

Design and Experimental Testing of a Force-Augmenting Exoskeleton for the Human Hand

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1 **1. TITLE PAGE**

2 **Title:** Design and Experimental Testing of a Force-Augmenting Exoskeleton for the Human Hand

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27 2. ABSTRACT AND KEYWORDS

28 **Background:** Many older Americans suffer from long-term upper limb dysfunction, decreased
29 grip strength, and/or a reduced ability to hold objects due to injuries and a variety of age-related
30 illnesses. The objective of this study was to design and build a five-fingered powered assistive
31 exoskeleton for the human hand, and to validate its ability to augment the gripping and pinching
32 efforts of the wearer and assist in performing ADLs.

33 **Methods:** The exoskeleton device was designed using CAD software and 3-D printed in ABS.
34 Each finger's movement efforts were individually monitored by a force sensing resistor at each
35 fingertip, and proportionally augmented via the microcontroller-based control scheme, linear
36 actuators, and rigid exoskeleton structure. The force production of the device and the force
37 augmenting capability were assessed on ten healthy individuals include one 5-digit grasping
38 test, three pinching tests, and two functional tests.

39 **Results:** Use of the device significantly decreased the forearm muscle activity necessary to
40 maintain a grasping effort (67%, $p<0.001$), the larger of the pinching efforts (30%, $p<0.05$), and
41 the palmer pinching effort (67%, $p<0.001$); however, no benefit by wearing the device was
42 identified while maintaining a minimal pinching effort or attempting one of the functional tests.

43 **Conclusion:** The exoskeleton device allowed subjects to maintain independent control of each
44 digit, and while wearing the exoskeleton, in both the unpowered and powered states, subjects
45 were able to grasp, hold, and move objects such as a water bottle, bag, smartphone, or dry-
46 erase marker.

47 **Keywords:** Exoskeleton device, medical robotics, rapid prototyping

48

49 3. INTRODUCTION

50 Approximately 795,000 Americans suffer from a stroke, the leading cause of serious long-term
51 disability, per year, reducing mobility, including upper limb dysfunction, in over half of stroke
52 victims age 65 and older (1). Upper limb dysfunction, including decreased grip strength and/or

53 diminished ability to hold objects is also prevalent in populations with carpal tunnel syndrome (2).
54 Furthermore, grip strength has been seen to gradually decline between 60 to 75 years of age-
55 this decline more drastically noted among men (3).

56 Robotic exoskeleton devices can be primarily designed to augment user strength in order to
57 assist with activities of daily living (ADLs), or as rehabilitative devices that are used under the
58 guidance of a physical therapist to help patients regain greater functionality of damaged joints
59 and/or muscles (4). Assistive exoskeletons for the hand can be grouped according to how the
60 augmenting forces enhance the concentric movement of the digits. Devices have been designed
61 to apply the augmenting forces to the dorsal aspect of the fingers via mechanical linkages (5–8)
62 or fabric-based pneumatic bladders (9). A ventral approach has also been used, where pseudo-
63 tendons applied tension that is transmitted to the digits through soft (10) or hard exoskeleton
64 structures (11). Heo, *et al.* (12) and Bos, *et al.* (13) have both published comprehensive listings
65 and reviews of exoskeleton devices for the hand.

66 Regardless of the technique used to apply the augmenting force, for an assistive device to
67 function, finger movement or another indication of the user's intent to move must be sensed and
68 transformed into a signal that controls the application of the assistive forces. Ideally, there needs
69 to be a consistent coordination between the device and the user that results in a coupling of the
70 human hand and the augmenting system, allowing the robotic device to consistently provide
71 assistance as needed through the detection and amplification of the user's effort. Some grip-
72 assistive devices, however, have pre-programed algorithms with which users do not initiate by
73 intent to move. These types of devices, such as the HERO Grip Glove (14) move the user's hand
74 through gripping and/or pinching patterns that allow for a set force production, which is then
75 augmented by a user's own strength. Devices by Yap, *et al.* and Polygerinos, *et al.* operate in a
76 similar fashion, where the user shows intent to move, and the device then moves through a pre-
77 determined motion without any subsequent input from a user (15,16). Such devices can both be
78 used for hand motion training with the guidance of a physical therapist, as well as assist in ADLs.

79 Hand exoskeleton designs vary in overall weight, complexity, and cost. In attempts to provide
80 the full range of motion of the human hand to the user, most of these devices have become both
81 bulky and complex, and due to this are restricted to a single functional activity- either hand-
82 opening or pinching. These exoskeleton devices often use a single motor or driving feature to
83 assist multiple fingers (14), such as with Yoo et al.'s design which used one motor to drive three
84 fingers (17) and Gasser et al.'s design which uses two motors to control four fingers (18).
85 Alternatively, some devices actively assist fewer than all five fingers (19), for example, Pu, *et al.*'s,
86 Nycz et al.'s, and Gasser, *et al.*'s designs exclude the thumb (6,18,20). Devices that allow for
87 more degrees of freedom and independently assist all five digits become exceedingly cost
88 prohibitive as more joints, motors, and custom electrical components become necessary (5,21).
89 These additional motors and therefore batteries will also make the device heavier and potentially
90 tethered to a power source dependent on the current draw (9,22). The previous design from the
91 laboratory used machined aluminum segments to construct exoskeleton digits with a desktop
92 computer-based control system tethered to the device (23,24). In order to reduce both the
93 manufacturing cost and time of these previous prototypes as well as the weight, the most recent
94 designs were constructed with 3-D printed thermoplastics. Furthermore, a minicomputer-based
95 control system replaced the desktop computer, which provided a further reduction in cost, weight,
96 and complexity, and also allowed for greater freedom of movement (11,25).

97 The main objective of this study was to design and produce a wearable powered exoskeleton
98 for the human hand to improve structural stability of the fingers while also augmenting pinching
99 and grasping efforts, and to validate that the device augments both the user's pinching and
100 grasping efforts and ability to perform ADLs by evaluating healthy human subjects. The
101 exoskeleton device should be user friendly, allow for individual finger movement, and be cost
102 optimized. This device aims to not compromise cost and weight for individual, independent
103 movement of all five fingers. To be user friendly, the device must be able to incorporate a range
104 of sizes that users may experience on a daily basis, as well as have a minimal user interface,

105 and be easily donned and doffed. Additionally, the device must be portable and easily carried,
106 and the batteries should last multiple hours. For cost optimization, electronic components must
107 be commercially available, and the device should be modular such that broken parts are able to
108 be replaced as necessary. Additionally, the modularity of the design must be such that different
109 sized pieces are able to be added and removed for users of differing size in the future. The
110 exoskeleton structure was designed using CAD (computer aided design) software to enclose all
111 five fingers of the right hand and was 3-D printed in ABS plastic. Each finger's movement efforts
112 were individually monitored and proportionally augmented via the microcontroller-based control
113 scheme, linear actuators, and rigid exoskeleton structure.

114

115 **4. MATERIALS AND METHODS**

116 **Mechanical Structure Design:** The mechanical structure of the device was designed as three
117 components: an exoskeleton that surrounded and supported the movement of each of the five
118 digits of the hand; a rigid wrist-forearm structure that attached to the forearm and prevented any
119 movement of the wrist; and a laser-cut acrylic box attached to the dorsal aspect of the forearm
120 structure that contained the control system, electric motors, and batteries. The exoskeleton
121 digits and the wrist-forearm structures were designed in SolidWorks and 3-D printed in ABS
122 plastic (Dimension SST 1200s). The wrist and forearm member was designed to distribute the
123 weight of the electrical components and motors along the dorsal aspect of the forearm, and to
124 be easily donned and doffed using two Velcro straps, as illustrated in Fig. 1(a).

125 **Figure 1:** CAD rendering of **(a)** the exoskeleton wrist-forearm member, which provided a secure
126 mounting for the electrical components and Velcro wrist straps. The design provided attachment
127 points for the five exoskeleton digits and was 3-D printed as a single piece. **(b)** Full hand assembly
128 including all of the exoskeleton digits, the thumb assembly, and wrist-forearm structure. **(c)** The
129 index digit exoskeleton and pinky digit were designed with similar concentric ring structures with
130 bilateral joints. The distal sections of each finger assembly encase the fingertips, and the section

131 proximal to the wrist and forearm structure attached to the corresponding wrist-forearm
132 attachment point with a pin and securing cap. Individual sections were 3-D printed separately
133 using ABS. **(d)** The ring digit exoskeleton flexible knuckle joint and middle digit knuckle joint, which
134 is constructed in the same manner, were 3-D printed as shown, with the distal cap of the same
135 design to the index and pinky digits 3-D printed and hand-assembled.

136 The exoskeleton digits were 3-D printed individually as shown in Fig. 1(c), and assembled as
137 describe previously by Triolo *et al.* (26) (Fig. 1(b)) to provide powered flexion to each digit.
138 Additionally, rubber bands were attached to the dorsal aspect of each digit to provide passive
139 assistance in fully extending the digits and to offset friction produced by insulated electrical wires
140 and rubbing of the individual pieces of the exoskeleton digits. The index and pinky exoskeleton
141 digits each have 3 degrees of freedom, allowing for powered flexion and passive extension of the
142 fingers by lining the rotational joints up with each knuckle (Fig 1(c)). The ring and middle
143 exoskeleton digits each have 4 joints but allow for 3 degrees of freedom, allowing for powered
144 flexion and passive extension of those fingers by lining up the distal two knuckles with rotational
145 joints and using the top two joints for proximal knuckle motion (Fig. 1(d)). This knuckle joint allows
146 for non-assisted adduction and abduction. The thumb has three degrees of freedom, which allow
147 for flexion and extension of the thumb vis rotational joints lined up with the distal two knuckles
148 and rotation via a hinge joint adjacent to the wrist-forearm structure. In total, the exoskeleton
149 device has 15 degrees of freedom with mechanical stops on the dorsal aspect of each digit to
150 prevent hyperextension, but allow for the full 164° range of motion, which allows able-bodied
151 individuals to move their fingers to accomplish standard activities of daily living. The device also
152 allowed for a 15.4cm open hand length total (tip of exoskeleton thumb to tip of exoskeleton pinky).

153 The design of the device is modular, so the wrist-forearm structure was designed to allow for
154 the exoskeleton digits to be individually attached or removed, as illustrated in Fig. 1(b). The
155 exoskeleton digits were attached to the wrist-forearm member using a pin and cap design to allow
156 to replacement and repair of the pieces of digits directly attached to the member without the need

157 to reprint the large wrist-forearm structure, reducing manufacturing time and cost. The thumb was
158 connected directly to the wrist, with the distal component of the thumb designed to be attached
159 after printing. The components of middle and ring digits were designed similarly, to allow for
160 assembly after printing. This modular design also allows the digits to be replaced with smaller or
161 larger digits in order to allow for smaller or larger hand sizes.

162

163 **Electrical Components and Control System Design:** A 0.2" diameter force sensing resistor
164 (FSR) was attached to the inner ventral aspect of the each of the exoskeleton digits using small
165 sections of Velcro to prevent damage to the FSRs. Each FSR was connected to the
166 microcomputer control system to monitor individual finger movement via insulated wires that
167 were routed through holes designed into the dorsal aspect of the exoskeleton structure.

168 The five FSRs provided independent inputs to the microcontroller (Arduino micro) based control
169 scheme, in which the FSR on each finger individually commands the corresponding linear
170 actuator (Actuonix L12-I, 50 mm stroke length) proportional to the force provided. Each of the five
171 linear actuators were connected to the distal exoskeleton digit fingertip via a polymer cable that
172 was threaded though the ventral aspect of the exoskeleton digit. A 6V Ni-MH rechargeable battery
173 was used to provide sufficient power to the actuators, and a 9V rechargeable battery provided
174 power to the microcontroller and FSRs. A schematic of the control circuit is presented in Fig. 2.

175 **Figure 2:** Circuitry schematic for the final exoskeleton hand deign, the five servos representing
176 the five linear actuators, the series of AAA batteries representing the 6V rechargeable battery,
177 and the 9V battery representing the rechargeable 9V battery.

178 The batteries, microcontroller, circuitry, and actuators were enclosed in a box constructed
179 from 1/8" thick acrylic plastic and assembled using the guidance of the laser-cut partial finger
180 joints. The linear actuators and the wires connected to the FSRs passed through openings cut in
181 the acrylic box facing the digits. On the side of the box, distal from the exoskeleton digits, were
182 two switches that controlled power to the device, and an LED to indicate when the device was

183 calibrating. The mass of the completed device, batteries included, was 0.91 kg, and the total cost
184 of the device based on cost of parts is approximately \$600. Given that every one of the motors
185 are fully engaged half of the time the device is on, the battery life for the device before the battery
186 must be recharged is 2.6 hours. Photographs of the complete device are presented in Fig. 3.

187 **Figure 3:** From top to bottom, a dorsal, lateral, and ventral perspective of the complete device
188 on a user's hand.

189 Each time the device was powered on, the device began a ten-second calibration
190 sequence during which the motors were inactivated, indicated to the user via an illuminated LED
191 located next to the power switches. While the device was in calibration mode, the user was
192 instructed to make 3-5 maximal grasping efforts around a tube, and the control system
193 independently calibrated each linear actuator to the movement of each corresponding digit,
194 described as a flow chart in Fig. 4. The smallest pressure detected by each FSR during the
195 calibration period was mapped to the corresponding linear actuator being fully extended (finger
196 fully extended). Alternately, the half of the largest pressure sensed by each FSR during the
197 calibration period was mapped to the corresponding linear actuator fully contracted (finger fully
198 contracted). This calibration was performed by the control on a digit-by-digit basis, so each digit
199 had its own force-position curve post-calibration (during normal use), and each actuator only
200 moved when pressure was applied to its corresponding FSR. This allowed for precise,
201 independent digit control, regardless of the strength of one of the user's digits compared to their
202 other digits.

203 **Figure 4:** Flowchart of the 10 second calibration period, shown for the Index finger as an
204 example. Each digit undergoes this calibration process simultaneously during the calibration
205 period. The right plot shows the calibration curve for user force production versus motor
206 positioning used during normal use based on the values determined during calibration.

207

208 **User-Independent Exoskeleton Force Production:** To assess the exoskeleton device's user-
209 independent grasping and pinching force production, the unworn device was fixed into a custom
210 wooden test-stand that allowed the digits to be positioned around a grip force dynamometer
211 (BioPac Systems Inc.), demonstrated in Fig. 5. While affixed in the test-stand a locally designed
212 software algorithm commanded the device to produce pinching movements to the dynamometer
213 with the index and thumb digits, independent grasping movements against the custom stand (to
214 mimic the palm) with the index, middle, and ring fingers independently, and a grasping force
215 with all of the digits. For each movement, the device was commanded to produce three ten
216 second contractions, with an un-activated rest of ten seconds between each movement.

217 **Figure 5:** Exoskeleton hand attached to custom wooden stand, grasping around the hand force
218 dynamometer used to determine the maximum force production of the device without human
219 interactions.

220 The force measured during the un-activated phase was subtracted from the force
221 measured during the activated phase to compensate for any baseline drift. The results of this
222 independent force production test are shown in Fig. 6, where the maximum grasping force, during
223 which all digits were completely contracted, was identified as 17.2N. The smallest force produced
224 by a unique finger configuration by the exoskeleton was the index-thumb pinch at 5.0N. These
225 values approximate the maximum amount of force (all motors fully engaged) that the exoskeleton
226 is applying when assisting a user. For example, if a user is performing a grasping motion with the
227 device powered and all of the motors are fully engaged, we can assume that the exoskeleton is
228 assisting in 17.2N of force during that grasp.

229 **Figure 6:** Average force production of the unworn full exoskeleton device during a pre-
230 determined algorithm causing the device to perform multiple trials of index finger and thumb
231 pinches (IfThP), index finger grasps (IfG), middle finger grasps (MfG), ring finger grasps (RfG),
232 and full hand grasps (HandG).

233 **Experimental Methods:** Ten healthy subjects with normal range of motion in the right hand,
234 aged 18 to 23 (5 male, 5 female), participated in the study. Prior to participation, all subjects
235 were informed of the experimental procedure, and each provided written consent. This study
236 was approved by the Institutional Review Board of The College of New Jersey.

237 Prior to experimental testing, a fit test of the exoskeleton device was conducted. Each
238 subject donned the device and determined if their hand fit comfortably, that it was possible to
239 move all of their digits throughout the range of motion of the device, and were able to make full
240 grasping and pinching efforts. It was also required that each of the subject's fingers maintained
241 contact with each corresponding FSR throughout finger movements. If necessary and on a
242 subject-by-subject basis, the polymer cables were tightened or loosened to provide comfortable
243 movement of each of the exoskeleton digits and to ensure that each fingertip remained in
244 constant contact the corresponding FSR. Subjects who could not comfortably fit their hands
245 within the exoskeleton device and/or could not complete the fit-test movements were excluded
246 from participation.

247 After the fit test was concluded and it was assessed that the device was properly fit to
248 the subject's hand, subjects were allowed a short familiarization phase. The familiarization
249 phase was first performed with the exoskeleton device worn, but unpowered so the subjects
250 could become acclimated to the device. Subjects were asked to pick up several objects of
251 varying shapes and sizes, including a water bottle, tote bag, lacrosse ball, and cell phone, as
252 well as practice gripping and pinching maneuvers around the hand force dynamometer
253 mentioned previously. The subjects were then asked to perform those same tasks with the
254 exoskeleton device powered on. This familiarization phase took subjects between 5 and 15
255 minutes.

256 Grasping and pinching forces produced by the users were recorded using a hand-grip
257 dynamometer (BioPac Systems Inc.). Three surface electromyography (EMG) electrodes (Heart
258 Trace, Cardiology Shop) were placed on the ventral aspect of the forearm proximal to the elbow

259 to record the surface EMG of the aggregate of forearm muscles, mainly the Flexor Carpi
260 Ulnaris, Pronator Teres, Palmaris Longus, and Flexor Carpi Radialis (Fig. 7). This simple
261 configuration of electrodes is able to distinguish flexion due to grasping and pinching motions
262 from extension due to opening the hand (27). A more complex array of electrodes was not used
263 due to both obstruction of movement of the subject during the trial and the low discrimination
264 rate possible when observing muscle activation in the forearm due to grasping (27,28) when
265 compared to the additional data that would have been acquired. Additionally, activation patterns
266 of individual muscles in the forearm have been shown to change during the same motions after
267 a familiarization period with an exoskeleton device (29). To assist in the visual placement of the
268 electrodes, subjects were instructed to open and close their bare hand multiple times in order to
269 locate the corresponding muscles by observing muscle flexing. Grasp force was low pass
270 filtered with a cutoff at 66.5Hz, and EMG was band pass filtered from 5 to 1000Hz. All data were
271 simultaneously recorded and saved with a pc-based data acquisition system (Biopac Systems,
272 Inc.), sampled at 1kHz.

273 **Figure 7:** Surface EMG electrode placement on a human subject

274

275 **Experimental Protocol:** In order to determine whether the exoskeleton device is significantly
276 augmenting both pinching and grasping efforts, two options for assessment were considered.
277 Either the force produced by only the fingers both with and without the exoskeleton's assistance
278 would be measured, or there would be a set force that the subjects were asked to provide, and
279 EMG measurement both bare-handed and while wearing the powered device would be
280 compared. Because it was not feasible with the current exoskeleton device to measure the force
281 produced by only the subject's fingers without the assistive forces supplied by the device, the
282 second option was pursued for analysis.

283 With their arm resting on the benchtop, each subject produced three five-second 25N
284 grasping efforts, first while bare handed, second while wearing the unpowered exoskeleton, and

285 finally while wearing the powered exoskeleton. The testing-states (bare handed, wearing the
286 unpowered device, and wearing the powered device) were repeated while the subject produced:
287 5-second pinching efforts of 15N with their thumb and forefinger; the same pinching effort with a
288 force of 8N; and 15N pinching efforts with their thumb, forefinger, and middle finger (palmer
289 pinch). To assist in maintaining the target forces, the subject was provided constant visual
290 feedback on a computer monitor of the force measured by the dynamometer.

291 In addition to these grasping and pinching tests, two functional tests were also
292 performed; however, only EMG was recorded and the duration of the efforts was increased to
293 ten seconds per replicate. In the first, the subject lifted a plastic water bottle (0.5 kg) off the table
294 with their elbow resting on the table. In the second, the subject picked up a tote bag filled with
295 binders and papers (2.4 kg) off the floor with a straight arm. These trials were recorded with the
296 same filtering as the previous tests. Subjects performed all of the above tasks first bare-handed,
297 then while wearing the unpowered device, and the finally while wearing the powered device.
298 The entire experimental protocol took subjects between 45 minutes to 1 hour and 15 minutes to
299 complete.

300

301 **Data Analysis:** A locally designed MATLAB algorithm was used to identify peak pinching and
302 grasping forces per test, as well as the troughs in force between efforts (used as a baseline),
303 and to extract 1 second of EMG and force data with the peak or trough as the midpoint. To
304 accomplish this task, the force data were moving time averaged (MTA) at 2000ms and zero-
305 phase filtered to exaggerate large changes in the data before being assessed for peaks and
306 troughs with a minimum distance between peaks set as 5000ms. The force data in the
307 determined 1-second peak/trough intervals were then MTA at 500ms, and the EMG data in the
308 same 1-second intervals were detrended and MTA at 800ms. The reference values of the force
309 and EMG data detected as troughs by the algorithm were subtracted from the test values in the

310 vicinity of the effort to account for baseline drift in either the force or EMG data throughout the
311 trials.

312 The average force, zero-phase filtered and MTA at 500ms, for each 1-second interval
313 surrounding the center of a peak or trough was divided by the average concomitant EMG, zero-
314 phase filtered and MTA at 800ms, to normalize the measurements for subtle variations in
315 measured force. At the constant forces chosen, any relative decrease in the force/EMG
316 relationship for a device state indicates decreased electrical activity in the forearm muscle for a
317 given effort in that device state, as, in efforts well below the individual's maximum grip strength,
318 the electrical activity necessary to contract a muscle linearly increases with increasing percent
319 of maximum muscle effort (26,30).

320 To analyze the data from the functional tasks, a modified version of the MATLAB
321 algorithm was used to identify peaks and troughs in the detrended and filtered EMG data, and to
322 extract 2 seconds of the EMG data with the identified peak or trough as the midpoint. To
323 accomplish this, the processed EMG data were moving averaged over 5000ms and zero-phase
324 filtered before being assessed for peaks and troughs with a minimum distance between peaks
325 set as 5000ms. The initially processed data were extracted based on the times of the peaks and
326 troughs as identified by this procedure. The 2 seconds of EMG data were, again, zero-phase
327 filtered and MTA at 800ms. As before, the reference values of the EMG data identified by the
328 trough detection in the vicinity of the lifting efforts were subtracted from the peak test values to
329 account for any baseline drift.

330 Results of the tests in which the subjects were bare handed, wearing the unpowered
331 exoskeleton, and wearing the powered were compared using a one-way repeated measures
332 ANOVA, and multiple comparisons were assessed with Fisher's L.S.D. This analysis was
333 performed for each of the trials described- the 25N grasping efforts, the 15N pinching efforts,
334 the 8N pinching efforts, the 15N palmer pinching efforts, the tote bag listing efforts, and the

335 water bottle lifting efforts. Statistical analyses were performed using OriginPro 2018 (OriginLab)
336 with a statistically significant difference identified as $p < 0.05$.

337

338 5. RESULTS

339 During the grasping and pinching efforts that were measured by the hand-force
340 dynamometer and as expected, there was no significant increase or decrease between the
341 forces the subjects produced across all three testing states ($p > 0.05$), or in other words, the
342 subjects produced similar forces in the trials in which they were bare handed, wearing the
343 unpowered device, and wearing the powered device for each of the force-measured tests (25N
344 grasp, 15N pinch, 8N, pinch, and 15N palmer pinch).

345 **Figure 8:** Average across 3 efforts per testing state in 10 subjects of **(a)** full hand grasping, **(b)**
346 15N pinching, **(c)** 8N pinching, **(d)** 15N Palmer pinching force/forearm muscle EMG ratio
347 expressed in arbitrary units (a.u.), and **(e)** lifting a tote bag, **(f)** lifting a plastic water bottle
348 forearm muscle EMG, expressed in millivolts (mV), where error bars designate standard
349 deviation (*, $p < 0.05$; **, $p < 0.001$).

350 During the 25N full-handed grasping efforts, there was no statistically significant change
351 in the force/EMG ratio comparing between the trials where subjects were barehanded and
352 where subjects were wearing the unpowered exoskeleton structure ($p > 0.05$). However, there
353 was a statistically significant (67%) increase in force/EMG ratio in the trial where subjects were
354 wearing the powered exoskeleton device compared to the barehanded trials, meaning that there
355 was less forearm muscle activation when the user produced the same force while wearing the
356 powered and calibrated exoskeleton device compared to when they had no assistance ($p <$
357 0.001). This effect was also statistically significant when comparing the force/EMG ratio
358 between the trials in which the subjects were wearing the unpowered structure and when
359 wearing the powered device ($p < 0.001$). This is illustrated across the entire cohort in Fig. 8(a)
360 and is also demonstrated in the data from a single subject in Fig. 9.

361 **Figure 9:** From top to bottom, recorded grasping force, recorded EMG, and detrended, filtered
362 EMG from a representative subject during a 25N grasping effort during all three testing states.
363 In the columns from left to right, the subject performed grasping efforts while bare-handed,
364 wearing the unpowered device, and while wearing the powered and functional device.

365 During 15N thumb and forefinger pinching efforts, there was no statistically significant
366 change in the force/EMG relationship comparing between trials where subjects were
367 barehanded and where subjects were wearing the unpowered exoskeleton structure ($p > 0.05$).
368 There was, however, a statistically significant (30%) increase in force/EMG ratio in the trial
369 where subjects were wearing the powered exoskeleton device compared to the barehanded
370 trials, meaning that there was less forearm muscle activation when the user produced the same
371 force while wearing the powered and calibrated exoskeleton device compared to when they had
372 no assistance ($p < 0.05$), as shown in Fig. 8(b). During the 8N pinching efforts, there was no
373 statistically significant benefit to wearing the device. There was no statistically significant
374 change in the force/EMG ratio where the subjects performed these light pinching efforts when
375 using device any of the testing states ($p > 0.05$), shown in Fig. 8(c).

376 During 15N palmer pinching efforts, there was no statistically significant change in the
377 force/EMG ratio comparing between the trials where subjects were barehanded and where
378 subjects were wearing the unpowered exoskeleton structure ($p > 0.05$). There was, however, a
379 statistically significant (67%) increase in force/EMG ratio in the trial where subjects were
380 wearing the powered exoskeleton device compared to the barehanded trials, meaning that there
381 was less forearm muscle activation when the user produced the same force while wearing the
382 powered and calibrated exoskeleton device compared to when they had no assistance ($p <$
383 0.001). This effect was also statistically significant when comparing the force/EMG ratio
384 between the trials in which the subjects were wearing the unpowered structure and when
385 wearing the powered device ($p < 0.001$). This is illustrated across the entire cohort in Fig. 8(d).

386 There were no trends attributed to wearing the device, powered or unpowered, and no
387 statistically significant change was observed between the average EMG produced in lifting a
388 tote bag off the floor when the subjects were barehanded, wearing the unpowered structure,
389 and when wearing the powered device ($p > 0.05$), as shown in Fig. 8(e).

390 In lifting a water bottle off the table, there was a significant increase in the forearm EMG
391 produced when the subject wore the device, either powered or unpowered, when compared to
392 not wearing the device ($p > 0.05$), as shown in Fig. 8(f). Therefore, the device significantly
393 impeded lifting a small object significantly lighter than the device itself.

394

395 **6. DISCUSSION**

396 **Limitations of the Design and Testing Protocols:** Since the exoskeleton was designed to
397 provide a rigid support, individual digit movement was constrained to concentric and eccentric
398 trajectories in a single plane of movement. Additionally, the digits were limited to 15 degrees of
399 freedom in order to decrease weight and cost by reducing the number of active motors
400 necessary. In the effort to reduce weight, complexity, and cost, adduction and abduction
401 motions of the fingers were not assisted. The entire device, including the batteries and control
402 system, weighed approximately 0.91 kg, a potentially significant weight to be carried on the arm
403 of an individual with any amount of reduced arm strength; however, this weight is comparable to
404 that of other similar devices that assist motion of 5 digits (22,31,32). Along with increased
405 weight which impeded the functional test of lifting a light weight, the joints of the device provided
406 additional friction to digit movement. Although the control system compensated for the added
407 friction on the concentric efforts, actuator activation only applied assistive forces during these
408 concentric efforts. Therefore, the user was required to contribute to all eccentric, or digit
409 extension, efforts without any motor assistance, although the non-adjustable rubber bands
410 assisted in this movement.

411 In order to optimize the functioning of the FSRs and linear actuator function for each
412 subject, the lengths of the polymer cables were adjusted to best fit the subject's combined finger
413 and palmer lengths in order to allow for an optimal contact of the fingertips and the FSRs, and
414 therefore maximizing the user's interface with the control system of the device. This required the
415 investigator to disconnect, shorten, and re-attach 5 polymer cables on the device for each
416 subject after checking the fit of the device, but prior to recording any data. Finally, the force
417 produced solely by the user was not recorded, the forces reported were the combination of the
418 user's effort and the assistive force of the device. It was determined that the separate recording
419 of user and device force would have required additional force sensors and wiring placed inside
420 the device that would add additional weight and friction in the movement of the joints resulting from
421 the additional wires.

422

423 **Objective Assessment of Device Performance:** In previous studies, a grasping effort showed
424 a statistically significant reduction in forearm muscle activation during grasping efforts for both
425 the three-fingered (11) and five-fingered versions of this device (26). However, in the previous
426 pilot study with fewer participants using the five-fingered device, the 15N pinching effort did not
427 provide a statistically significant reduction in forearm muscle activation (26). Now, in a sample of
428 ten subjects with a slightly modified control scheme, while wearing the device the user needed a
429 significantly reduced amount of forearm muscle activation for a grasping effort by 67% (Fig.
430 8(a)), a 15N palmer pinching effort by 30% (Fig. 8(d)), and a 15N pinching effort by 67% (Fig.
431 8(b)). These percent differences are comparable to reduction in EMG recorded while using a
432 similar exoskeleton device, for either the hand or arm, whose intent is to augment a user's force
433 production (21,33). There are devices, however, that allow the user to produce minimal muscle
434 effort, but these are devices that intend to only minimally voluntary movement, where the user
435 implies movement and the device moves semi-autonomously (15,16).

436 Although there was no statistically significant increase in the force/EMG ratio in the 8N
437 pinching effort (Fig.8(c)), the average pinching force/EMG ratio increased in both the trials were
438 subjects wore the unpowered structure and the trials were subjects wore the powered device
439 trials as compared to the barehanded trials (35% and 32% increase respectively). These
440 percent differences in the 8N pinching effort is comparable to Kadowaki, et al., where it was
441 found that their soft exoskeleton device assisted with 20% of the pinching effort (34). This is
442 also comparable to the reduction in EMG produced in devices of similar structure and function,
443 but for a different limb, for example by the major hip flexor, minor knee extensor muscle in a
444 study investigating a powered hip exoskeleton device during walking (35). This implies that
445 wearing the device, powered or unpowered, provided enough support to the fingers during light
446 pinching efforts to reduce muscle activation. It is also possible that there was reduction in
447 activation in the other muscles of the arm and hand that were not investigated. For example, the
448 exoskeleton also assisted in the movement of the thumb, especially in the pinching efforts, but
449 the EMG of these muscles, such as the abductor pollicis, were not recorded. Additionally, in
450 comparison to the HERO Grip Glove (14), this exoskeleton device itself, with no human
451 interaction, produced 17.2N of grip force, compared to their 12.7N, but only 5.0N of pinch force
452 compared to their 11.0N. This would appear to indicate that the thumb exoskeleton digit may be
453 the limiting factor in the reduced pinching forces produced by this device. This is also supported
454 by the increase in force produced when performing single/multi-finger grasps as opposed to
455 finger-thumb pinches. These single-digit user-independent grasping forces, however, are
456 comparable to other, similar powered assistive devices for the hand, although some with fewer
457 digits than five, with forces ranging from 5N to 12N per digit (20,36,37).

458 Overall EMG increased when lifting a water bottle while wearing the exoskeleton device,
459 powered or unpowered, when compared to the trials in which the subjects were barehanded
460 (Fig. 8(f)). However, the majority of subjects showed a decrease in EMG production when the
461 device was powered on compared to when the device was unpowered, while a two saw an

462 increase (Fig. 11).), indicating that powering the device still had a beneficial impact when
463 grasping an object over wearing the unpowered device. This increase in EMG from bare-
464 handed to wearing the device is likely attributed to the weight of the device, as the subjects also
465 had to lift the device along with the water bottle in the trials in which they wore the exoskeleton
466 device, and the weight of the water bottle was significantly smaller than the weight of the device.
467 However, in order to reduce the weight of the device, the ability to move all five fingers
468 independently would be lost, such as with Yoo, et al. (17), where only one motor was used to
469 control multiple fingers to decrease weight and cost. Based on some participant feedback,
470 however, it may be possible to have one motor control both the pinky and the ring finger. Some
471 subjects expressed that they did not feel their pinky finger contributed to their gripping
472 capability, so having the pinky driven in parallel with ring finger motion may be a feasible
473 method to remove some weight.

474 While there was no overall trend of improvement when lifting a tote bag off of the ground
475 (Fig. 8(e)), most subjects showed reductions in EMG production when the device was powered
476 as compared to their trials with the unpowered device or bare-handed, while two subjects saw
477 an increase when comparing the powered device trials to the unpowered device trials (Fig. 10).
478 This suggests that for some individuals, wearing the device while powered was beneficial in
479 reducing EMG to lift certain objects, while others had a difficult time wearing or controlling the
480 device for these purposes. For example, subject 8 had difficulty in using the powered
481 exoskeleton for both of these tests as shown in figures 10 and 11.

482 **Figure 10:** Normalized average forearm EMG (mV) from 3 efforts during the lifting of a plastic
483 water bottle, across three states, bare handed, wearing the unpowered device, and while
484 wearing the powered and functioning device.

485 **Figure 11:** Normalized average forearm EMG (mV) from 3 efforts during the lifting of a weighted
486 tote bag, across three states, bare handed, wearing the unpowered device, and while wearing
487 the powered and functioning device.

488

489 Again, it is possible that there was reduction in activation of other muscles of the arm and hand
490 were not investigated. In a study investigating an exoskeleton for the arm, the EMG of 16 upper
491 limb muscles were recorded, and it was found that in different movement patterns, different
492 muscles showed a decrease in EMG with the use of the device (38). In the future, a more
493 extensive array of EMG electrodes could be used to determine if different muscles of the hand
494 and forearm showed reduction in activation during functional tests.

495

496 **Assessment of Potential Functionality for ADLs:** Many studies assessing the functionality of
497 novel exoskeletons for assistance in ADLs and rehabilitation assess theoretical sensory
498 feedback (39,40), joint torques and grip forces in controlled motion of the device (18,31,41), and
499 force/EMG measurement for controlled full-hand grasps (11,26). This type of assessment,
500 however, does not necessarily correlate to a device's usefulness in performing ADLs such as
501 lifting various objects. Although the device appeared to increase the muscle activation needed
502 to lift an object lighter than the device itself and showed no significant increase or decrease in
503 the muscle activation needed to lift an object heavier than the device itself; this generalization
504 was not true on a subject-by-subject basis.

505 The majority of subjects saw a reduction in EMG when lifting an object heavier than the
506 device when the device was in the powered state compared to their trials with the unpowered
507 device or bare-handed (Fig. 11). This is likely attributed to both the subject's grip on the object
508 and the fit of the device. If the device was fit poorly to the individual, the subject would be more
509 likely to lose contact with some of the FSRs in the fingertips and therefore not be fully assisted
510 in their grip. This would also cause the subject to adjust their hand's position in the device
511 during the test, increasing their muscle activation. This spike in muscle activation due to
512 repositioning would also occur when the subject adjusted their grip on the tote bag. The
513 subjects that were more adept at controlling the device and felt more comfortable wearing it

514 were less likely to attempt to reposition either the device or the bag, resulting in a decrease in
515 EMG when wearing the powered device. So, while the device is not well suited to assist
516 subjects lifting an object lighter than the device, it was beneficial when assisting subjects who
517 felt comfortable wearing the device in lifting an object heavier than the device itself.

518 This would imply that the intended users of the device, or subjects who require
519 assistance in ADLs, would require a training regimen involving repetitively using the device to
520 complete tasks that the device would be used for. This kind of training regimen is commonly
521 used in studies evaluating a device's usefulness in assisting stroke patients perform ADLs (5).
522 Post-task-oriented training, subjects with impairments due to stroke have shown improvement in
523 their hand functions (5), so this type of training would be beneficial for subjects who might feel
524 uncomfortable using the device initially. In the future, subjects should undergo a task-oriented
525 training regimen after initial grasping efforts, then their ability to perform functional tasks should
526 be re-assessed to account for initial comfortability in using the device. Additionally, in future
527 studies with this device, subjects with upper limb impairments should be recruited to investigate
528 how effectively the device assists in their realistic ADLs.

529

530 **7. CONCLUSIONS**

531 In this study, the function of a newly-designed battery powered, five-fingered, 3-D printed force
532 augmenting orthotic exoskeleton for the human hand was tested both independently and on ten
533 healthy individuals. A control system implemented using an Arduino microcontroller
534 proportionally commanded assistive linear actuators based on the pressure sensed by
535 corresponding FSRs located in the distal and ventral aspect of each exoskeleton digit. The
536 exoskeleton device allowed subjects to maintain independent control of each digit, although
537 some of the subjects indicated that they were afraid to break the 3-D printed digits during
538 testing. While wearing the exoskeleton, in both the unpowered and powered states, subjects

539 were able to grasp, hold, and move common objects such as a water bottle or a bag, as well as
540 smaller and more delicate objects, such as a smartphone or dry-erase marker.

541

542 **8. LIST OF ABBREVIATIONS**

543 **ADLs:** activities of daily living

544 **CAD:** computer aided design

545 **FSR:** force sensing resistor

546 **Ni-MH:** nickel-metal hydride

547 **IfThP:** index finger and thumb pinch

548 **IfG:** index finger grasp

549 **MfG:** middle finger grasp

550 **RfG:** ring finger grasp

551 **HandG:** full hand grasp

552 **EMG:** electromyography

553 **MTA:** moving time averaged

554 **a.u.:** arbitrary units of force/EMG

555

556 **9. DECLARATIONS**

557 **Ethics Approval and consent to participate:** Prior to participation, all subjects were informed
558 of the experimental procedure, and each provided written consent. This study was approved by
559 the Institutional Review Board of The College of New Jersey.

560 **Consent for publication:** Not applicable.

561 **Availability of data and materials:** The datasets used and/or analyzed during the current
562 study are available from the corresponding author on reasonable request.

563 **Competing interests:** The authors declare that they have no competing interests.

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565 New Jersey Space Grant Consortium.

566 **Authors' contributions:** BFB was responsible for the conceptualization of the device and study
567 design. ERT was responsible for recruitment and conducted the experiments. BFB and ERT
568 equally contributed to the data analysis, writing and editing of the manuscript, and approved the
569 final manuscript.

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572

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687

Figures

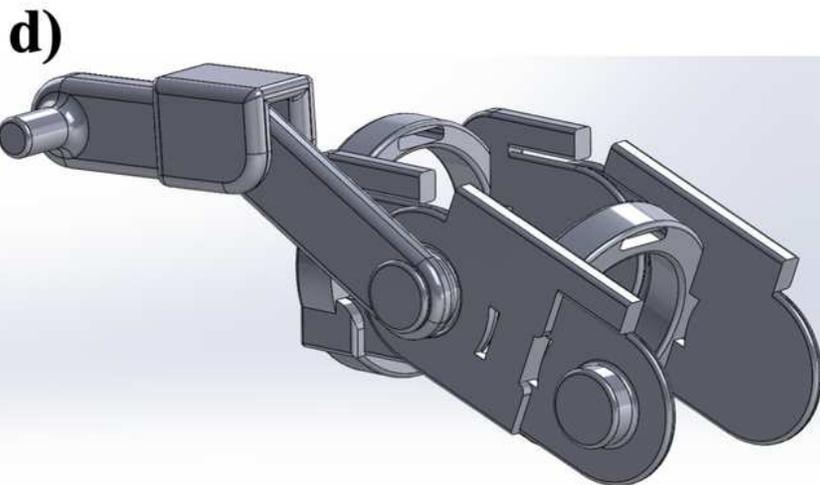
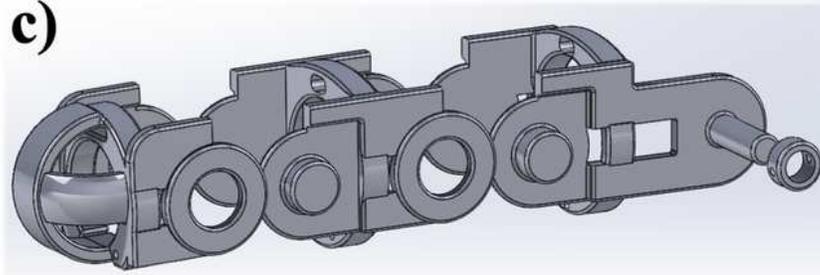
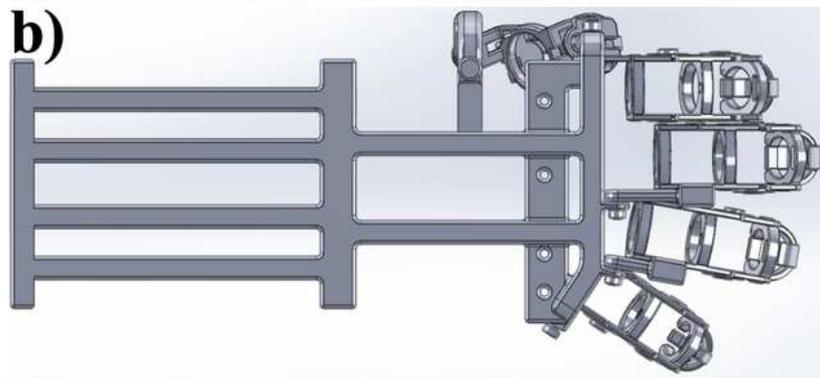
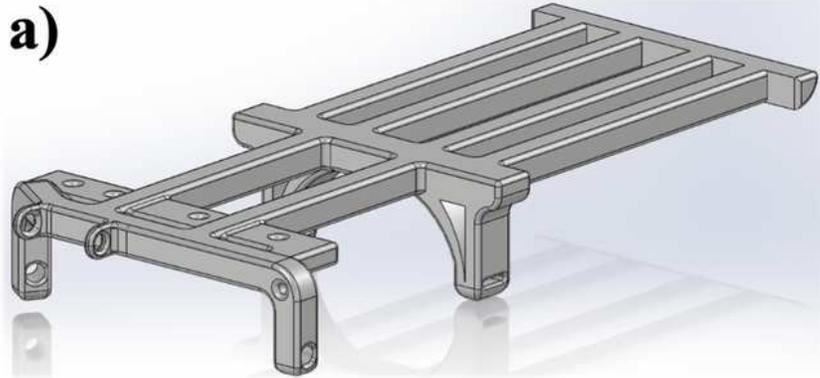


Figure 1

CAD rendering of (a) the exoskeleton wrist-forearm member, which provided a secure mounting for the electrical components and Velcro wrist straps. The design provided attachment points for the five exoskeleton digits and was 3-D printed as a single piece. (b) Full hand assembly including all of the

exoskeleton digits, the thumb assembly, and wrist-forearm structure. (c) The index digit exoskeleton and pinky digit were designed with similar concentric ring structures with bilateral joints. The distal sections of each finger assembly encase the fingertips, and the section proximal to the wrist and forearm structure attached to the corresponding wrist-forearm attachment point with a pin and securing cap. Individual sections were 3-D printed separately using ABS. (d) The ring digit exoskeleton flexible knuckle joint and middle digit knuckle joint, which is constructed in the same manner, were 3-D printed as shown, with the distal cap of the same design to the index and pinky digits 3-D printed and hand-assembled.

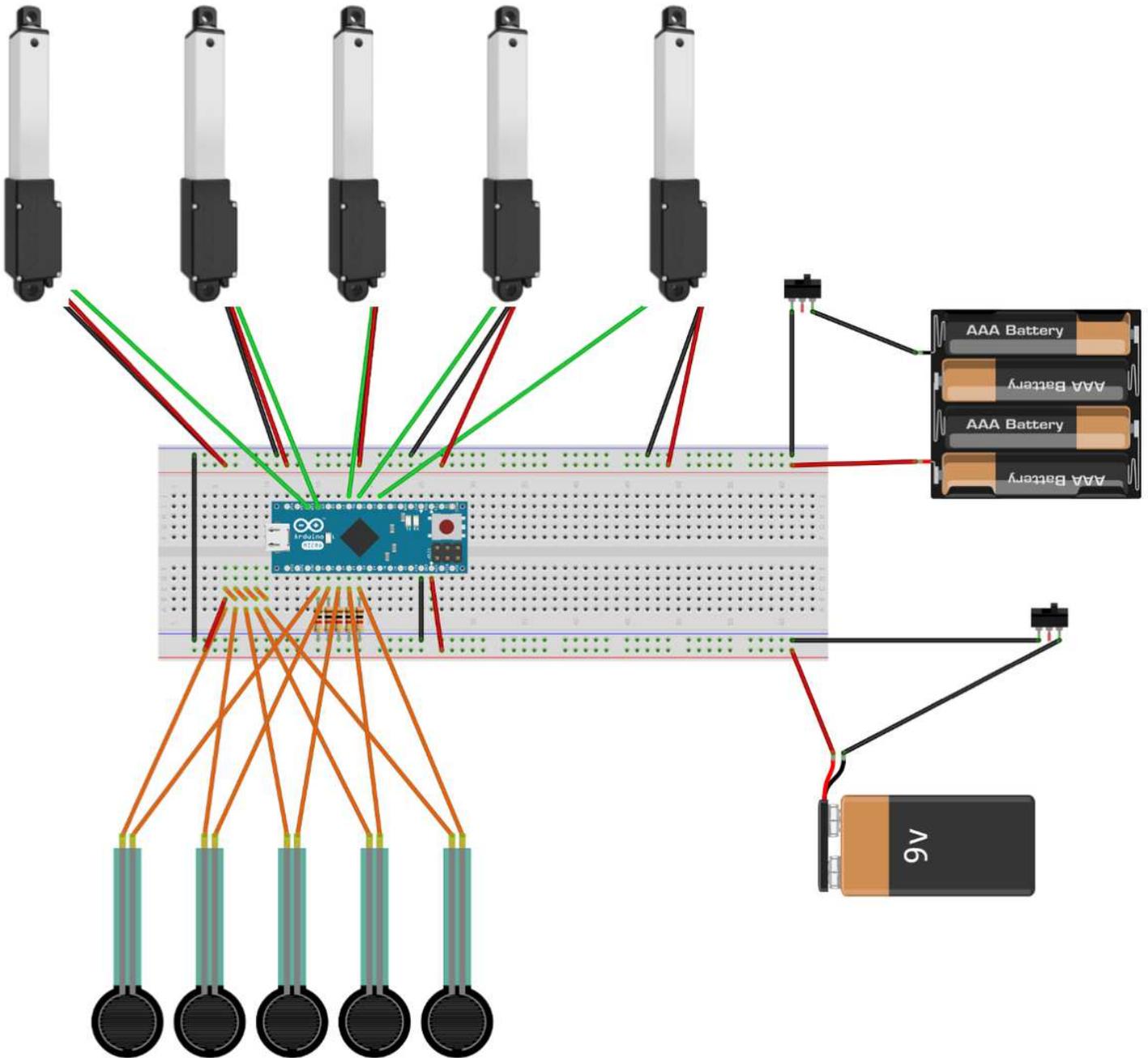


Figure 2

Circuitry schematic for the final exoskeleton hand design, the five servos representing the five linear actuators, the series of AAA batteries representing the 6V rechargeable battery, and the 9V battery

representing the rechargeable 9V battery.

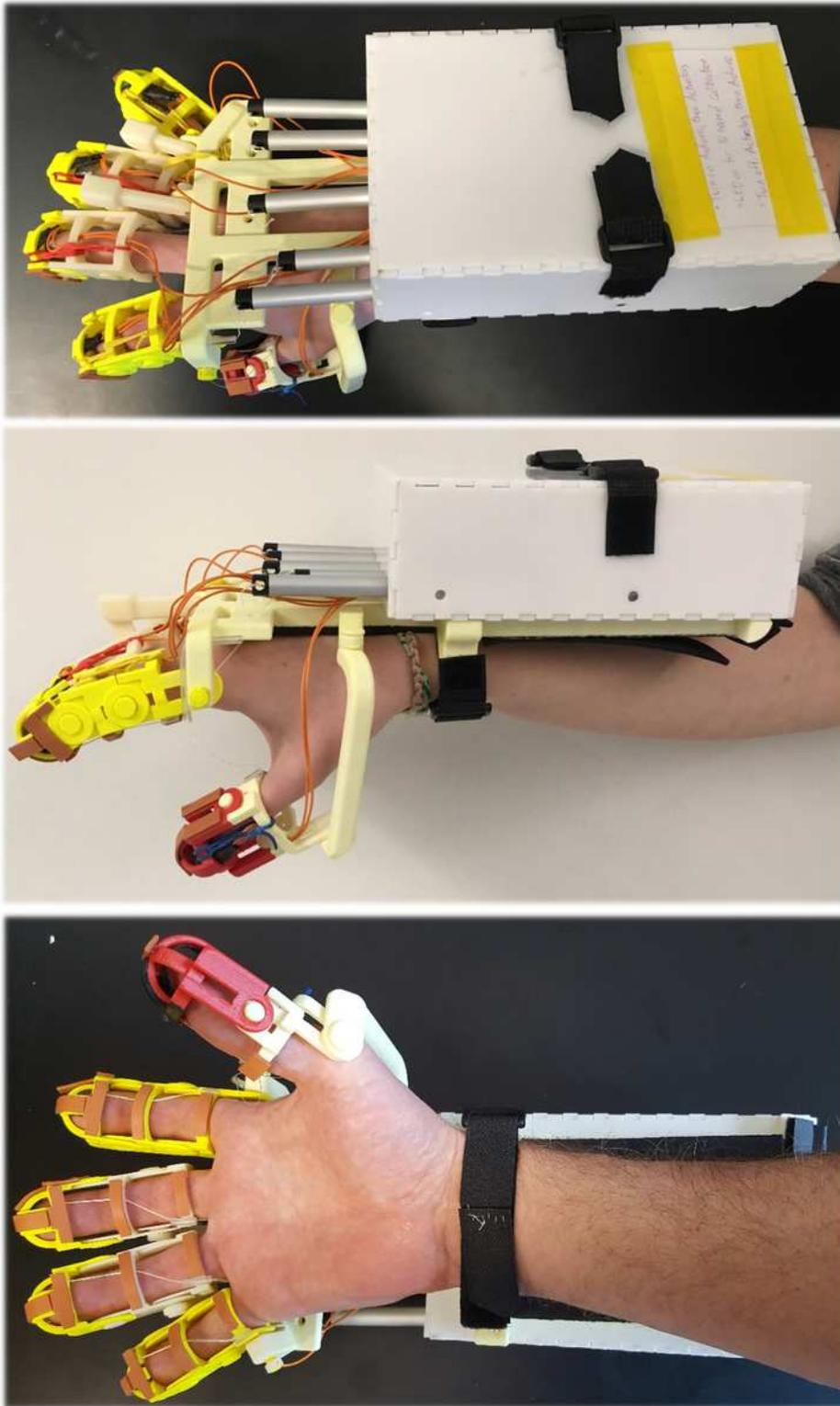


Figure 3

From top to bottom, a dorsal, lateral, and ventral perspective of the complete device on a user's hand.

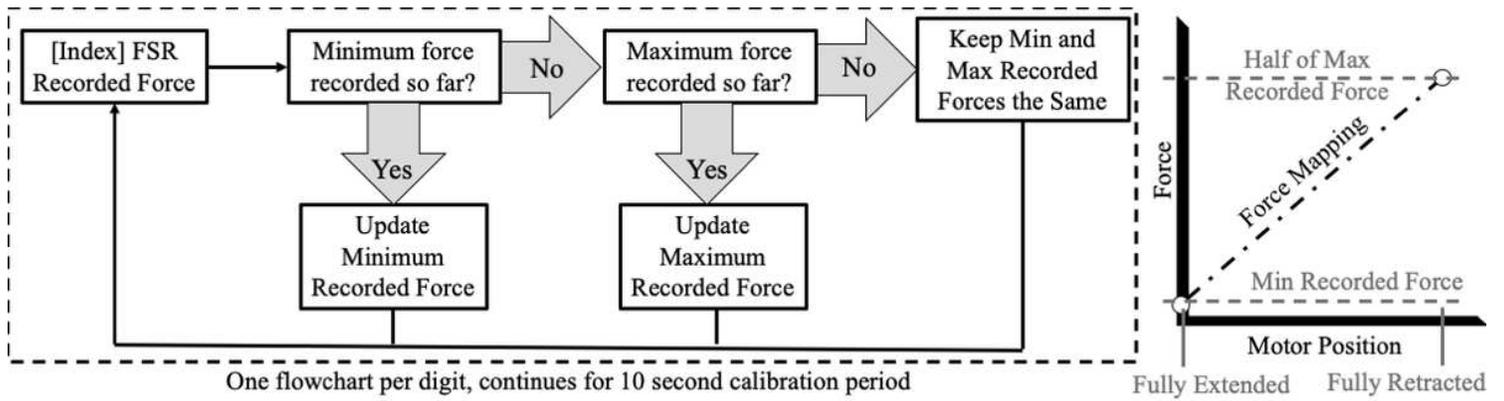


Figure 4

Flowchart of the 10 second calibration period, shown for the Index finger as an example. Each digit undergoes this calibration process simultaneously during the calibration period. The right plot shows the calibration curve for user force production versus motor positioning used during normal use based on the values determined during calibration.

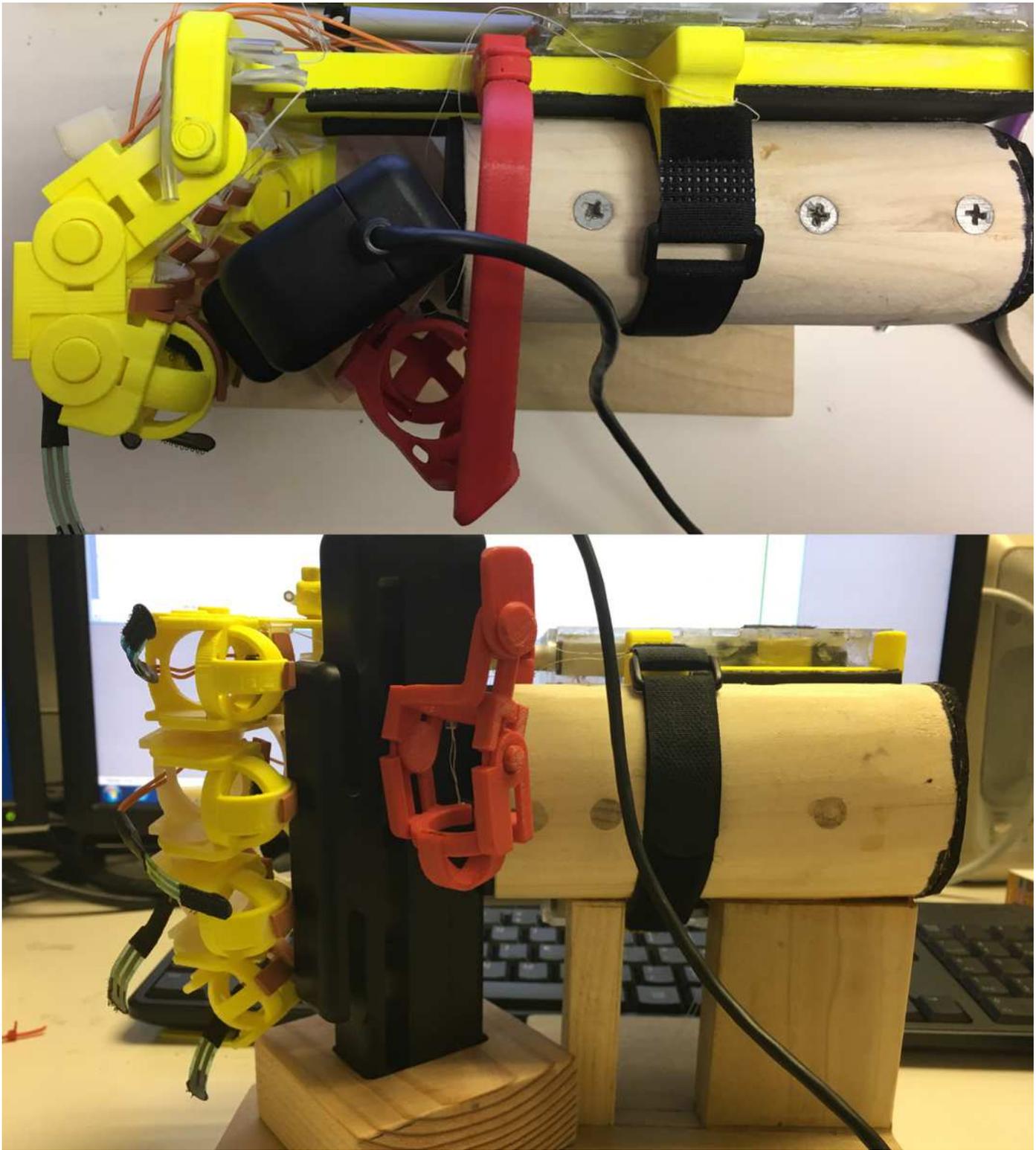


Figure 5

Exoskeleton hand attached to custom wooden stand, grasping around the hand force dynamometer used to determine the maximum force production of the device without human interactions.

Exoskeleton Force Production

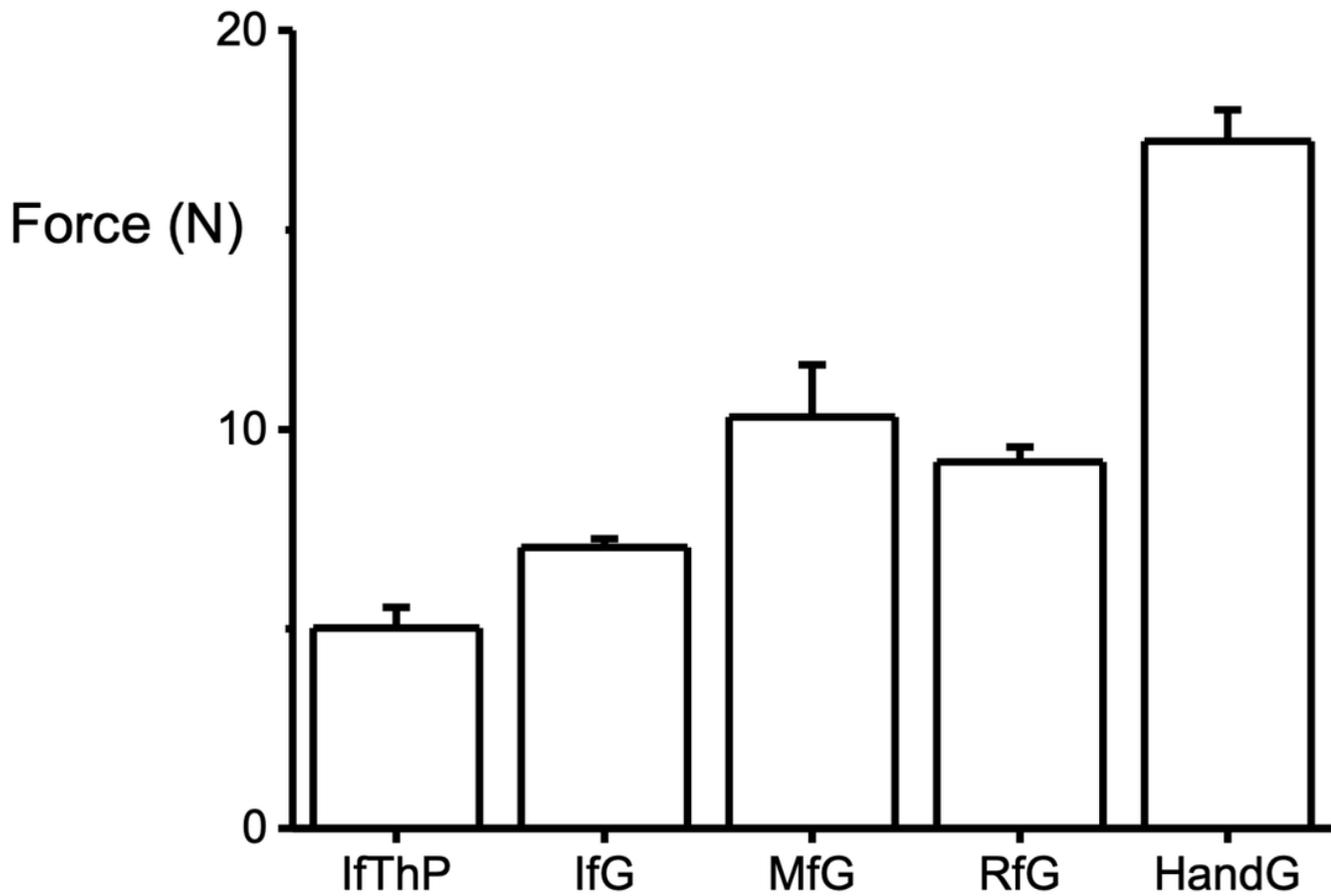


Figure 6

Average force production of the unworn full exoskeleton device during a pre determined algorithm causing the device to perform multiple trials of index finger and thumb pinches (IfThP), index finger grasps (IfG), middle finger grasps (MfG), ring finger grasps (RfG), and full hand grasps (HandG).

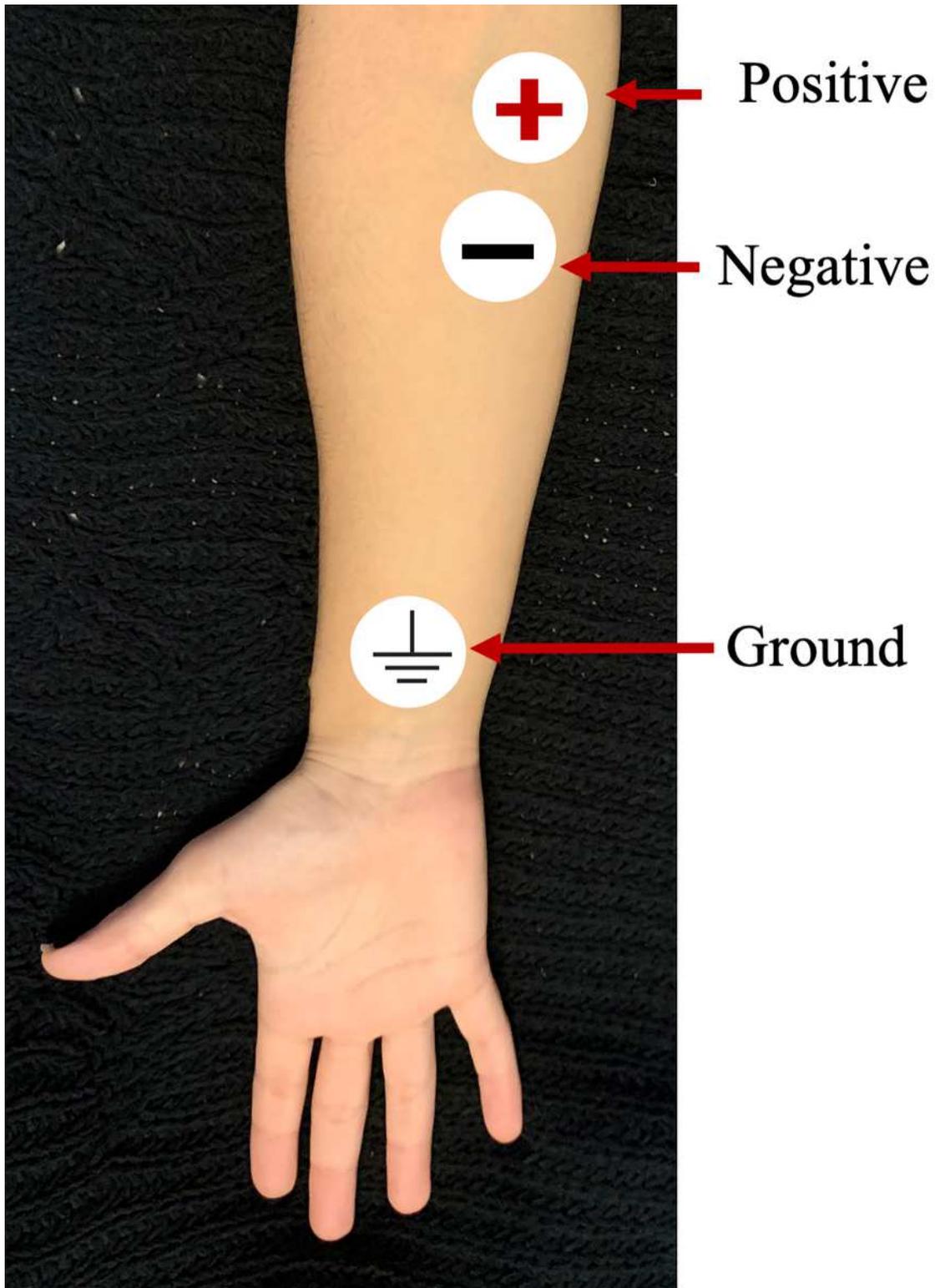


Figure 7

Surface EMG electrode placement on a human subject

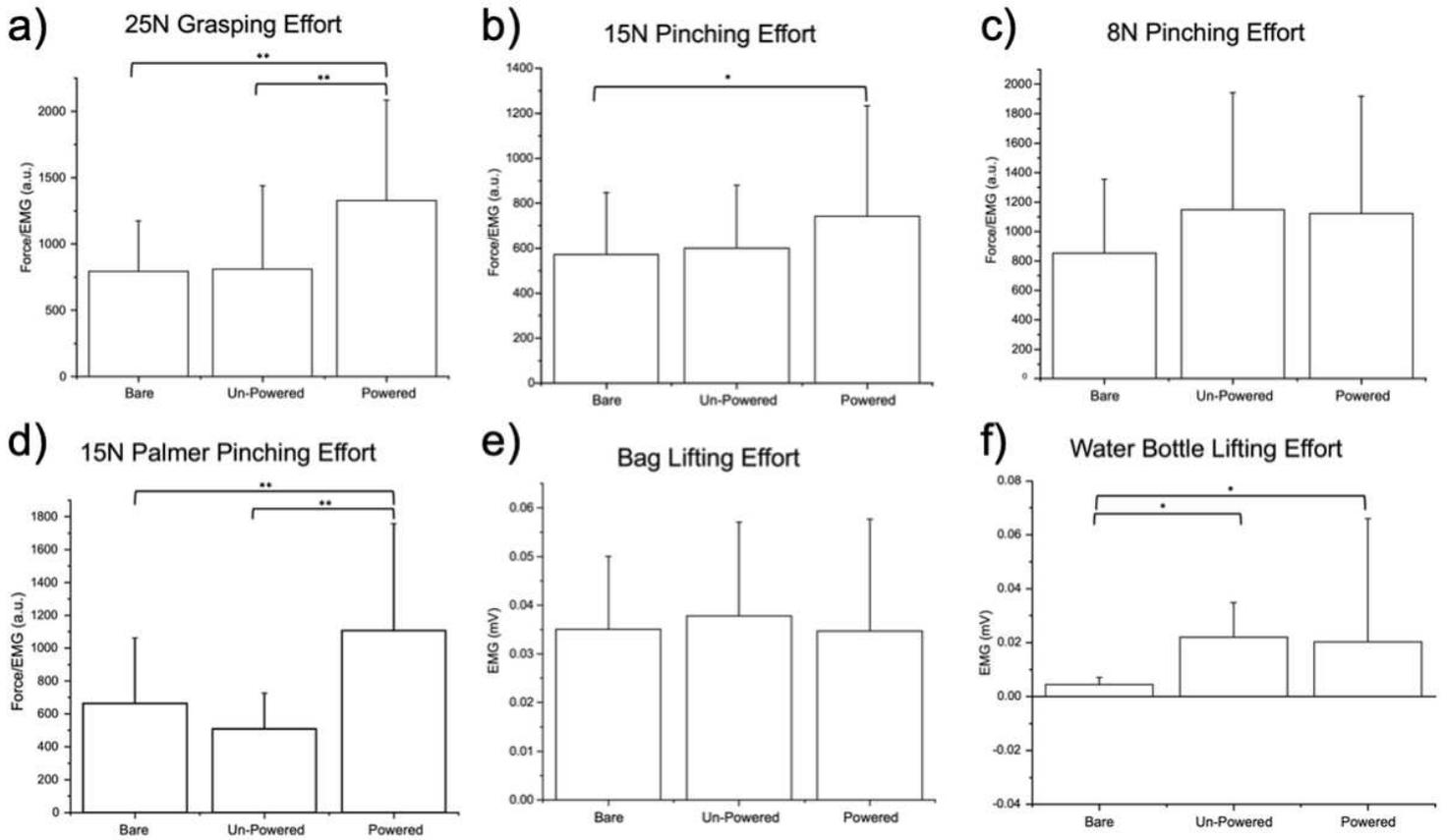


Figure 8

Average across 3 efforts per testing state in 10 subjects of (a) full hand grasping, (b) 15N pinching, (c) 8N pinching, (d) 15N Palmer pinching force/forearm muscle EMG ratio expressed in arbitrary units (a.u.), and (e) lifting a tote bag, (f) lifting a plastic water bottle forearm muscle EMG, expressed in millivolts (mV), where error bars designate standard deviation (*, $p < 0.05$; **, $p < 0.001$).

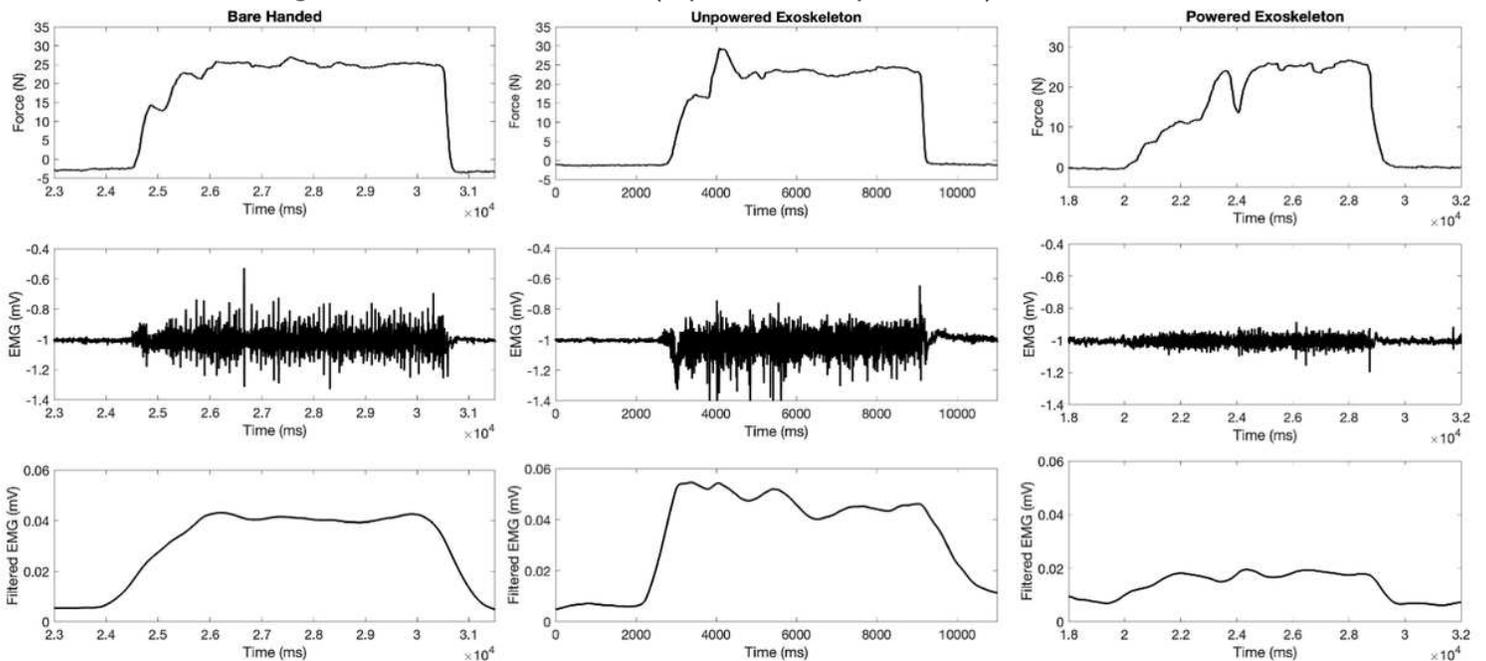


Figure 9

From top to bottom, recorded grasping force, recorded EMG, and detrended, filtered EMG from a representative subject during a 25N grasping effort during all three testing states. In the columns from left to right, the subject performed grasping efforts while bare-handed, wearing the unpowered device, and while wearing the powered and functional device.

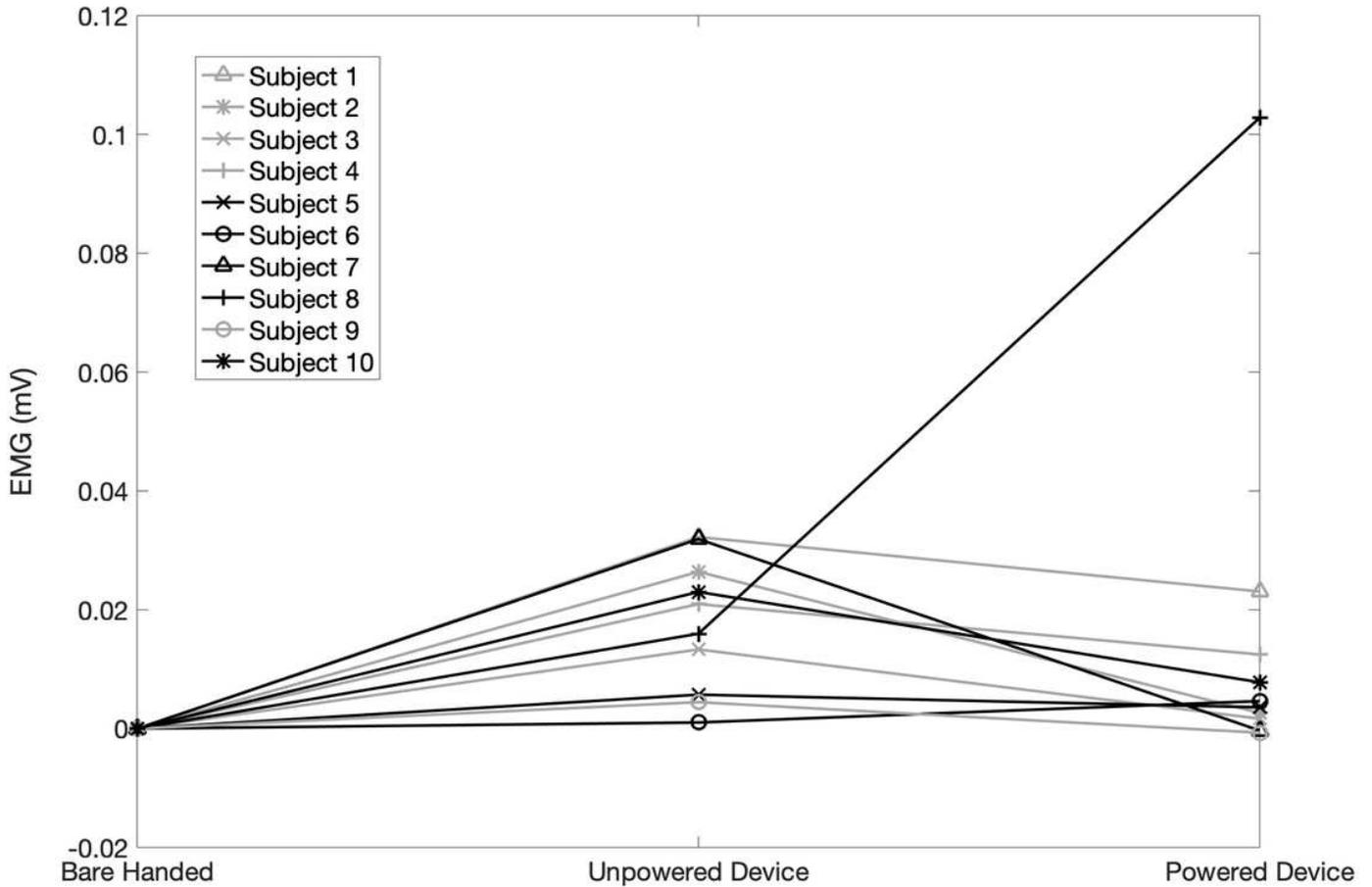


Figure 10

Normalized average forearm EMG (mV) from 3 efforts during the lifting of a plastic water bottle, across three states, bare handed, wearing the unpowered device, and while wearing the powered and functioning device.

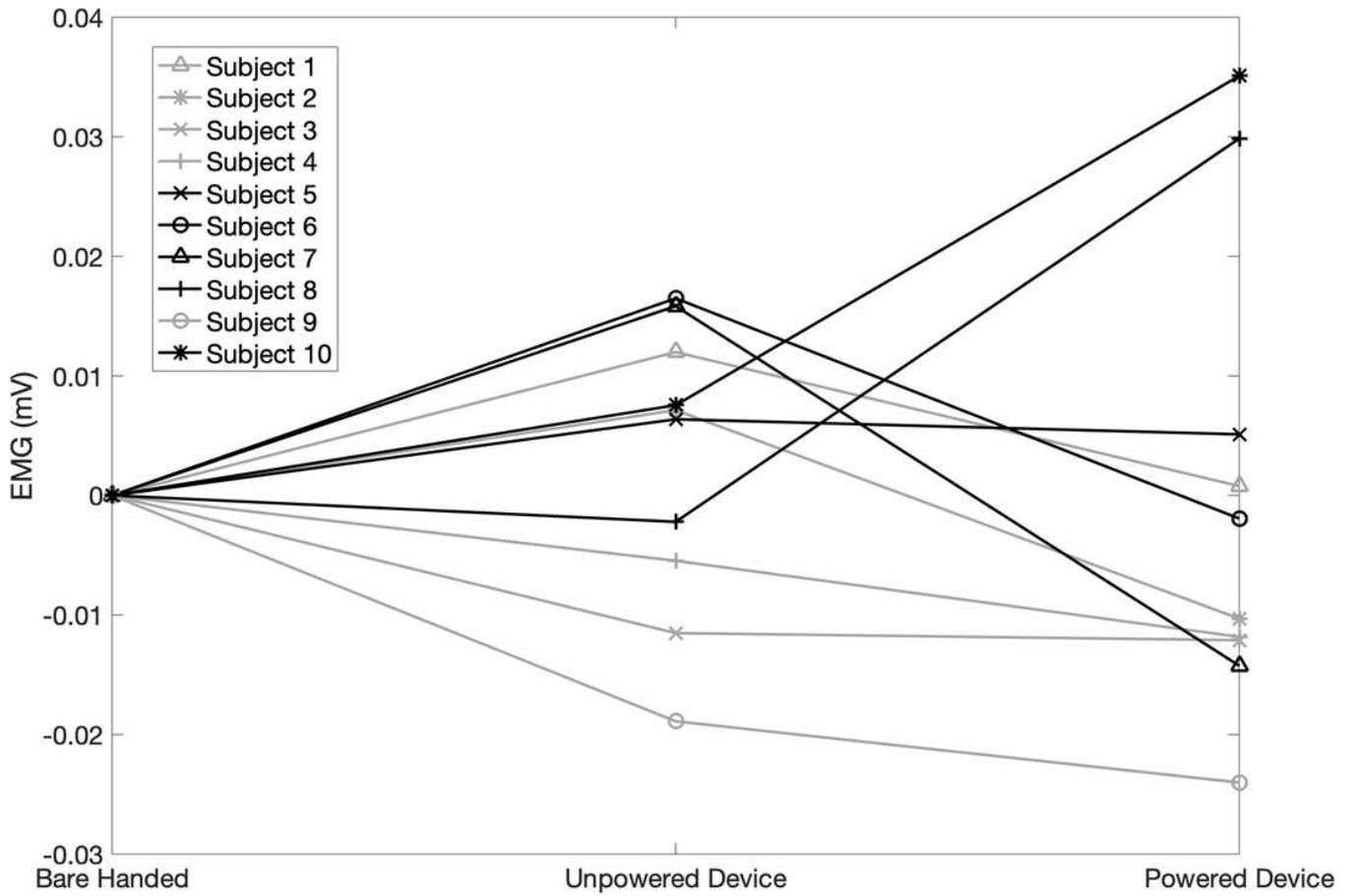


Figure 11

Normalized average forearm EMG (mV) from 3 efforts during the lifting of a weighted tote bag, across three states, bare handed, wearing the unpowered device, and while wearing the powered and functioning device.