K.-J. Cho, "Exo-glove pm: an easily customizable modularized pneumatic assistive glove," *IEEE Robotics and Automation Letters*, vol. 2, no. 3, pp. 1725–1732, 2017.

[15] L. Cappello, J. T. Meyer, *et al.*, "Assisting hand function after spinal cord injury with a fabric-based soft robotic glove," *Journal of neuroengineering and rehabilitation*, vol. 15, no. 1, p. 59, 2018.

[16] M. Zhu, T. N. Do, *et al.*, "Fluidic fabric muscle sheets for wearable and soft robotics," *Soft Robotics*, vol. 7, no. 2, 2020.

[17] F. Negrello, H. S. Stuart, and M. G. Catalano, "Hands in the real world," *Frontiers in Robotics and AI*, vol. 6, p. 147, 2020.

[18] L. Birglen and C. M. Gosselin, "Geometric Design of Three-Phalanx Underactuated Fingers," *Journal of Mechanical Design*, vol. 128, no. 2, pp. 356–364, 04 2005.

[19] R. Brumfield and J. Champoux, "A biomechanical study of normal functional wrist motion," *Clinical orthopaedics and related research*, no. 187, p. 23—25, 1984.

[20] M. King, J. Verkaaik, *et al.*, "A wrist extension operated lateral key grip orthosis for people with tetraplegia." *Technology Disability*, vol. 21, no. 1/2, pp. 19 – 23, 2009.

[21] Q. A. Boser, M. R. Dawson, *et al.*, "Defining the design requirements for an assistive powered hand exoskeleton," *bioRxiv*, 2018, accessed: 21 Jan 2020.