A Case Study With Symbihand: An sEMG-Controlled Electrohydraulic Hand Orthosis for Individuals With Duchenne Muscular Dystrophy

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***Abstract*— With recent improvements in healthcare, individuals with Duchenne muscular dystrophy (DMD) have prolonged life expectancy, and it is therefore vital to preserve their independence. Hand function plays a central role in maintaining independence in daily living. This requires sufficient grip force and the ability to modulate it with no substantially added effort. Individuals with DMD have low residual grip force and its modulation is challenging and fatiguing. To assist their hand function, we developed a novel dynamic hand orthosis called SymbiHand, where the user's hand motor intention is decoded by means of surface electromyography, enabling the control of an electrohydraulic pump for actuation. Mechanical work is transported using hydraulic transmission and flexible structures to redirect interaction forces, enhancing comfort by minimizing shear forces. This paper outlines SymbiHand's design and control, and a case study with an individual with DMD. Results show that SymbiHand increased the participant's maximum grasping force from 2.4 to 8 N. During a grasping force-tracking task, muscular activation was decreased by more than 40% without compromising task performance. These results suggest that SymbiHand has the potential to decrease muscular activation and increase grasping force for individuals with DMD, adding to the hand a total mass of no more than 241 g. Changes in mass distributions and an active thumb support are necessary for improved usability, in addition to larger-scale studies for generalizing its assistive potential.**

***Index Terms*— Daily assistance, duchenne muscular dystrophy, hand orthosis, electrohydraulic, sEMG control.**

I. INTRODUCTION

DUCHENNE muscular dystrophy (DMD) is a progressive neuromuscular disease and is the most common form of muscular dystrophy, affecting approximately 1 in 5000–6000 live births [1], [2]. It results in severe disability, a strong dependence on care [3], and a subsequent decline in functional abilities [4]. Recent scientific advances have increased the life expectancy of individuals with DMD up to 40 years [5], leading to an increase in the number of adults with DMD living with severe physical impairments and decreased functionality [6].

The hand plays a central role in performing activities of daily living (ADL), and its use is related to an increased quality of life in individuals with DMD [7]. ADL require sufficient grip forces and additionally the ability to modulate those, without additional effort or fatigue. In DMD, the hand grip force significantly declines after the age of 12, accompanied by early fatigue onset [8], leading in increasing inability of performing ADL [9]. However, hand treatment for such individuals is not receiving a lot of attention [10], and there is no evidence of training grip force modulation or hand fatigue reduction in individuals with DMD. Existing studies highlight the importance of hand function in DMD and the need for more studies regarding grasping force that showcase that early interventions might slow the deterioration process [11].

Current hand treatment for individuals with DMD, includes physical therapy [10] or the use of hand splints during the night, which preserve the passive range of motion of the wrist and thumb [12], yet do not train grip force modulation or attenuate fatigue. Active assistive devices, however, can improve the quality of life of individuals with DMD and enhance their social participation [13], by addressing those issues. Evidence is increasingly highlighting the need for a comprehensive and multidisciplinary rehabilitation of individuals with DMD [5], [14] that favors the use of dynamic hand orthoses.

Dynamic hand orthoses require a robust and intuitive way of decoding the user's intention and controlling the resulting

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mechanical output [15]. Surface electromyography (sEMG) is a well-established method of decoding the motor intention of a user [16] and is broadly used to enable the control of active hand orthoses [17]. Direct sEMG control was successfully tested in the past with individuals with DMD, combined with a first-order admittance model to control active elbow/shoulder orthoses [18], [19]. Two conference proceedings from Polygerinos et al. [20], [21] with participants suffering from muscular dystrophy show promising results for the motor intention decoding of the hand motion. Additionally, there is work measuring weak sEMG signals in other patient populations such as stroke [22], and designing active orthoses for people with stroke or spinal cord injury (SCI) [23], [24]. However, these conditions are not directly comparable to DMD due to differences in muscle activation, muscle strength and the presence of spasticity [25]. To the authors' best knowledge, there is no evidence of the use of this sEMG for the real-time decoding of hand motor intention with individuals with DMD, in combination with a first-order admittance model and hydraulic transmission. This is applied for the first time in the current study combined with a new dynamic hand orthosis.

A large number of existing hand orthoses can be found [17], but none of them were deemed suitable for individuals with DMD. Important requirements are the ability to don individual finger elements, minimum shear forces on the skin and minimum perceived mass on the hand [26]. This resulted in choosing for a hydraulic transmission for its high energy density and transparent force transmission, and flexible structures to minimize the shear force components on the skin. Additionally, a hydraulic circuit is able to couple each finger element by force with flexible tubing, allowing for each finger element to be donned one-by-one while also providing a self-adaptive grasp. However, small-scale hydraulic components are not easily available as commercial products [17]. In this study, hydraulic components were customized to fit into a low-profile mechanism while still providing sufficient pressure resilience. Additionally, a first order admittance model was employed, in order to manipulate the virtual dynamics of the hand orthosis and add an extra level of control customization for the participant as proposed in [25]. In combination with sEMG control, the combined system is called SymbiHand.

The objective of this study was to assess SymbiHands' potential to actively assist the grasping function of an individual with DMD in a case study. The primary purpose of SymbiHand is to augment the user's grasping force and additionally reduce the muscular activation needed to open/close the hand. This can help to extend the hand functionality of individuals with DMD and delay the onset of fatigue related to grasping.

II. METHODS

A. Participants

One 23-year-old male participant, diagnosed with DMD, took part in this study. He had not used hand splints in the past, and his dominant right arm was actively assisted by an arm support (TOP/HELP, Focal Meditech, Tilburg, Netherlands). He had a Brooke score [27] of 5 (range 0 - 6), meaning that he cannot raise hands to the mouth, but could use his hands to hold a pen or pick up pennies from the table. The Performance of Upper Limb (PUL) score [28] was 8 out of a maxmimum of 74 (summation of: 0 on the shoulder dimension, 1 on the elbow dimension, and 7 on the wrist/hand dimension). Minimal contractures relevant to finger movement were observed, and the range of motion (ROM) of the fingers was quite well preserved, yet slightly limited. However, he was experiencing early fatigue onset and a substantial decrease in grasping force. The severe hand/wrist weakness of the participant could highlight the effect of SymbiHand, combined with the absence of extensive finger contractures (that would made donning/doffing challenging and would not allow a large ROM support) and his availability for participation in the needed time-frame, made him an ideal participant for this case study.

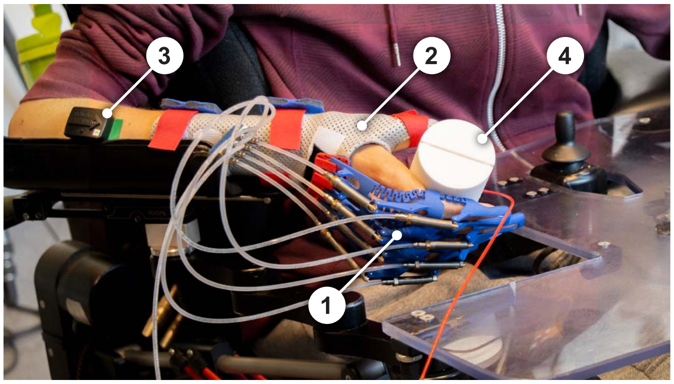

Fig. 1. The participant with DMD grasping the sensorized object while wearing SymbiHand orthosis. 1) SymbiHand, consisting of four finger modules. 2) The thermoplastic hand splint, used to stabilize the wrist and thumb while providing an anchoring surface for the four finger modules. 3) Wireless sEMG sensor, placed on the extensor digitorum communis muscle. 4) The cylindrical sensorized object, used for measuring grasping force.

The study design, experimental protocol, and procedures were approved by the Delft Human Research Ethical Committee (HREC) under ID 482. The study was conducted according to the ethical standards given in the Declaration of Helsinki of 1975, as revised in 2008. The participant was informed via a letter and signed a consent form prior to the experiment.

B. SymbiHand

A picture of the manufactured prototype of SymbiHand worn by the participant is shown in Fig. 1 and a video of the participant controlling SymbiHand in real-time in [29]. The total mass on the hand was 241g. Table I shows a more detailed mass distribution. The piston pump assembly, which includes the master cylinder, had a mass of 526g.

SymbiHand consists of components in the signal, energy, and mechanical domain (Fig. 2) [17]. It aids the user in performing tasks by exchanging signals and physical interactions with the user, who, in turn, interacts with the environment. The intention of the participant was decoded in real time with the use of direct sEMG control, combined with a first-order admittance model and enabled voluntary opening/closing of the hand orthosis. A sensorized cylindrical object (Fig. 1) was

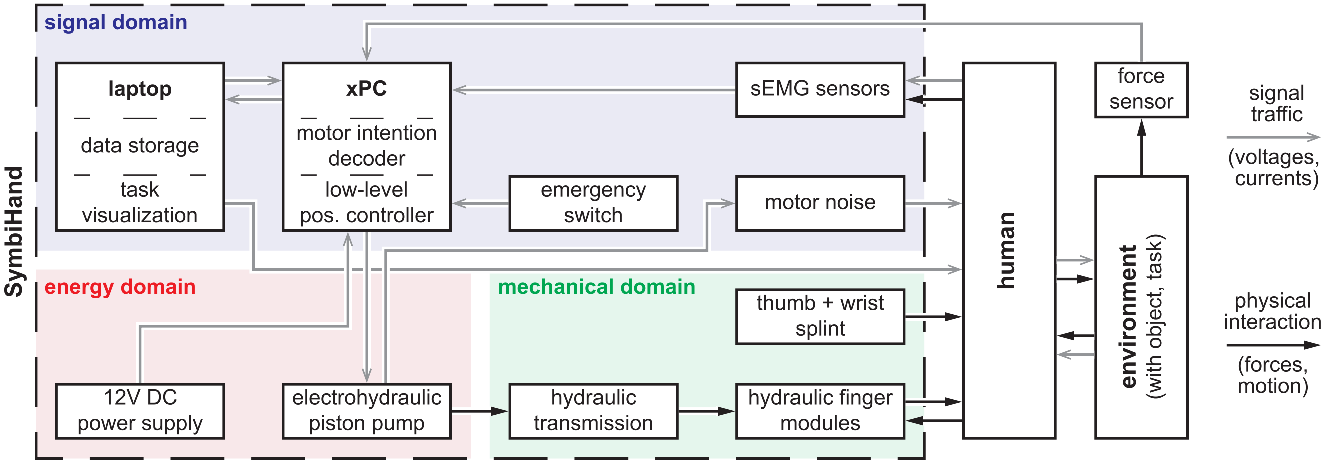

Fig. 2. System overview of the different components of SymbiHand, subdivided into a signal, energy, and mechanical domain.

TABLE I

MASS DISTRIBUTION OF THE PARTS ON THE HAND

Part	**Mass (g)**
Finger interfaces (4x)	29
Slave cylinders (8x)	65
Manifold	25
Hoses with fluid	24
Wrist and thumb splint	70
Trigno Avanti Sensor (x2)	28
Total mass on hand	*241*

used to measure the grasping force, as input for a real-time force-tracking task. The following paragraphs describe the key components in detail and are supported by a visual representation of the working principle of the device's actuators, sensors and control methods in Fig. 3.

1) Signal Domain: In this study, direct sEMG control [15] was used to decode a one degree-of-freedom (DOF) hand motion (open/close). After cleaning the participant's skin with alcohol to enhance signal quality, two dry wireless electrodes (Trigno, Delsys Inc., Natick, MA, USA) were put in place. One above the muscle belly of the extensor digitorum communis (EDC) and one above the muscle belly of the flexor digitorum superficialis (FDS). The exact placement was performed by palpation until a clear signal was found in relation with the requested motion (i.e hand closing for FDS and hand opening for EDC). The two sEMG signals were used to decode the hand opening-closing motor intention of the participant and enable the direct sEMG control of the orthosis. The EDS signal (Fig. 1) corresponded to hand opening and the FDS to hand closing. The same sEMG signals were used to measure muscular activation during the task.

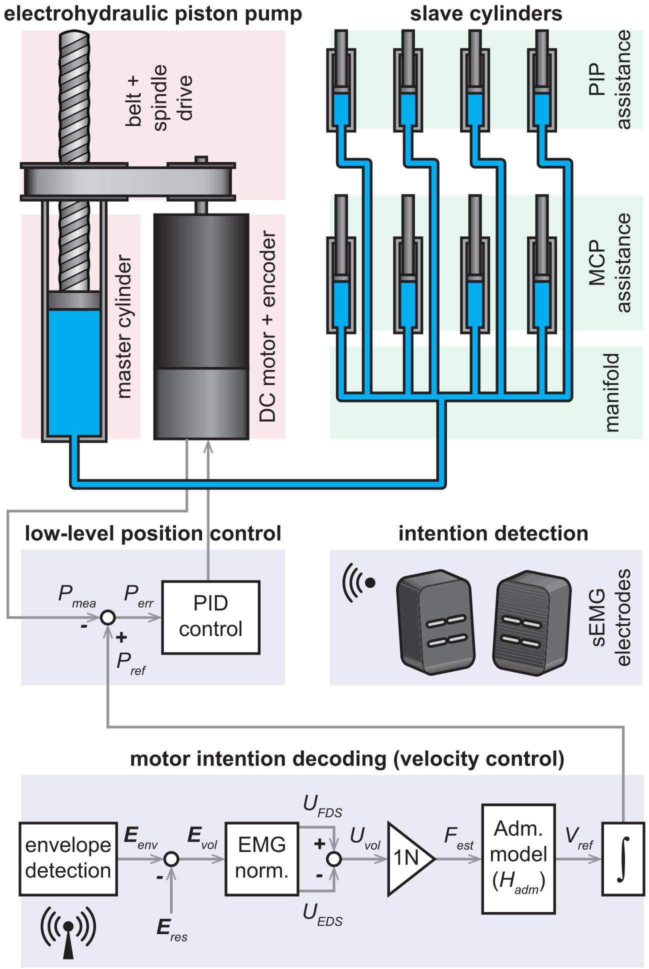

Fig. 3. Detailed overview of the system, illustrating overall working principle and key components.

The lower part of Fig. 3 presents a detailed diagram of the signal processing. Raw sEMG signals were initially digitally filtered with a high-pass filter (2nd order Butterworth filter, $f_{c,hp} = 20\ Hz$) to reduce any movement artefacts. The envelopes of the sEMG signals ($\mathbf{E}_{env}$) were obtained by applying full-wave rectification and a low-pass filter (4th order Butterworth filter, $f_{c,lp} = 2\ Hz$). The offsets of both the EDS and FDS envelopes were corrected by subtracting the resting sEMG envelope ($\mathbf{E}_{res}$), which was measured while the participant was completely relaxed. The resulting signals ($\mathbf{E}_{vol}$) were subsequently normalized to their own maximum voluntary contraction (MVC) value. Lastly, the normalized extensor envelope (U_{EDS}) was subtracted from the normalized flexor envelope (U_{FDS}) in order to create the normalized sEMG control signal (U_{vol}). This was multiplied by a conversion gain of 1N in order to acquire the estimated force (F_{est}), which served as input to a first-order admittance model similar to that carried out by Lobo-Prat et al. [19]:

$$H_{adm}(s) = \frac{1}{As + B} \tag{1}$$

Here, A represents the parameter related to virtual inertia (10^{-1}) and B the parameter related to virtual damping (10). The values were chosen in accordance with the participant's preferences and determined during a pre-trial. The manipulation of the virtual dynamics with the help of the admittance model aimed to create a responsive (dictated by inertia) yet stable (dictated by damping) interaction between the user and the device. The admittance model expected a force (estimated from the sEMG signals) as an input, i.e., a normalized signal that is negative for hand opening and positive for hand closing. The output of the admittance model was the reference velocity for the linear spindle (V_{ref}) based on the participant's intention. The reference position was obtained through integration (P_{ref}) and was sent to the low-level position controller (Fig. 2 in the signal domain and Fig. 3), in order to control the position of the linear spindle. The PID controller sent the calculated voltage to the motor driver (ESCON 24/2, Maxon Motor AG, Sachseln, Switzerland which in turn controlled the current of the motor (118743, RE25 10W, Maxon Motor AG, Sachseln, Switzerland).

The grasping force was measured in real time with the use of a sensorized cylindrical object (Fig. 1). For this purpose, a miniature S-beam load cell (FH04086, FUTEK Advanced Sensor Technology, Irvine, CA, USA) was incorporated in a 3D-printed cylindrical object with a diameter of 60 mm. The measured grasping force was normalized to the maximum voluntary force (MVF) produced by the participant without the orthosis and used for the visualization of the force-tracking task. The object included an indentation where the thumb could be placed in order to ensure that the grasping force direction was aligned with the axis of the load cell.

The analog signals of the sEMG electrodes and the force sensors were measured with the use of a real-time computer (xPC Target, MathWorks Inc., Natick, MA, USA) and by means of a data acquisition card (PCI-6229, National Instruments Corp., Austin, TX, USA). The analog data was converted to a digital signal with a 16 bit resolution and at a sampling frequency of 1 kHz.

2) Energy Domain: In order to minimize the perceived mass on the hand, the actuation module was separated from the finger modules that were donned on the hand. This required a flexible force transmission to accommodate free movement of the hand in space. Due to the constant friction value and its independence on hose routing [30], a hydraulic transmission was chosen over a Bowden cable transmission. This makes the force transmission more transparent for the user, which ideally leads to a more predictable link between the generated sEMG signal and desired assistive force.

To support this transmission, a hydraulic piston pump was used to convert electrical energy from the power supply into mechanical work in the form of hydraulic pressure. Differently than our previous design [26], a custom-made pump was used, because an off-the-shelf version could not be found that was able to provide the desired pressures and flow rates. The pump was able to create pressures well up to 5.0 MPa. However, because of the frailness of the fingers among individuals with DMD, and thus to reduce the risk of harming the participant, the current to the piston pump was limited to approximately 35% of the motor's maximum continuous current. This way, pressures could not exceed 1.5 MPa during the study.

Fig. 3 shows the working principle of the electrohydraulic pump. It used a 12V DC motor (118743, RE25 10W, Maxon Motor AG, Sachseln, Switzerland) to move a spindle drive via a belt transmission. The spindle was directly connected to the piston of the master cylinder with a ⌀8 mm bore diameter and was able to generate pressure in a closed hydraulic circuit. The spindle drive's travel distance was limited with mechanical stops at 60 mm, which resulted in a maximum fluid displacement of 3 mL. The linear velocity of the spindle was limited to 10 mm/s (i.e., flowrate of 0.5 mL/s, 6 s for full flexion/extension). This value was, after a few trials, chosen by the participant as the maximum velocity that gave him a feeling of stable and safe control.

3) Mechanical Domain: Mechanical work was transmitted using a hydraulic master-slave system [26]. The master cylinder was integrated in the electrohydraulic piston pump, dividing its pressure among all slave cylinders that were fixed on the finger modules, creating an underactuated system with an adaptive grasp. Fig. 3 shows how the slave cylinders were connected. Each finger module was equipped with two slave cylinders that acted on the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint. The distal interphalangeal (DIP) joint was not actuated but was protected from overextension using passive structures. Valves can be used to selectively move one or multiple finger modules, allowing for individual finger movements or movement patterns [26]. In this study, in the interest of a simple control method, only a single DOF was controlled, and the use of valves was therefore omitted. The mechanical structure of SymbiHand was previously described in more detail in [26].

The slave cylinders were custom-made single-acting hydraulic cylinders, with an active protraction and passive retraction using return springs. The return springs were fixed on the outside of the cylinder and could easily be interchanged with springs with a higher or lower stiffness, allowing for adjustments towards the preferences and conditions of an individual. In this study, all cylinders were equipped with stainless steel springs with a stiffness of 0.01 N/mm (T40740E, Tevema Technical Supply BV, Almere, Netherlands). Water was used as the hydraulic fluid, which was degassed before filling the hydraulic circuit. A ⌀3 mm tubing material (Legris 1025P03 00 18, Parker Hannifin Corporation, Cleveland, OH, USA) was used to connect all slave cylinders to a manifold, which was connected to the piston pump using a single tube.

The finger modules served as the interface between the slave actuators and each finger, where the size was adjusted to the measurements of the participant's fingers [26]. In addition, the wrist and thumb were fixed in a functional position using a thermoplastic splint (Rolyan PAT-081572429, Performance Health, Warrenville, IL, USA). The wrist was slightly extended with the thumb in opposition, such that the tip of the thumb could oppose the tip of the index and middle fingers to allow for a three-jaw chuck grasp. Similar to all other fingers, the thumb's most distal joint (interphalangeal (IP) joint) was only protected against overextension, leaving the palmar area and as much as possible of the lateral side available for tactile feedback.

The orthosis could be donned by first securing the wrist and thumb splint using Velcro straps. Each finger module could then be slid on the fingers one by one, and attached to a snap-fit mechanism on the dorsal side of the splint. These snap-fit mechanisms were attached to the splint using Velcro, allowing for corrections in the distal or proximal direction.

C. Experimental Protocol

The participant took part in two sessions, the first of which included the construction of the thermoplastic hand splint with the help of an occupational therapist and the measurement of the fingers for customizing SymbiHand. During the second session, and in order to assess whether SymbiHand could potentially provide assistance during activities of daily living, the participant was asked to perform a force-tracking task using the grasping force as input. For this purpose, an open-fist cylindrical grasp [31] was carried out on a sensorized cylindrical object, without and with the hand orthosis.

At the start of the second session, and prior to the force-tracking task, the participant was asked to grasp the object as hard as possible for two seconds, simultaneously giving an MVF measured with the sensorized object and an MVC measured with both sEMG signals. Both MVF and flexor MVC were acquired as the mean signal over the period of two seconds of active grasping. The extensor MVC was recorded separately by asking the subject to extend his fingers against resistance. The envelopes were used for the calculation of the MVC. During the force-tracking task, the participant was asked to grasp the same object, while also tracking a reference force trajectory that ramped up (hand close) to a specific percentage of the MVF for 3 s, remained there (hold) for 1.5 s, and then ramped down (hand open) to zero again for 3 s. These percentages were varied between 10, 20, and 30% of the MVF, in order to keep the participant effort low and avoid fatigue onset. The chosen reference trajectory (similar to the one applied by Kurillo et al. [32]) provided a complete task with a proportional component that required force tuning (necessary for various ADL tasks) and a force steadiness component (necessary for holding objects). Each force level was repeated three times in a group of nine trials, and each group was repeated twice, resulting in a total of 18 trials without and 18 trials with the orthosis, and 6 trials per MVF level. After every nine trials, a resting period of at least two minutes was given to the participant to avoid the effects of fatigue in our data. All trials were executed in a randomized order to avoid order effects on our data.

Afterwards, the participant was fitted with SymbiHand, while the sEMG sensors remained donned. At first, the participant was allowed to familiarize himself with the device and its control for 10 minutes. This was followed by the same task as described previously, including a new measurement of the maximum attainable grasping force, only now with SymbiHand. To conclude the experiment, any additional informal feedback was registered. The datasets generated for this study can be found online in the IEEEDataPort repository (DOI: 10.21227/gerz-8s29).

D. Data Analysis

1) Muscular Activation & Grasping Force: Muscular activation and grasping force were taken as the main outcome measures in this study. The raw force signal was low-pass filtered (2^{nd} order Butterworth filter, $f_{c,lp} = 20\ Hz$), before the analysis. The grasping force was used to determine force-tracking performance, defined as the root mean squared error (RMSE) between the imposed force trajectory and the average grasping force exerted by the participant, per MVF level. Additionally, force generation rate was calculated as the slope of the average normalized force exerted by the participant during the grasping phase. MVC and MVF measurements were taken as a measure of the participant's maximum capacities and used to normalize force and sEMG. All data were recorded both without and with SymbiHand.

2) Maximum Flexion Angle: Maximum flexion angle of the index finger was assessed by photogrammetry [33]. Photographic images (EOS 70D, EF-S 18–135mm, Canon Inc, Tokyo, Japan) were taken from the radial side of the participant's hand and analyzed in image processing software to quantify the angle between the phalanges. This was done both without and with the hand orthosis to evaluate any differences that the orthosis may impose. We chose to perform this analysis only for the index finger in order to create a representative example without encumbering the participant further by taking photos of each finger separately.

III. RESULTS

A. Muscular Activation & Grasping Force

Muscular activation from the extensors and flexors for all repetitions at every force level are shown in boxplots in Fig. 4 (The relevant raw and filtered sEMG data can be found online: DOI: 10.21227/gerz-8s29). The average and minimum/maximum values of the force-tracking tasks for every force level are shown in Fig. 5. SymbiHand was able to increase the participant's maximum grasping force of the cylindrical object from 2.4 to 8 N, with a slight increase in flexor muscular activation (+12%). This slight increase in flexor muscular activation may be the results of donning the orthosis (external finger load, changes in muscle length and stabilization of the wrist). Moreover, without compromising force-tracking performance, extensor muscular activation was reduced by an average of 40% and flexor by an average of 55%. The participant exhibited a similar reaction delay in the onset of tracking both with and without the orthosis during the force-tracking task, but exhibited higher force generation rate in all conditions except the 10% MVF, while wearing SymbiHand (Fig. 5).

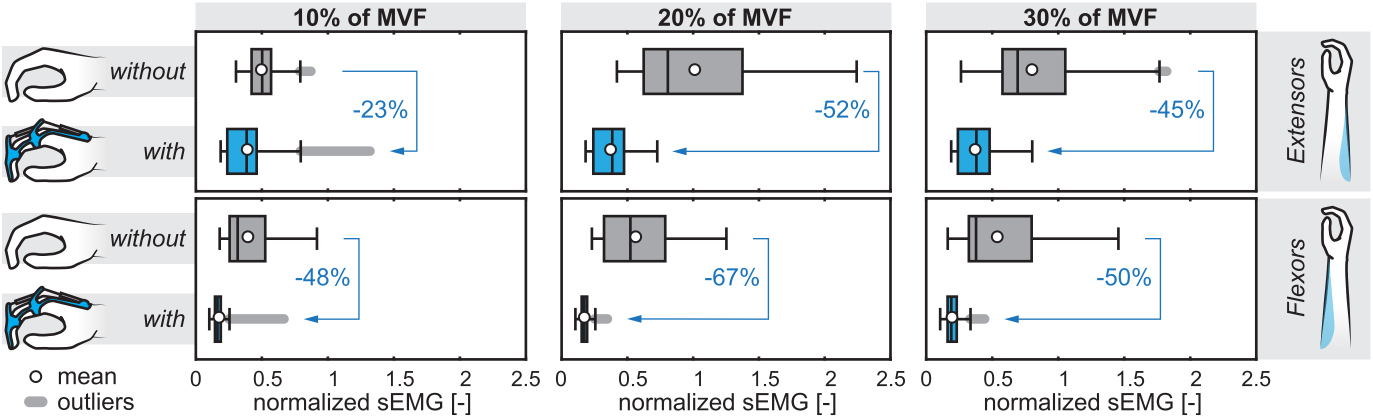

Fig. 4. Normalized muscular activation of the extensor and flexor muscles while performing the task at 10%, 20%, and 30% of the participant's MVF, without and with SymbiHand. For each level of MVF, the muscular activation was averaged over the duration of the 6 trials, corresponding to that level. Percentages inside the figure windows indicate drops according to the median value. sEMG was normalized according to the MVC without SymbiHand (Flexor: 8.3 mV, Extensor: 12.3 mV). Horizontal lines represent the median while circles represent the mean values. The outliers were used for the calculation of the median and were visualized as those observations falling below Q1 − 1.5·IQR or above Q3 + 1.5·IQR.

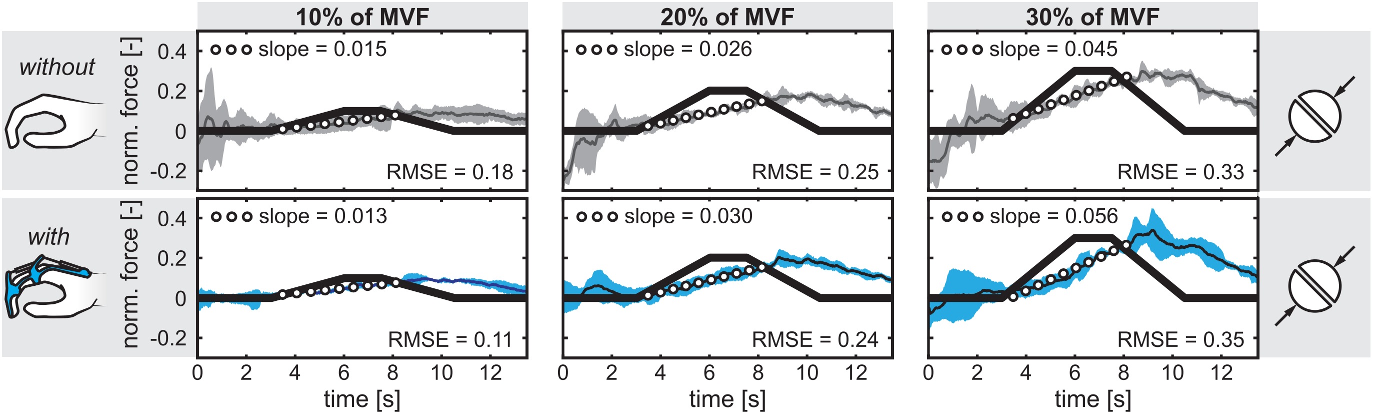

Fig. 5. Normalized force-tracking performance while performing the task at 10%, 20%, and 30% of the participant's MVF, without and with SymbiHand. Generated force with and without SymbiHand was normalized according to the MVF (2.4 N) and averaged across the 6 trials per MVF level. The root mean square error (RMSE), between the imposed force trajectory and the average grasping force exerted by the participant is showed as well as the slope of the participant's average grasping force (equidistant circles) with and without SymbiHand.

B. Maximum Flexion Angle

Since the participant was experiencing minimal contractures,(which was reflected by a slightly reduced active maximum flexion angle), we limited the range of motion of the SymbiHand to accommodate the participant's comfortable limits. Taking the index finger as an illustrative example, maximum flexion angles without/with the hand orthosis were approximately 46°/51°, 91°/84° and 39°/22° for the MCP, PIP, and DIP joint, respectively. The hand orthosis therefore barely limited the active maximum flexion angle.

C. Participant Feedback

The participant indicated that the finger modules did not feel comfortable. Despite a polished finish, the 3D-printed material felt rough and had a few ragged edges. Because the participant's fingers and skin were much more sensitive than that of a healthy individual, a cutting feeling was experienced at the skin creases on the palmar side of the finger joints. The wrist and thumb splint was quite comfortable for the participant while he was wearing it, and it provided sufficient support. However, donning the splint was quite cumbersome; in particular, when the MCP knuckles had to be slid through an opening that was a little bit too small, it was unpleasant to the participant.

IV. DISCUSSION

A. Motor Intention Decoding

The combination of direct sEMG control with a first-order admittance model enabled the participant to control SymbiHand, by providing an additional level of control customization. Results showed a decrease in muscular activation while wearing the orthosis, without the loss of tracking performance. This is supporting evidence for the intuitiveness of the proposed motor intention decoding method. The participant adapted within 10 minutes of training, showing a strong training effect, as already suggested in previous studies with individuals with DMD [19].

Being able to open and close the hand allows for a large variety of power grasps frequently used during household activities [34], such as medium wrap and power sphere. Our choice for direct sEMG was largely motivated by the fact that only a single DOF needed to be controlled. For more DOF, however, direct sEMG control requires the generation of independent sEMG signals and the identification of independent sites for their acquisition, which can be cumbersome for the user and may result in a limited number of simultaneously controlled DOF [35]. In order to increase the range of assistance provided by SymbiHand (e.g., with an active thumb), in addition to enabling the control of more grasps used during dynamic ADL [36] (e.g., by adding valves), different sEMG-based motor decoding approaches should be explored. Future work will investigate the possibility of employing regression [37], pattern recognition [35], or EMG-driven model-based techniques [38], [39]. Nevertheless, such approaches are still not broadly applied in clinical practice for hand orthoses, mainly due to the challenges they present for daily use in a home environment compared to direct sEMG control. Such challenges include the larger number of electrodes, longer and more frequent training and calibration, and a lack of robustness to electrode shift due to arm movements (e.g., pronation/supination as opposed to the fixed resting arm position used in this study).

In addition to an intuitive intention detection, it was essential that the participant could use his own intrinsic physiological feedback mechanisms (e.g., tactile and auditory feedback, proprioception, and vision) during the experiment. Hence, no explicit forms of augmented feedback were applied, resulting in a simple and easy-to-use approach. Implicitly, aside from the interaction force between the orthosis and the participant, motor noise could also be used as additional auditory information on the orthosis' operating conditions.

The reaction delay in tracking onset that the participant exhibited during the force-tracking task was similar both with and without the orthosis and cannot be attributed to the motor intention decoding. This delay in reaction time may be the result of the limited training time and the specific condition of the participant. Despite this, the participant was able to modulate forces of the same magnitude, albeit with lower muscular activation, and additionally, in two out of three conditions (20% and 30% conditions) his force generation rate was higher while wearing SymbiHand.

B. Mechanical Design

The hardware components of SymbiHand were well able to provide the necessary assistance to improve the participant's grasping performance. The mass on hand is slightly less than the comparable soft hydraulic hand orthosis from Polygerinos et al. [20], [21], with the added advantage that the rigid pistons are capable of providing maximum assistance across the ROM. Yap et al. [24] and Capello et al. [23] achieved masses of 180g and 77 g respectively for their orthoses. However, these studies used a compressible gas as medium as opposed to a hydraulic fluid. Using a gas can indeed result in a lower mass, but it decreases energy density and reduces transparency of force transmission due to its compressible nature. Nonetheless, even though these hand orthoses were subject to different design choices due to differences in target groups (i.e., spasticity and different level of assistance in stroke and SCI survivors compared to individuals with DMD), it implies that further mass reductions are required to compare with the state-of-the-art.

The output force of SymbiHand is comparable with and in many cases exceeds that of the devices listed in [17]. However, it is emphasized that these capabilities exceed the assistance needs of this participant, which provides an opportunity for further device optimization by miniaturization of components and improvement of comfort, if this is generalizable across individuals with DMD. The flexure elements proved to be effective in aligning the orthosis' rotational centers with those of the anatomical joints. The bending shape of the flexure elements was able to self-align to the location of the anatomical joints. The use of standard hand sizes (e.g., small, medium, and large) are therefore possible, avoiding the need to manufacture bespoke parts. The retraction springs on the slave cylinders were strong enough to extend the fingers back to a slightly flexed resting position. These factors indicate that the overall design of the hand orthosis works as intended and has the potential to help increase the hand functionality of an individual with a muscular weakness.

Donning the different parts of the hand orthosis was difficult and uncomfortable for the participant. First, the tight fit of the wrist and thumb splint made it unpleasant to don. Second, because the fingers were so sensitive, sliding the finger modules on the fingers was not quite comfortable. As a result, the finger modules could not be donned easily one by one because the stiffness of the hydraulic hoses would add additional forces to the fingers. We believe that a modular or hinged splint with additional straps could help to reduce these problems, as well as finger modules that allow for quick and easy donning from the dorsal side of the hand. Changes in material may also contribute to a more comfortable interaction, as long as the load-bearing portions provide sufficient rigidity to transfer the loads without deformations. Third, positioning the thumb in opposition to the volar pads of the index and middle finger put it in an awkward resting position. This means that an additional thumb mechanism that is able to switch between a resting and functional position is necessary.

Despite the low mass of SymbiHand, the added mass was still an issue for the participant. The arm support could help with lifting the arm, but the high concentration of mass on the dorsal side of the hand made it impossible to pronate/supinate. A more strategic distribution of mass could be used to reduce the moment of inertia around the center of rotation of this particular movement. Additionally, overall mass reductions are possible, e.g., by making the hydraulic parts more lightweight. We also believe that the little finger does not need active support because the corresponding finger module only seemed to get in the way while grasping an object or while orienting the hand along the wheelchair tray. The ring finger can possibly be omitted as well, but further research is required with regard to how this reduction in mass and complexity affects the attainable grasping performance.

C. Relevance

As this paper presents a case study, we cannot generalize the results over all individuals with DMD that might benefit from SymbiHand. For our participant, the assisted grasping force was still low (8 N), yet fitting to the individual's comfortable limits and still sufficient for a subset of ADL that require a maximum of 7.4 N (such as drinking, using a fork/pen or lifting a can/book [40]–[42]). Especially compared to the original 2.4 N the participant could exert without SymbiHand, that is barely sufficient for any ADL. Due to various levels of contractures, preferred assistance or time for familiarization with the device that may help the user build confidence in its control, the magnitude of (assisted) grasping force and muscular activation may vary. This can lead to larger grasping forces and broaden the range of ADL that the user can perform. The applied current limit to the motor, however, implies that the device was over-dimensioned for this particular participant. The main reason for this added limit was to prevent exerting excessively high forces and flexion velocities on the sensitive fingers and skin of an individual that is not familiar in being assisted by a dynamic hand orthosis.

The increased muscular activation observed during the tracking task without the orthosis - especially in the extensor muscles, which were not expected to be that active during a grasping task - may be attributed to the effort of the participant to stabilize his wrist without the orthosis. While wearing SymbiHand, the wrist was supported by a thermoplastic splint, which may have contributed to the large reduction in baseline muscular activation. This may be a strong indication of the importance of supporting the wrist. However, further research is needed to investigate the effect of passively supporting the wrist on the reduction of muscular activation during functional hand use. Additionally, since many individuals with DMD suffer from strong contractures of their finger flexor muscles [12], it is interesting, in the future, to test the capacity of SymbiHand to assist an extension focused task.

The fact that the participant was able to control the hand orthosis without any artificial sensors at the end-effector (i.e., strain gauges and potentiometers placed on the hand) shows that the hydraulic transmission provided a predictable link between muscular activation and the speed of the orthosis. This makes the use of miniature hydraulic technology very interesting in the field of assistive devices controlled by the means of human intention detection schemes. In the presented hand orthosis, however, pressures are still quite low for a hydraulic system ($<$1.5 MPa). Even smaller hydraulic cylinders can be used to further improve efficiency, and a smarter way of integrating the hydraulic circuit within the mechanism can result in a more inconspicuous design. The hydraulic hoses in the presented prototype, for example, decrease overall cosmesis and may get in the way in a daily environment.

The combination of SymbiHand with elbow/shoulder [19] and trunk [43] orthoses for individuals with DMD can increase the reachable workspace, by allowing individuals with DMD to functionally interact with their environment. Furthermore, we believe that the use of SymbiHand can be extended to more pathologies, e.g., the daily assistance of elderly individuals with weakened muscles due to sarcopenia or individuals with stroke and SCI that have reduced hand strength. However orthoses for such conditions would require different control in order to decouple voluntary from involuntary sEMG due to spasticity and additionally offer assistance as needed. They may also require different mechanical and hardware design choices, tailored to the specificity of each condition (i.e. different power output or donning/doffing). Another interesting application is a combination with augmented reality for a broad range of physical therapy exercises, as proposed by Bushby et al. [5], [14].

Future work will include more participants with similar condition as the participant of this study (low grip strength and preserved ROM). A more extensive protocol including ADL relevant tasks and measurements both in clinical and home settings would offer further insight in the long-term changes of the control over time and the feasibility of our approach for daily support. Nonetheless, the presented quantitative differences without and with Symbihand show that this participant was able to preserve force-tracking task performance, reduce muscular activation while wearing the hand orthosis, and his maximum grip force was tripled. As we mainly focused on force reference tracking, we did not provide any analysis on force steadiness or smoothness. Acknowledging the need for an intervention to address the hand function of individuals with DMD [10]–[12] we believe that after the recommended design improvements, SymbiHand can reduce the burden on the muscles, delay the onset of fatigue, and lengthen the time span in which the user can use his own hand.

V. CONCLUSION

This case study has shown that an individual with DMD underwent an amplification of grip strength, with no loss of tracking performance, while wearing SymbiHand. The results have shown that, along with grip strength amplification, SymbiHand enabled reduction in muscular activation during a force-tracking task. This was realized using a direct sEMG control approach with a tuned admittance model, in combination with a hydraulic transmission and differential mechanism. This has never been demonstrated before for individuals with DMD, highlighting the potential of this approach to enhance hand function and reduce fatigue while grasping. For use in a daily setting, however, adjustments need to be made to facilitate more comfortable donning of the device and reduce unfavorable effects due to its total mass and mass distribution. These adjustments can assist the development of SymbiHand towards a larger-scale study and broaden its use for a larger group of potential users and applications.

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