DISENTANGLING SENSORY AND MOTOR DEFICITS OF FINE HAND FUNCTION USING AN ELECTRONIC GRIP GAUGE (EGG) TO SIMULATE TRANSFERRING FRAGILE OBJECTS

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ABSTRACT

Evaluating hand dexterity is a critical aspect of assessing novel prosthetic technology and informing patient care. Current upper-limb dexterity assessments primarily target gross motor function and do not directly measure the ability of an individual to finely regulate their grip force. An increasingly popular test of fine motor function among researchers is a fragile-object test, in which participants are instructed to lift and transfer an object while minimizing their applied grip force. Here we present another instantiation of this fragile-object test, dubbed the electronic grip gauge (EGG). We use the EGG to quantify grip force and transfer rate for intact hands and myoelectric prostheses under three distinct conditions: 1) implicit grasping when transferring the object as fast as possible, 2) grasping when participants are instructed to minimize their grip force using endogenous tactile feedback and/or indirect sensory feedback, and 3) grasping when participants are instructed to minimize their grip force and have auditory feedback proportionate to their grip force. We show that a lack of tactile feedback is a significant reason for poor prosthetic control, as evidenced by significantly better prosthetic control with auditory feedback. We also show that even with supplemental auditory feedback, performance of the prosthetic hand was still substantially worse than the performance of the intact hand. These results suggest that artificial sensory feedback can improve prosthetic control, but that improvements in mechanical design and/or real-time control are also needed to replicate the dexterity of intact human hands.

INTRODUCTION

Up to 50% of amputees abandon their prostheses, often citing poor control and a lack of sensory feedback as primary reasons [1]–[3]. Clinical measures of upper-limb function typically focus primarily on gross manual dexterity. For example, the Box and Blocks test (BBT) is a widely used test of upper-limb prosthesis function in which participants transfer small wooden blocks over a vertical barrier from one side of a box to another as quickly as possible in one minute [4]. However, the BBT, like many other clinical measures of upper-limb function, does not directly measure the ability of an individual to finely regulate grip force, which is a vital aspect of hand control when manipulating fragile objects [5].

A common variant to the BBT to assess fine motor function involves introducing a “break” threshold to the wooden blocks to replicate transferring a fragile object such as an egg. This modification requires the user keeps their grip force above the force required to pick up the object and below the force required to “break” the object. Instantiations of this fragile-object task have involved metal plates separated by a weak magnetic field [5]–[7], paper blocks held together loosely with toothpicks [8], and 3D-printed blocks held together weakly with embedded magnets [9]–[11]. A more recent instantiation involves a 3D-printed block embedded with a strain gauge and accelerometer to precisely measure the grip force and load force exerted on the object [12], [13].

Here we build on these prior studies and introduce a similar instantiation as [12] involving a 3D-printed block embedded with a strain gauge and accelerometer, referred to as the electronic grip gauge (EGG). We first present an overview of the device design and different testing conditions. Then, we use the instrumented egg to quantify differences in the control of myoelectric prostheses and intact hands for healthy participants. We show that both grip force and object transfer time are substantially greater for myoelectric prostheses compared to intact hands. We also show that providing supplemental sensory feedback (auditory feedback) in proportion to the applied grip force significantly reduces prosthetic grip force and transfer time, further supporting the idea that a lack of tactile sensory feedback is a primary reason for poor control. This work also provides quantifiable benchmarks for intact hands and myoelectric prostheses for this increasingly popular fragile-object test.

METHODS

Device Design

The EGG consists of a 100-lb load cell (TE Connectivity Measurement Specialties), triple-axis accelerometer (Adafruit), and wireless microcontroller (Arduino MKR WiFi 1010) contained in a 3D-printed polylactic acid (PLA) shell (Fig. 1). The microcontroller amplifies and streams data from the load cell and accelerometer to the computer wirelessly at 100 Hz using the User Datagram Protocol. An LED on the microcontroller can be programmatically set to visually show the state of the EGG. The base of the EGG can be filled with small lead weights to vary the weight of the object between 132 g and 414 g. The assembled instrumented egg measures 60.5x42.7x80.5 mm and can be readily grasped by various prostheses. An embedded battery provides roughly 2 hours of battery life.

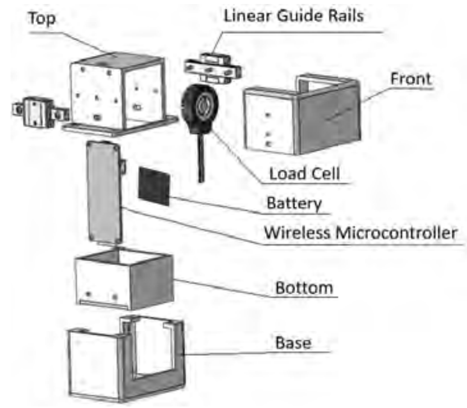

Figure 1: Exploded view of the EGG. The 3D-printed shell consists of top, bottom, front and base pieces connected with linear guide rails. The load cell and wireless microcontroller are housed between the top and bottom pieces.

Experimental Conditions

The EGG can be used under three different test conditions. In the first test condition, participants simply pick up and transfer the EGG as many times as possible within one minute while grip force is recorded. This test condition provides a measure of the transfer rate, similar to the BBT, and the users implicit grasping force, similar to the Grasping Relative Index of Performance [14].

In the second test condition, the experimenter sets an upper threshold on the grip force, such that the EGG will "break" and emit an audible sound if the participant's grip force exceeds the threshold. The participants are instructed to pick up and transfer the EGG as quickly as possible without breaking it. The difficulty of the task can be adjusted by lowering the break threshold or by increasing the weight of the EGG. In this study, the breakpoint was set to 11.2 N and the device weighed 414 g. The ratio of break force to weight in this study was 0.027 N/g; prior studies have used ratios of 0.032 N/g, 0.02 N/g, 0.015 N/g, and 1.34 N/g [7], [5], [9], [11], [8]. Because the EGG does not visually deform with increasing grip pressure, the only feedback the participants have regarding their applied grip force is endogenous (e.g., proprioception from forearm muscles or efference copy) or indirect (e.g., sounds of the prosthesis motor). Thus, this test condition provides a measure of the participant's innate sensorimotor grasping precision.

In the third test condition, the participant is again instructed to pick up and transfer the EGG as quickly as possible without breaking it. However, in this test condition, the participant is provided with auditory feedback regarding the grip force applied to the EGG. That is, a tone is played continuously and the pitch of the tone increases as the applied grip force approaches the break threshold. If the break threshold is exceeded, a second tone is played indicating the EGG has broken. This test condition also provides a measure of the participant's grasping precision. Using this test condition (continuous feedback) in conjunction with the previous test condition (discrete feedback) provides a way to systematically probe the impact of tactile sensory feedback on grasping precision. Significantly greater performance with continuous auditory feedback implies tactile feedback is impaired.

Participants and Experiment

Three neurologically healthy and physiologically intact participants volunteered in this study. Participants were between the ages of 18 and 21 (100% male). Informed consent and experimental protocols were carried out in accordance with the University of Utah Institutional Review Board. Participants were instructed to complete the three aforementioned test conditions (no feedback, discrete feedback, and continuous feedback), ten times each, with using both their intact hand and an EMG-controlled prosthesis. Participants moved the EGG over a 2-in vertical barrier.

Figure 2: Prosthesis Setup. Participants wore an sEMG sleeve around their forearm and held a prosthesis via bypass socket fit around their wrist.

Prosthesis Control

Surface EMG from the participants was collected using a custom EMG sleeve [15]. EMG was sampled at 1 kHz and filtered using the Summit Neural Interface processor (Ripple Neuro Med LLC) as described in [16]. EMG features used for estimating motor intent consisted of the 300-ms smoothed mean absolute value on 528 channels (32 single-ended channels and 496 calculated differential pairs) calculated at 30 Hz, as described in [16].

A modified Kalman filter was trained to predict hand flexion and extension, as described in (Thomson et al., MEC 2022) and previous reported in [16], [17]. The participants donned a prosthetic hand (LUKE Arm; DEKA) using a custom bypass socket [18]. A latching filter was applied to the kinematic output of the prosthetic hand to increase grasping stability [7], [19].

Performance Metrics and Analysis

Data consisted of the transfer time and peak grip force for each test condition, each hand, and each participant. All data were screen for normality. Data were aggregated across participants and two-way analysis of variance (factors: hand and test condition) was performed. Subsequent pairwise comparisons (Wilcoxon rank-sum test) were performed using the Dunn-Sidak correction for multiple comparisons. Additionally, a grouped comparison with pooled data from the three test conditions was performed between the prosthesis and intact hand.

RESULTS

Overall, transfer time (Fig. 3) and grip force (Fig. 4) were significantly greater for the prosthetic hand compared to that of the intact hand (p's < 0.05; Wilcoxon rank-sum test). Across all three test conditions, average transfer time was 283.3% longer for the prosthesis and grip force was 92.6% stronger for the prosthesis.

When a break threshold was introduced (discrete feedback), we observed no significant difference in performance for the prosthetic hand or intact hand. For the prosthetic hand, this resulted in a substantial failure rate (i.e., roughly 50% of the peak forces exceed the blue line representing the break threshold in Fig. 3). For the intact hand, implicit grasping force (no feedback condition) was already below the break threshold and remained similar.

When continuous auditory feedback was introduced on top of the break threshold, prosthetic performance improved significantly ($p < 0.05$; Wilcoxon rank-sum test). That is, transfer time was reduced by 20.3% and grasping force was reduced by 23.7%. For the intact hand, continuous auditory feedback did not significantly improve the task performance relative to the discrete feedback condition. Overall, the median transfer time and grip force of the intact hand was similar across all three test conditions.

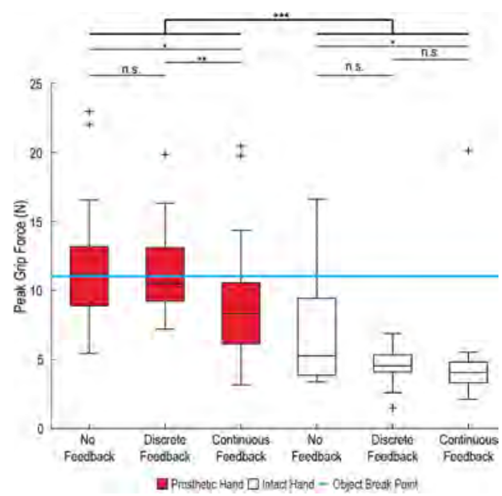

Figure 3: Grip force is significantly greater for the prosthetic hand compared to that of the intact hand. Data show peak grip force exerted on the EGG for ten trials for each of the three participants (N=30). Boxplots show median, inter-quartile range, and most-extreme, non-outlier values. Plus marks denote outliers. Blue line indicates the break threshold that participants attempted to keep their grip force below for the discrete-feedback and continuous-feedback conditions. Asterisks indicate different medians between conditions * ($p<0.05$), ** ($p<0.01$), *** ($p<0.001$); Wilcoxon rank-sum test; N=30 per group between test conditions and N=90 per group for the pooled comparison between the prosthetic and intact hands.

CONCLUSION

This study introduces another instantiation of a fragile-object test, based heavily on the design previous introduced in [12]. We expand upon the work in [12] by highlighting the embedded design and exploring different test conditions with both prosthetic and intact hands. The EGG introduced here quantifies grip force, load force, and object transfer time to enable more in-depth comparisons of fine motor function across people and technologies. Furthermore, the different test conditions provide an opportunity to systematically probe an individual's ability to finely regulate their grip force and quantify their innate tactile sensory feedback.

The results present here show that a lack of tactile sensory feedback is a significant reason for poor prosthetic control, as evidenced by improved dexterity when continuous auditory feedback is provided in proportion to exerted grip force. Furthermore, we also show that even with supplemental auditory sensory feedback, performance of the prosthetic hand was still substantially worse than the performance of the intact hand. Thus, it is likely that a combination of diverse improvements in the areas of mechanical design, real-time control and sensory feedback are necessary to make prosthetic hands as dexterous as healthy intact hands.

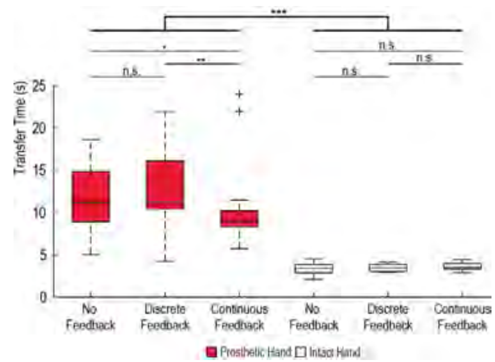

Figure 4: Transfer time is significantly greater for the prosthetic hand compared to the intact hand. Data show peak force exerted on the instrumented egg for ten trials for each of the three participants (N=30). Boxplots show median, inter-quartile range, and most-extreme, non-outlier values. Plus marks denote outliers. One outlier at a value of 32.04s is not shown for the prosthetic-hand no-feedback condition. One outlier at a value of 63.45s is not shown for the prosthetic-hand discrete-feedback condition. Blue line indicates the break threshold that participants attempted to keep their grip force below for the discrete-feedback and continuous-feedback conditions. Asterisks indicate different medians between conditions * ($p<0.05$), ** ($p<0.01$), *** ($p<0.001$); Wilcoxon Rank Sum Test (N=30 per group between test conditions and N=90 per group for the pooled comparison between the prosthetic and intact hands).

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