Design and Validation of a Novel Exoskeleton Hand Interface: The Eminence Grip

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***Abstract*— How best to attach exoskeletons to human limbs is an open and understudied problem. In the case of upper-body exoskeletons, cylindrical handles are commonly used attachments due to ease of use and cost effectiveness. However, handles require active grip strength from the user and may result in undesirable flexion synergy stimulation, thus limiting the robot's effectiveness. This paper presents a new design, the Eminence Grip, for attaching an exoskeleton to the hand while avoiding the undesirable consequences of using a handle. The ergonomic design uses inverse impedance matching and does not require active effort from the user to remain interfaced with the exoskeleton. We compare the performance of the Eminence Grip to the handle design in a healthy subject target reaching experiment. The results show that the Eminence Grip achieves similar performance to a handle in terms of relative motion between the user and the exoskeleton while eliminating the requirement of grip force to transfer loads to/from the exoskeleton and avoiding stimulation of the flexion synergy. Taken together, the kinematic equivalence and improvement in ergonomics suggest that the Eminence Grip is a promising exoskeleton-hand attachment interface supporting further experiments with impaired populations.**

Fig. 1: The Eminence Grip facilitates consistent and stable connection between the human and the Harmony Exoskeleton by constraining the hand in a comfortable and adjustable novel interface.

I. INTRODUCTION

Millions of individuals possess upper extremity impairments which result in reduced ability to perform activities of daily living (ADLs) and reduced quality of life (QOL) arising from neuromuscular injuries such as stroke, traumatic brain injury, and spinal cord injury [1–3]. Robotic devices have shown promise as tools for improving QOL through advanced rehabilitation regimens and assistance to augment function [4–6]. However, the traditional robotic design consists of rigidly connected translational and revolute joints and is severely limited when interfacing with and transmitting loads to the human wearer. This limitation in physical Human Robot Interaction (pHRI) has been well explored in terms of kinematic overconstraint by Jarrassé and Morel [7] as well as by Schiele and van der Helm [8]. These works consider either the kinematics imposed by the interface [7], or the kinematics of the entire robot [8], and propose general design guidelines to minimize pressure gradients and avoid shear imposed by forces and moments.

Unfortunately, the application for most of these general guidelines is for the large segments of the body, and few options have been proposed for the hand. Among the 128 devices reviewed by Maciejasz *et. al* [9], there were a few basic trends. Earlier devices, such as the ASSIST [10], often relied on a mixture of splints, straps, or custom thermoplastic cuff designs for hand interfaces. One limitation with this type of design was that constraining the limb relied on introducing shear at the wrist. Recent literature, perhaps in an attempt to overcome this limitation, has shifted over to using cylindrical handles, used by devices such as the MIT MANUS [11], OpenWrist [12], MAHI Exo-II [13, 14], the Harmony Exoskeleton [15] (Fig. 1), Ergoexo [16], and ARMin [17]. Even the proposed dynamic interfaces aimed at restoring passive and active range of motion (ROM) [18, 19] do not drastically change handle design language.

These cylindrical handles (Fig. 2) have been used successfully in the literature, particularly in terms of achieving kinematic coordination between the human and the robot. However, this design suffers limitations with respect to efficient and ergonomic human-robot interaction. First, the human user is expected to actively maintain a strong grip force on the handle throughout training, which is unreasonable given that the intended users would possess upper extremity impairments. The proposed solution for many designs, using bandages or other wraps to attach users to exoskeletons [13], is less desirable from a safety and comfort perspective. The lack of a stable connection between the robot and the human could result in both inefficient training as well as unsafe conditions for the human. Second, the handle design results in undesirable and inconsistent tactile stimulus. Due to the biomechanical couplings between the hand and the wrist,

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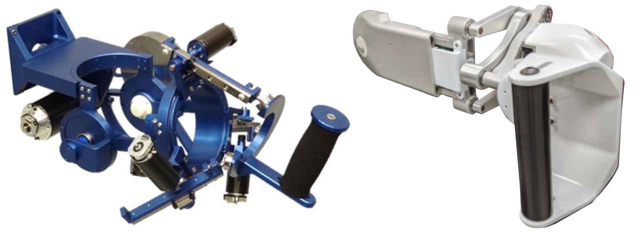


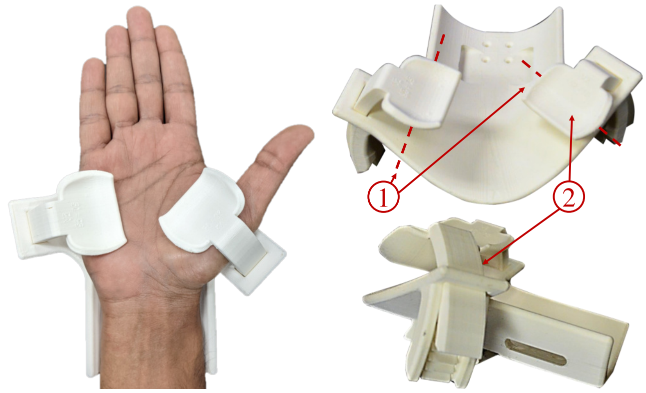
Fig. 2: The typical handle design, as seen in the MAHI Exo [14] (left) and the Harmony Exoskeleton [15] (right), require active interaction from the user and can create undesirable sensory and biomechanical couplings between the hand and the proximal joints of the upper extremity.

small aspects of the handle design, such as angle with respect to the forearm and handle diameter, result in unexpected changes in important interaction properties like the wrist range of motion [12]. Anecdotal evidence suggests that after neurological injury such as stroke, the flexion synergy [20], similar to that in early infant grasping [21], is activated and exacerbated by stimulation of the palm.

There exists a dearth of hand interfaces which enable passive ergonomic attachment without stimulating undesirable responses. We address this gap by proposing a novel hand interface design, the Eminence Grip. In Section II, we detail the guidelines which governed the development of the Eminence Grip and detail novel aspects of the design. In Section III, we introduce the experimental methods and results comparing the kinematic performance of the new design to the handle, both used with the Harmony Exoskeleton [15]. In Section IV, we discuss the implications of these results as well as identify promising avenues for future work continuing the development of novel human-robot interfaces before concluding the manuscript in Section V.

II. EMINENCE GRIP DESIGN

Towards the development of more ergonomic interface designs, we propose to follow the broad design language put forward in the prosthetic socket design community [22, 23]. Whereas the robotics community has presented standard interface design guidelines that would work for large body segments [7, 8], prosthetic interface design research has spent considerable effort and resources towards the development and study of safe, comfortable sockets, with the location, or topology, of the interface driving the design. In addition to the rules set as a function of robot and human kinematics [7, 8], recent works in socket design have proposed the use of inverse impedance matching paradigms for the interface [22–24]. At the highest level, this inverse impedance matching follows the intuition of using soft, low impedance interfaces where tissue impedance is high (e.g., bony prominences) and using more rigid, higher impedances on soft tissue. This design guideline has resulted in dense impedance measurement devices [22, 24] and custom socket design [23]. Such topological, data-driven approaches to interface design have seen only limited implementation in exoskeleton attachments, but follow principles which are particularly well suited towards the development of new hand interfaces.



(a) Donned novel Eminence Grip. (b) Detailed view of the design.

Fig. 3: The Eminence Grip only contacts the relatively soft thenar and hypothenar eminences of the hand, and avoids touching sensitive areas near the center of the palm (left). The broad, curved dorsal interface (right, top) is covered with fabrifoam (Fabrifoam products, Pennsylvania) to ensure the surface can be sanitized between uses. The individual grippers are fixed through a ratcheting and quick-release track (right, 2) centered on the approximate axes of rotation (dashed lines, 1) of the eminences, enabling clinicians to adjust the amount of thumb opposition and interface pressure.

A. Hand Attachment Design Requirements

To maintain consistent interaction, hand attachments must ensure a passive and stable connection at a range of grasp apertures, since significant portions of individuals with neurological injury exhibit tone or otherwise flexed hands at neutral positions. Next, the topological design of a hand interface requires identification of the ‘appropriate’ regions of the hand which can be used for the interface (e.g. low tissue impedance and sensitivity) and the ‘inappropriate’ regions which must be avoided (e.g. high tissue impedance and sensitivity). Further, this design must not rely on shear forces between the attachment and the hand to maintain the stable connection. Lastly, the design must use best practices such as inverse impedance matching throughout the interface. In summary, we propose that a topologically-sound design of exoskeleton hand interface should:

1) Provide passive and stable attachment without requiring grip force over grasp aperture range.
2) Contact regions which do not stimulate biomechanical or sensory couplings and have sufficient tissue characteristics to enable power transmission.
3) Minimize shear loading over grasp aperture range.
4) Provide inverse impedance interfaces to reduce peak pressures.

These design conditions have been developed towards improving efficiency and ergonomic compatibility of the interface beyond the typical handle, without sacrificing the good kinematic performance achievable with a handle.

B. Design Evaluation

Meeting these design requirements at the hand interface is not a trivial challenge. To fully locate the hand without requiring shear loading, it must be either flexed or extended to provide an orthogonal surface for force transfer. Flexing the wrist and using the palmar surface is not desirable since wrist and finger extension is often a goal of rehabilitation, and the interface should avoid stimulating unwanted synergistic responses. Extending the wrist and using the dorsal surface is similarly undesirable due to the biomechanical coupling of wrist extension and finger flexion, known as tenodesis [25]. The ulnar side of the hand is also sub-optimal as it is narrower than the palmar and dorsal sides, creating potential for pressure concentrations on bony prominences. The Eminence Grip design effectively avoids these challenges by holding the hand in an adjustable, neutral position.

The main contact areas for the interface are chosen to be across the entire dorsal surface of the hand and wrist and at the thenar and hypothenar eminences. The dorsal surface presents a high impedance region and thus the interface here is padded to reduce any pressure concentrations at the radial or ulnar heads. The thenar and hypothenar eminences have sufficient muscle belly to serve as low-impedance and low-sensitivity regions for force transmission. The sensitive areas in the palm are not being contacted during use, as seen in Fig. 3a, preventing the undesirable stimulation of the flexion synergy. The use of grippers at these points on the hand and wrist results in a stable interface independent of active user interaction.

The design of these grippers, shown in the bottom panel of Fig. 3b, provides increased adjustability for comfortable positioning of the hand, even with tone. The grippers apply pressure to the thenar and hypothenar eminences through a ratcheting mechanism which also has a quick-release feature. The two grippers follow a curved path, with the center of rotation in the approximate center of the thumb metacarpal joint (thenar eminence) and the hypothenar eminence respectively. This curved path enables stability at each intermediate grasp aperture position, even with a completely passive wearer. Since the grippers are concentric with the rotations of the thenar and hypothenar eminences, there is minimal shear force required to maintain a stable attachment. In short, by virtue of its design, the Eminence Grip inherently meets the design requirements for hand interfaces as completely as possible given the complex hand anatomy.

III. EXPERIMENTAL VALIDATION

The design of the novel Eminence Grip interface successfully solves some of the issues with using the handle interface, specifically ensuring stable passive connection to the robot while avoiding any undesired tactile stimulation. However, as the handle has been known to perform very well in terms of human-robot motion coordination, and given that the Eminence Grip provides a completely new mode of interaction with the robot, we present experimental results to validate the kinematic efficiency of the new interface , 3D printed using polylactic acid (PLA) filament(Fig. 3). The experiment compares the kinematic performance of the novel Eminence Grip with that of the typical handle interface in the reaching task shown in Fig. 4 with the goal of verifying that the two interfaces have equivalent kinematic performance.

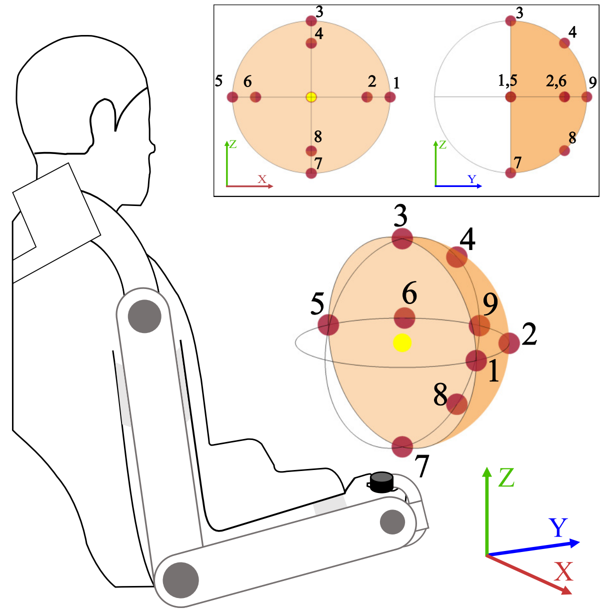


Fig. 4: Distribution of 9 targets from the subject's perspective with respect to the home position (yellow): 1. Right; 2. Right and out; 3. Up; 4. Up and out; 5. Left; 6. Left and out; 7. Down; 8. Down and out; 9. Out.

A. Experiment Protocol

The experiment consists of a series of reaching movements going from a home position towards one of nine targets distributed in three-dimensional space and back to the home position. The targets are distributed in two semicircles of the same radius (centered on the home position), one in the sagittal plane and one in the transversal plane, containing 5 targets each, which intercept in the middle resulting in a total of nine targets (Fig. 4). The targets are adjusted such that the home position is aligned with the participant's right shoulder in the medial-lateral and superior directions and located at a distance equal to 35% of the subject's workspace in the anterior direction (W_a). The radius of the semicircles was set to 40% of W_a.

The subjects perform the movements with the right arm wearing the Harmony Exoskeleton in transparent mode (baseline controller with gravity and friction compensation, and scapulohumeral rhythm controller [26]). The movements are first executed with the Eminence Grip interface (Int-G, Fig. 5 top) and then repeated with the handle interface (Int-H, Fig. 5 bottom). Subjects receive visual feedback of their current hand position and next target at all times. Real-time position of the hand for task feedback is acquired with the Oculus Touch Controller (Oculus VR, Menlo Park, CA, USA) attached to the hand interface. We provid visual feedback through an immersive virtual reality environment using the Oculus Rift (Oculus VR, Menlo Park, CA, USA). We control movement speed using visual cues by shrinking the current target's size and giving auditory cues from a metronome, both following the desired speed. The speed is defined to achieve a reaching time of 0.4s. Subjects are instructed to initiate movement towards the active target as soon as they are cued, controlling their speed to reach the target at the same time as it shrinks to its normal size.

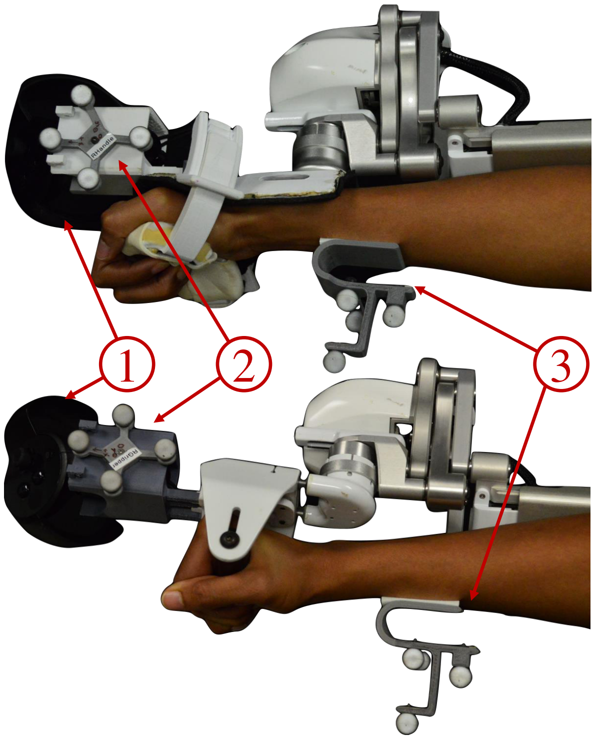


Fig. 5: Experimental setup: top - Eminence Grip interface (Int-G); bottom - handle interface (Int-H). 1. Oculus Touch Controller; 2. Motion capture rigid body on interface; 3. Motion capture rigid body on forearm.

All movements are first practiced outside of the robot to allow familiarization with the speeds and range prior to the experiment. Each subject performs four blocks, two with Int-H and two with Int-G, each containing 2 repetitions of each target in a random order (which was fixed across subjects), totaling 4 repetitions per subject/target/interface.

B. Participants

Nine right-handed able-bodied individuals (Gender: 6M/3F, Age: 27.8±5.9) were enrolled in the study. None had any known shoulder injury and all of their body dimensions were within the limits of the Harmony Exoskeleton. We were unable to follow the protocol described here for two of the nine subjects, so analysis is only performed on the remaining seven subjects. The experimental procedure was approved by the Internal Review Board organized by the Office of Research Support in The University of Texas at Austin and the participants provided written informed consent (study number 2013-05-0126).

C. Data Acquisition

We track motion capture data with the Optitrack Prime 17W system (NaturalPoint Inc., Corvallis, OR, USA) using 10 cameras with a sampling rate of 120 fps. We group markers into rigid bodies that allow tracking of position and orientation. Two such rigid bodies are placed on the subject, one on the forearm and one at the interface attachment to the Oculus Touch Controller (Fig. 5). Manual observation shows no rigid bodies missing all markers for more than a few milliseconds, and we perform interpolation using cubic spline followed by a pattern-based interpolation algorithm as necessary. We use a fourth-order low pass Butterworth filter with cut-off frequency of 2 Hz to filter tracked positions of all markers before solving for the rigid bodies.

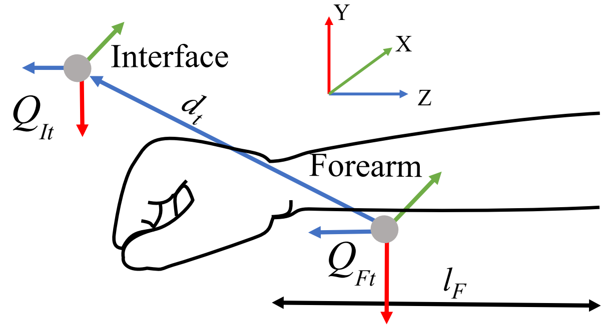


Fig. 6: Calculation of evaluation metrics for data analysis: l_F is the length of the forearm; d_t is the distance between the rigid bodies at time t; Q_{Ft} and Q_{It} are the forearm and interface quaternions at time t respectively.

D. Data Analysis

The goal of the analysis presented here is to quantify how well the hand interfaces (Int-G and Int-H) achieve kinematic coordination between the human and the robot, and to compare them. Based on the positions of the robot interface, we split each experiment into multiple sessions where each session corresponds to the motion from home position to a given target point and back. Each of the two (forearm and interface, Fig. 5) rigid bodies' motion is encoded in a 6 DOF pose. To study the robot's tracking accuracy in terms of position as well as orientation, we developed the following two metrics for comparison.

1) Relative Distance: The rigid body positions of the forearm and the interface were measured for both interfaces. The distance between the two rigid bodies was evaluated. At the start of each motion the subject returns their hand to the home position. The distance between the forearm and interface at this home position is the expected distance between the two rigid bodies throughout the motion. Any deviation from this initial distance suggests that the subject's forearm is sliding up or down relative to the robot's forearm. To perform the comparison across subjects, we normalize this distance with each subject's forearm length. The relative distance error (as a percentage of the subject's forearm length), d_{rel} is evaluated as

$$d_{rel} = \frac{(d_t - d_i)}{l_F} \times 100, \quad (1)$$

where d_i refers to the initial distance at the start of the movement, d_t refers to the distance between the rigid bodies at time t, and l_F refers to the subject's forearm length as shown in Fig. 6.

2) Relative Rotation: The motion capture data of the rigid bodies on the forearm and the interface also provides information on orientation in the form of a quaternion. These quaternions can be used to calculate relative rotation between the two rigid bodies [27]. Specifically, the inner product of two quaternions gives $< Q_1, Q_2 >= cos(\theta)$, where θ is related to the rotation offset between them. Therefore,

$$\theta_t = cos^{-1}(< Q_F, Q_I >), \qquad \theta_{rel} = \theta_t - \theta_i \tag{2}$$

where Q_F and Q_I are the forearm and interface quaterinions respectively (Fig. 6), θ_t the rotation offset at each time step, θ_i the initial rotation offset and θ_{rel} represents the relative rotation error metric used for comparison.

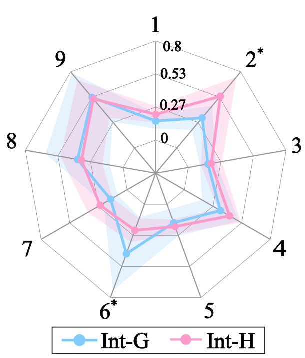
E. Statistical Analysis

In comparing the kinematic performance of the typical handle and the novel Eminence Grip, our null hypothesis is that $Error_{Int-H} = Error_{Int-G}$, where $Error$ may refer to the root mean square over a given target motion of either relative distance error or relative rotation error between the forearm and the interface. We perform a two-way repeated measures ANOVA with $\alpha = 0.05$, considering interface type and target direction as within subject factors.

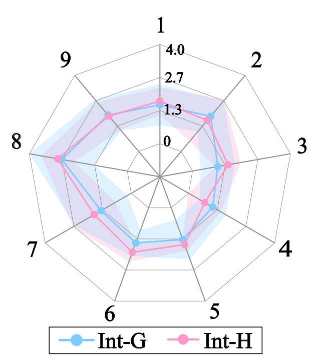
F. Experimental Results

We observe no significant effect of the interface type when we compare the relative distance error and relative angle errors across all subjects and target directions. The mean and standard deviation of both errors are detailed in Table I. We find low errors, with a maximum of $0.54 \pm 0.20\% l_F$ and $2.8 \pm 0.6°$ in Int-H for targets 2 and 8, respectively. This suggests both interfaces enable good movement tracking performance in healthy subjects. As an ad hoc analysis, we investigate the differences in interface performance in each target direction.

Figure 7a shows the average relative distance error for each direction. For example, on average subjects show a deviation of about $0.5\% l_F$ from the original distance between the forearm and the interface when they reach for the 9^{th} target (Fig. 4). This is the largest average error observed across all subjects, all directions, and both interfaces. Among the 9 directions, only the 2^{nd} and 6^{th} target directions show statistically significant dependence on the interface for the relative distance error. In the case of the 2^{nd} target, the handle interface (Int-H) shows larger relative distance error than the grip interface (Int-G), while in case of the 6^{th} target, we observe the inverse. As these two directions entail moving in opposite directions across the subject's body, the contrasting effects are not surprising. However, as the p values for these results, 0.0174 and 0.0337 respectively for the 2^{nd} and 6^{th} target directions, are close to 0.05, we suspect that these results may no longer be statistically significant in a larger subject population. Figure 7b shows the relative rotation error (in degrees) for each target direction. The largest rotation error observed is less than 3°. Motion in all directions is sufficiently similar using the two interfaces such that no statistically significant effect of the interface is observed.



(a) Relative distance error ($\% l_F$)



(b) Relative rotation error (°)

Fig. 7: Comparison of performance between the Eminence Grip (Int-G) and handle (Int-H) interfaces: mean (solid lines) performance across subjects (*: significant difference between interfaces) and standard deviation (shaded).

Based on the results depicted in Figures 7a and 7b, there is not enough evidence to reject the null hypothesis. Even in the case of the contradictory results observed in the relative distance error, the difference in the errors is less than $0.6\% l_F$ which is very small in such gross movements and falls within the scope of human variability.

IV. DISCUSSION

Physical human-robot interaction interfaces are often overlooked in the design of robots intended for human use. Careful analysis and investigation of new designs is especially important in the case of exoskeletons for stroke rehabilitation where the quality of interaction between the human and the robot significantly defines the effectiveness of the robot. In this paper, we discuss the drawbacks of the standard human-robot hand interface, the cylindrical handle, in terms of efficient and ergonomic design. We present a novel alternative called the Eminence Grip to combat these drawbacks using inverse impedance matching and minimizing the requirement of active effort from the user. The new design presents a more stable, consistent, and ergonomic interface than the handle. Specifically, the new interface does not require active effort from the user to form a stable connection, and the attachment points on the interface have been designed to maximize ergonomic comfort while minimizing shear force.

As the handle interface has been successfully used in literature, we verify that the new interface does not present any unexpected effects in practical performance when compared to the handle through a point-to-point reaching task with 7 subjects for 9 different target directions. We specifically compare the robot interface's accuracy in tracking both the position and orientation of the subjects' forearm. The results suggest that the performances of the two interfaces, handle and Eminence Grip, are sufficiently similar and there is no statistically significant difference when subjects used one or the other. As a consequence, we cannot reject our null hypothesis and conclude that the two interfaces (Int-H and Int-G) result in equivalent kinematic tracking of the subject's forearm. Thus, the results presented in this paper show that the novel Eminence Grip interface performs at least as well as the standard handle in terms of kinematic performance. More importantly, given the ergonomic benefits presented by the Eminence Grip, we believe the novel interface is an overall improvement over the handle.

A version of the Eminence Grip with a modified ratcheting attachment has previously been used for impaired popula-

TABLE I
RELATIVE ERROR ANALYSIS RESULTS OVER 9 DIRECTIONS (7 SUBJECTS X 2 REPETITIONS)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Int-G ($\%l_F$)	0.50 $\pm$ 0.06	0.32 $\pm$ 0.12	0.16 $\pm$ 0.06	0.34 $\pm$ 0.17	0.16 $\pm$ 0.11	0.42 $\pm$ 0.31	0.15 $\pm$ 0.06	0.37 $\pm$ 0.26	0.53 $\pm$ 0.25
Int-H ($\%l_F$)	0.21 $\pm$ 0.07	0.54 $\pm$ 0.20	0.19 $\pm$ 0.09	0.42 $\pm$ 0.11	0.19 $\pm$ 0.06	0.22 $\pm$ 0.1	0.25 $\pm$ 0.11	0.34 $\pm$ 0.17	0.52 $\pm$ 0.20
p-value	0.56	0.02*	0.76	0.35	0.72	0.03*	0.23	0.72	0.87
Int-G ($^\circ$)	1.7 $\pm$ 0.8	1.9 $\pm$ 0.7	1.2 $\pm$ 0.6	1.2 $\pm$ 0.6	1.5 $\pm$ 0.8	1.6 $\pm$ 0.5	1.5 $\pm$ 1.1	2.7 $\pm$ 1.2	1.9 $\pm$ 0.7
Int-H ($^\circ$)	1.8 $\pm$ 0.5	1.7 $\pm$ 1.0	1.5 $\pm$ 0.5	0.9 $\pm$ 0.7	1.7 $\pm$ 0.2	1.9 $\pm$ 0.4	1.8 $\pm$ 0.9	2.8 $\pm$ 0.6	1.9 $\pm$ 0.7
p-value	0.73	0.62	0.35	0.40	0.62	0.36	0.46	0.70	0.90

tions [28]. The design was found to have a practical limitation in that individuals with high levels of tone found it difficult to open their hand sufficiently to use the Eminence Grip. Contradictory opinions in the literature [29] suggest that it may or may not be good for the subject to have their hand passively stretched open during training. Towards solving this issue, we plan to explore the design of modular additions to the current Eminence Grip, tailoring the interface to each person's individual needs. We plan to explore customizable additions at other appropriate attachment locations, such as the metacarpal heads, for a variety of subject requirements as well as task requirements. Ultimately, we hope to perform usability studies for a range of interfaces and additions to the Eminence Grip to determine the performance of each. These studies are likely to inform us in the process of choosing the appropriate design for a given subject for a range of applications.

V. CONCLUSIONS

We present a new human-robot hand interface, the Eminence Grip, to replace the standard handle. The new design presents a more stable, consistent and ergonomic interface than the commonly used cylindrical handle. The Eminence Grip uses inverse impedance matching ensuring user comfort. The interface also eliminates the need for active effort from the user for a stable attachment to the robot. Our validation experiment results with healthy participants demonstrate the kinematic equivalence of the two interfaces: the Eminence Grip and the cylindrical handle. These results, taken together with the improved ergonomics of the attachment, suggest that the Eminence Grip is a promising alternative to the handle. Although further studies with impaired participants are required to determine the impact of tone, atrophy, and hand function on the different interfaces' performance, the new design brings us a step closer to the ultimate goal of interface customizability without loss of performance.

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