Utility of Contact Detection Reflexes in Prosthetic Hand Control

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Abstract— **Tactile sensations make grasping fragile objects a simple and unchallenging task for the human hand. Prosthetic hands lack these sensory capabilities and their users frequently struggle with such tasks. To address this problem, the benefits of compliant fingertips with contact-detection reflexes were assessed in one prosthesis user when grasping fragile objects (eggshells, foam packing peanuts, crackers, and soft clay). A commercially available myoelectric prosthetic hand was modified to include the compliant BioTac® tactile sensors (SynTouch, LLC), which have previously been demonstrated to be more sensitive to contact than the human fingertip. Upon sensing contact during hand closure on an object, the gain of the operator's EMG command signals to the prosthesis' motor was reduced to prevent excessive closing forces, a behavior similar to an inhibitory reflex. This allowed the prosthetic hand to quickly react to the presence of the object and permitted the operator to handle fragile objects with ease and without the usual dependency on visual feedback. The time required to grasp and move a set of fragile objects with this modified prosthesis was compared to the subject's usual prosthetic hand. The contact detection method demonstrated both utility and reliability through faster completion times and reduced variance in the times to complete these trials.**

I. Introduction

Despite advancements in myoelectric prosthetic hand technology, many problems still exist in commercially available prostheses, often related to the constraints of cost, power, weight, robustness and ease of use that such devices must satisfy [1]. With currently available prostheses, even mediocre performance handling fragile objects requires patience, intense concentration, and good visual feedback. Amputees must precisely time their controlling electromyographical (EMG) signals to stop their prosthesis before crushing a fragile object, often requiring many small movements before a successful grasp is made. Additionally, due to the high internal friction of these devices, large electrical currents are required to start the DC motors and gearing into motion. These signals, left unattended, result in high stalling forces when the fingers close on an object, making the grasping of fragile objects a very difficult task. As a result, unilateral amputees tend to avoid handling fragile objects with their prostheses altogether. Previous research projects have explored proportional force control (albeit at larger forces) [2], [3] and slip prevention [4], [5] in prosthetic limbs. This study presents a novel contact detection reflex to enable light grasping of fragile objects.

Able-bodied subjects have no difficulty in grasping fragile objects due to the wealth of tactile feedback available during these tasks [6], [7]. The timing of these tactile events plays a critical role in perception and dexterity [8]. Various sensing technologies have been developed to bring such human-like tactile sensing to robotics [9]-[11], yet few sensors have achieved the requisite robustness to be practical for prosthetic technologies. The BioTac (SynTouch, LLC) is one such sensor that meets this robustness and sensitivity, exhibiting a compliance and sensitivity to contact similar to the human fingertip [12]. Both compliance and sensitivity are essential for the grasping of fragile objects. Compliance has been shown to improve the delicate handling of fragile objects, as well as increasing the stability and robustness of grasps [13]-[16]. Compliance in hydraulic joints or in thin silicone skin has been examined in robotic grippers [15], [17], but the effect of fingertip compliance and the handling of fragile objects in prosthetics has not been quantified.

II. Methods

The BioTac sensors were incorporated into a commercially available prosthetic hand (Figure 1) to assess grasping performance in a variety of timed fragile grasping tasks. To prevent excessive grasping force, an artificial reflex was implemented to detect contact and inhibit the EMG command signals from the user to the prosthesis motor when contact was detected in the BioTac sensors.

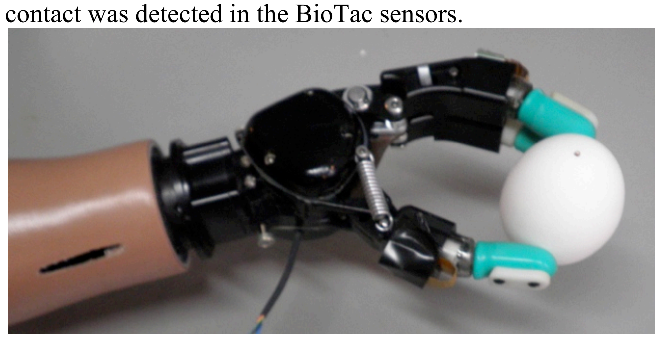

Figure 1 - Prosthetic hand equipped with BioTac sensors grasping an egg.

A. Hardware and Data Acquisition

1) The BioTac

The BioTac (SynTouch, LLC, Los Angeles, CA) (Figure 2) is a multimodal tactile sensor designed to mimic the sensory capabilities of the human finger [18], [19]. It consists of a rigid bone-like core covered with a silicone skin. The space between the skin and the core is inflated with a liquid

*This work was supported in part by the Eunice Kennedy Shriver National Institute of Child Health & Human Development of the National Institutes of Health SBIR Grant 5R44HD061165-03 to SynTouch LLC, where the research was performed.

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Conflict of Interest Statement: Gerald Loeb, and Jeremy Fishel are equity partners in SynTouch, LLC, which manufactures and sells the BioTac sensors described in this article.

giving the sensor biomimetic compliance comparable to primate fingertips [20]. The skin is easily replaceable and contains no electronics, making the sensor robust enough for everyday prosthetic use, yet easy to repair in the event of damage. The BioTac can simultaneously sense force [18], [21], vibration [12], [19], and temperature [22]. All data are digitized inside the device and transmitted via serial peripheral interface bus (SPI). Force estimates can be extracted either from a pressure sensor inside the fluid-filled chamber [23] or from an array of impedance-sensing electrodes [24]. In these experiments, contact forces were measured using the pressure sensor, which has been demonstrated to provide contact sensitivity that exceeds normal human performance [12].

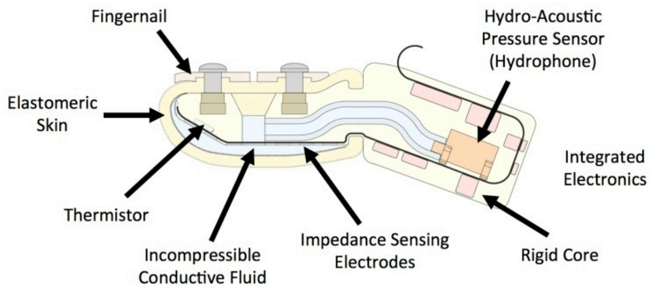

Figure 2 - Conceptual Schematic of the BioTac.

2) *Prosthetic Hand*

For this study a commercially available 1-DOF prosthetic hand (Motion Control Hand, Motion Control) was fitted with two BioTac sensors to take the place of the thumb and index finger (Figure 1). The cosmesis was removed along with the passively coupled ring and pinky fingers. A "dummy" BioTac, composed of a silicone skin on a plastic core of the same size and shape as a BioTac sensor but without electronics, was used in place of the middle finger; however, a third BioTac could be used in its place if desired.

3) *Data Acquisition and Control*

EMG signals were taken directly from the pair of electrodes in the subject's prosthetic socket used to control his prosthesis (13E200 MYOBOCK® Electrode, OttoBock). The electrodes have adjustable gain, rectification and filtering developed by OttoBock, designed to provide a DC voltage in proportion to muscle activation to control the prosthetic hand. Both the opening and closing EMG signals were acquired in LabVIEW with a data acquisition card sampling at 20Hz to reflect EMG integration and biological response times. The BioTac data were collected through an SPI controller and software developed by SynTouch. The computer controlled the motors of the prosthetic hand directly via analog output voltages (also updated at 20Hz) that were buffered using a high-current operational amplifier.

B. *Contact Detection Reflex*

The algorithm used in these experiments was designed to mimic an inhibitory reflex to facilitate the grasping of fragile objects with minimal force overshoot beyond the user's intent. Excessive forces are typically not a concern to prosthesis users when handling rigid non-fragile objects and operators typically send large EMG signals, letting the motors stall on the object. However, when handling fragile objects, the user must delicately alter the position of the fingers with small EMG signals until firm contact can be confirmed visually. Because of the high currents required to start the motor and the lack of awareness of the amplitude of the EMG signal that the user is generating, this process is slow, difficult to control, and heavily reliant on visual feedback and attention. Our goal was to create a biologically inspired reflexive algorithm that would greatly simplify this process and allow a user to securely grasp fragile objects by generating a simple EMG signal.

For these experiments, a state change was implemented to alter the relationship between net EMG (difference between closing and opening EMG signals) and motor command voltage when closing the hand (Figure 3), when contact was detected in opposing fingers. In normal operation, our subject's amplified net EMG signal had about 1.2V of background noise, so the motor command voltage was set to 0V in this range. In both opening and closing, voltages between ±5VDC were not sufficient to move the hand due to the internal friction of the motors. When sending a closing command with a positive net EMG signal (closing EMG larger than opening EMG) values above the 1.2V noise threshold were mapped linearly starting from 5V output for both the contact and no-contact states. In the non-contact state, control signals had greater gain to make the hand more responsive and easier to close at faster speeds; this gain was tuned to the subject's preference and mimicked the speed and behavior of the subject's personal prosthetic hand. In the contact state, this gain was reduced to prevent excessive voltages from causing the motors to stall on the object with high forces. To prevent damage to the BioTacs, the peak voltage in the contact state was limited to 7.75V which was found to correspond to 60N of grasp force in steady-state, equivalent to the suggested loading limit for the BioTac. The gain of this state was set so that the full range of EMG signals (about 3.5V) was mapped to the maximal motor command of 7.75V. For smoothing purposes, the algorithm used a running average of the last three EMG measurements.

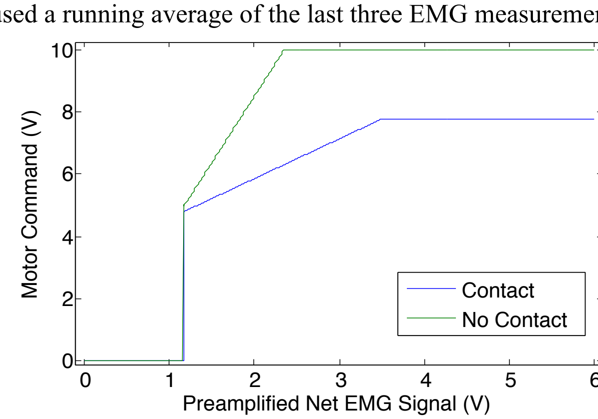

Figure 3 – Positive Motor Command for Contact and No Contact States.

The BioTac's pressure sensing capability was used to detect contact with an object. A *contact pressure* was defined as the threshold of pressure increase from its resting value in the non-contact state to allow for compensation of drift due to inflation volume and environmental factors. Contact was considered to be made when the pressure in both opposing fingers rose above this contact pressure; this was tuned to 20 binary units of the 12-bit gauge range of pressure (730Pa, found empirically to be ~0.2N of contact force), which was found to be sufficient to avoid false positives from vibrations in the motor and subject movement.

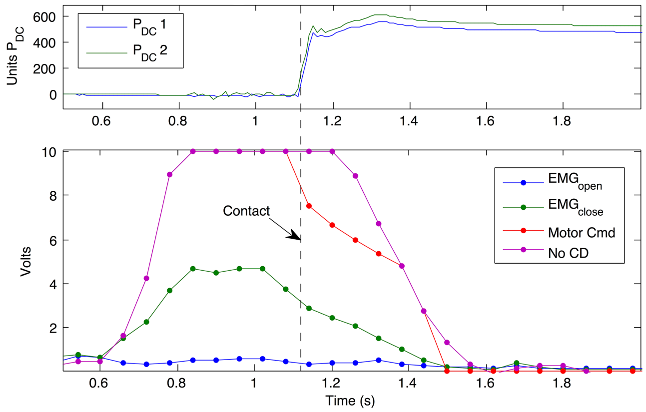

Figure 4 - Effect of the Contact Detection Algorithm: The top figure shows the DC pressure values in each BioTac during a grasping task (differences due to asymmetrical fingertip location). The lower figure shows the user's EMG values and the motor drive signal applied to the hand both with and without contact detection during the same task. Note that with contact detection, the motor signal drops off immediately after contact, where without it there is a sustained overshoot of about 200ms after contact.

Three user intent states were defined in software: opening, closing and neutral. A net EMG value of less than -1.65V was considered an opening intent from the user, and a value of greater than 0.24V was considered a closing intent (or intent to maintain grasp on an object); values in between were considered neutral. When the subject was opening the hand, the control would be switched to the no-contact state (Figure 3), and the resting pressure was set to the current pressure of the BioTacs to tare the sensor. When a closing intent was determined, the resting pressure would be fixed to the pressure at the start of the closing movement. If the intent was not determined to be opening or closing (neutral), the resting pressure would be reset to the current pressure of the BioTacs only if the controller was not in the contact state. Contact was assumed to be lost only if the pressure in the BioTacs dropped below the starting threshold (indicating the object had been removed from the hand) or if the operator sent an opening command (indicating the user's intent to let go of an object). The effect of the contact detection algorithm on the control signals can be seen in Figure 4.

C. *Experimental Comparison*

Four experiments were designed to test the speed, accuracy, and ease with which fragile grasping activities could be performed. These tests utilized simple objects that a prosthesis user could expect to encounter in everyday scenarios, as identified by the subject. A fifth experiment was designed for evaluating the performance when handling rigid objects to evaluate how these methods might impede these tasks for a prosthetic user. The following tests were performed (Figure 5):

i. Pick up ten foam packing peanuts from a table and place them into a container as quickly as possible. Peanuts gripped with excess force (~3N) would break and would not count towards the total.
ii. Grasp ten crackers handed to the user by the experimenter, and place them into a container as quickly as possible. Two variants were run, with the subject told to prioritize either speed or accuracy. In the speed trials, crackers that were broken (~5N) did not count towards the total. In the accuracy tests, broken objects resulted in a failed trial and the entire trial would be repeated.
iii. Move nine hollow eggshells from one carton to another as quickly as possible. Broken eggs (~25N) would not count towards the total. In an alternative condition, the subject was distracted while performing this task by being asked to simultaneously spell a series of words.
iv. Grasp a ball of clay with the goal of deforming it as little as possible. The distance that the ball deformed was measured with calipers.
v. Grasp and move ten unopened soda cans across a table as quickly as possible. This activity did not involve fragile or deformable materials and was designed to compare performance on grasping rigid non-fragile objects.

One twenty year-old male unilateral trans-radial amputee and myoelectric prosthesis user evaluated the performance of this system in the above grasping tasks. The subject was compensated for his time during testing and development.

All of these tests were performed by the subject with 1) his own prosthesis (VS, VariPlus Speed, Otto Bock), 2) the BioTac-equipped hand both with contact detection algorithms (CD) and without these algorithms (to evaluate the contribution of the compliant fingers themselves) (C), and 3) his intact dominant hand (DH). For each experiment, the subject was allowed to train until his performance became steady, then 5 trials were recorded.

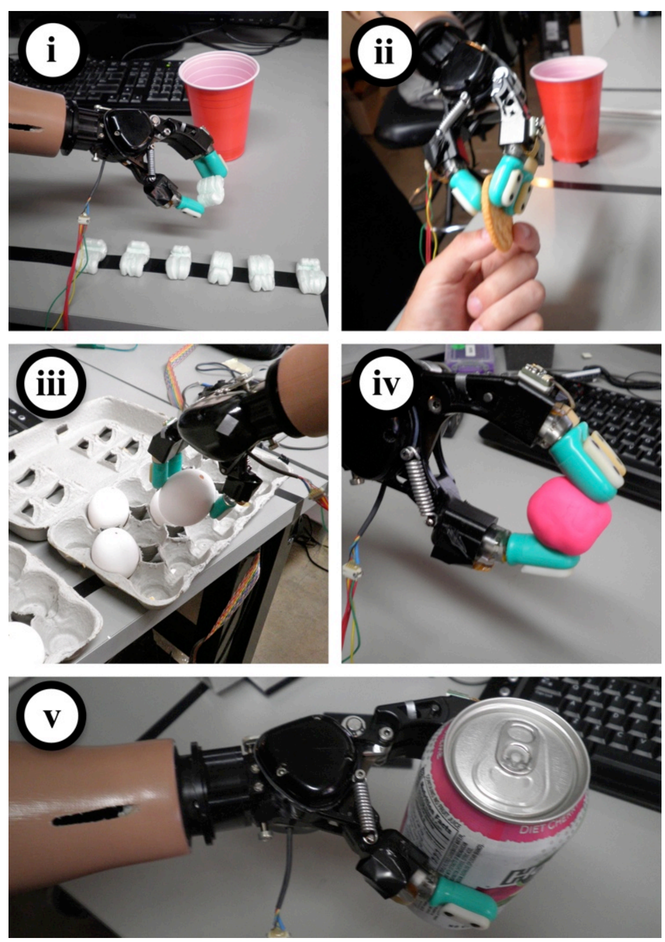

Figure 5 - Pictures of Experiments. i: grasping foam peanuts, ii: grasping crackers, iii: grasping hollowed eggshells, iv: grasping deformable clay, v: grasping a rigid soda can.

III. RESULTS

In every timed fragile-grasp task (i-iii), the subject's personal prosthesis (VS) had the worst performance, and the contact detection (CD) was the best of the prostheses. Performance was found to be more consistent (less variance between trials) when using the contact detection algorithms, similar to the subject's dominant hand.

A. Performance on Timed Grasping Tasks

The performance index normalized by the time to complete the task in the subject's dominant hand is presented in Table 1. The subject's personal prosthesis (VS) scored as poorly as 4.82 times slower than the dominant hand when grasping crackers for accuracy, and was never faster than the hand with compliant fingertips even with contact detection disabled (C). Enabling contact detection brought performance in every test to a score less than 2, i.e. much closer to biomimetic performance, and resulted in greater reproducibility (Figures 6-10).

	VS	C	CD	DH
Foam	3.59	3.04	1.85	1.00
Crackers - Speed	4.41	1.54	1.32	1.00
Crackers - Accuracy	4.82	1.78	1.43	1.00
Eggs - No Distraction	2.45	1.83	1.71	1.00
Eggs - Distraction	2.79	2.14	1.70	1.00
Soda	1.86	N/A	1.86	1.00

Table 1 – Performance scores normalized to dominant hand performance. VS = VariPlus Speed Hand, C = Motion Control Hand with compliant fingertips, CD = Motion Control Hand with compliant fingertips and contact detection, DH = Subject's dominant hand.

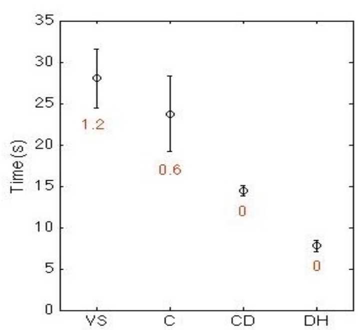

Figure 6 – Results from foam peanut experiment. Mean and 95% confidence interval displayed for each test. Red numbers indicate the average number of broken objects per trial. Performance with contact detection (CD) was not only faster, but also had less variability.

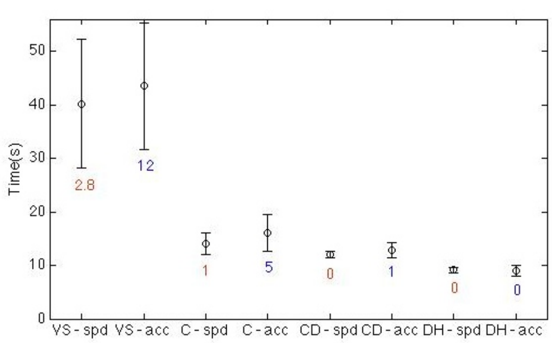

Figure 7 – Results of the cracker experiment, Red numbers indicate the average number of broken objects for speed trials; blue numbers indicate the number of failed accuracy trials due to broken objects.

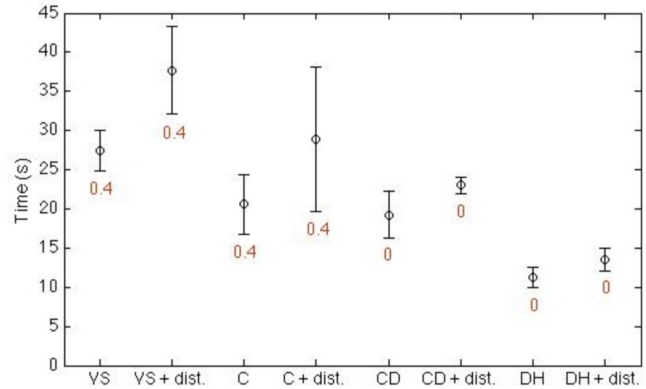

Figure 8 – Results of egg experiment for each prosthesis condition without and with (+ dist) distraction. Red numbers indicate the average number of broken objects per trial.

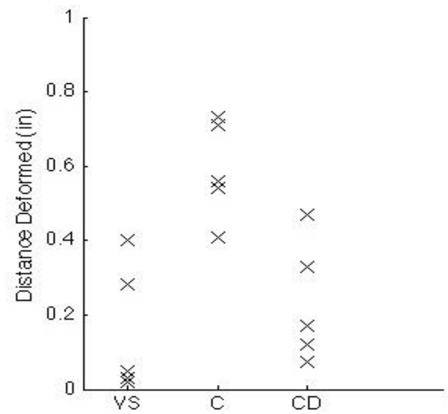

Figure 9 – Results of the clay experiment. The subject was able to perform this task well with his existing prosthetic hand when given enough time and had poorer performance with the modified prosthesis, although performance was improved with contact detection.

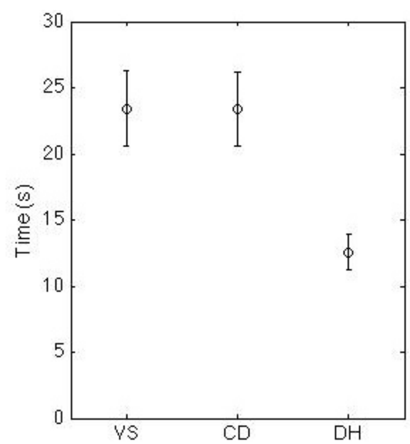

Figure 10 – Results of soda experiement. No statistical difference was observed between performance of either prosthetic hand.

The only exception to the improved performance came in the deformable-grasp task using clay, where the VariPlus Speed hand outperformed both compliance and contact detection on the modified prosthesis. This was likely due to the greater control and experience the subject had over the precise positioning of his personal prosthesis. High levels of internal friction made it challenging to operate the Motion Control hand at very slow speeds [3], which heavily impacted its performance in task iv. The result was still significantly better with contact detection than without.

A one degree-of-freedom ANOVA test (Table 2) was carried out for each test to verify the improvement for both compliant fingertips versus the subject's current prosthesis as well as contact detection versus no contact detection. The test showed that the compliant fingertips outperformed the VariPlus Speed hand at a high confidence level (P<0.01) for every timed fragile-grasp task. It also showed a difference between compliance and contact detection (P<0.01 significance level) for the foam, cracker, and clay experiments, as well as at the P<0.05 significance level for the egg experiment with the distraction. It showed no significant difference between control methods (P > 0.05) on the non-fragile object (unopened soda cans).

1 DF ANOVA results for VS vs. C

Test	P
Foam	0.010
Crackers-Speed	<0.001
Crackers-Accuracy	<0.001
Egg-No Distraction	<0.001
Egg-Distraction	0.007
Clay	**0.002**

1 DF ANOVA results for C vs. CD

Test	P
Foam	<0.001
Crackers-Speed	0.003
Crackers-Accuracy	0.006
Egg-No Distraction	0.243
Egg-Distraction	0.022
Clay	0.005

1 DF ANOVA results for VS vs. CD

Test	P
Soda	0.948

Table 2 - ANOVA test results. Compliant fingertips (C) were found to improve performance over the subject's personal prosthetic hand (VS) in all timed tests, but did worse in the clay test (red). Contact detection (CD) added further improvement over compliant fingertips without contact detection (C) in all tests, but results were more substantial for the more fragile objects.

IV. Discussion

A. *Effects of the Compliant Fingertips*

Simply providing prosthetic fingertips with compliance similar to human fingertips produced significantly improved performance when grasping fragile objects. In particular, when grasping rigid fragile objects (such as the crackers and eggshells in experiments ii and iii) the additional compliance offered much benefit when compared to the rigid urethane glove of the subject's personal prosthesis. The subject reported that firm grasps were significantly easier to achieve, due to the compliant fingers' ability to mitigate any accidental force overshoot, and the lower requirement of precision. Because of this, he felt confident to move more swiftly during grasping activities after minimal training.

B. *Effects of Contact Detection*

The contact detection reflex provided another significant improvement on fragile grasping activities when combined with compliant fingertips. Both speed and accuracy increased in all tests when contact detection was activated. Additionally, this had no detrimental effect on performance when grasping non-delicate objects (Figure 10).

The greatest benefit of contact detection was that the subject's performance between trials became substantially more consistent and with reduced variability between trials (similar to the performance of the subject's dominant hand). In many ways, consistency and reliability are more beneficial than speed as they help the prosthesis user anticipate how the hand will behave.

For the task of grasping eggshells with and without cognitive distraction (Figure 8), performance was best with contact detection in both conditions. While all times became slower with distraction, the trials without contact detection became disproportionately slower when normalized by the performance of the subject's dominant hand. However, the trials with contact detection were not affected in this manner, suggesting a similarly low cognitive burden between normal hand use and the prosthetic hand with contact detection.

The difference between performance with compliance and contact detection increased with the fragility of the object being grasped. On the sturdiest fragile object, the eggshells, adding contact detection yielded only a 14% improvement towards the dominant hand time. This is likely because compliance reduced force overshoot to levels that the eggs could withstand without breaking in most trials. However on the most fragile object, the foam packing peanuts, contact detection was more than 58% closer to ideal performance than compliance alone.

The subject reported that the compliant fingertips with contact detection made grasping feel more natural, and he developed a strongly improved confidence in his ability to grasp fragile objects without breaking them. He also reported subjectively that the hand was simpler to use and required less focus, consistent with his performance during the distraction task, claiming that the hand just "works" and he didn't need to worry about grasping fragile objects with care. With the other prostheses, he reported the necessity of choosing between doing a task quickly or doing it accurately, but contact detection alleviated this problem. While this study only explores the experience of a single subject, the reports from the subject were compelling and indicated that the contact detection prosthesis required less reliance on visual feedback, and felt more natural and humanlike.

In pilot experiments not presented here, the subject was fitted with primitive tactors that provided a conscious awareness of contact events. The subject was able to make some use of such sensations to improve performance, but described them as distracting and preferred to use the prosthesis with contact detection reflexes but no tactors.

C. *Dynamic Control of Grasping Force*

While contact detection thresholds were set at a fixed threshold and only two contact states were set, the inertial properties of the hand and delays in signal processing enhance a desirable dynamic control that allowed the intent of the user to regulate the stopping force of the hand (Figure 11). For example, when prosthesis users grasp objects known to be unbreakable, they tend to produce high EMG signals. These large control signals to the motors produce a faster closing rate, and the inertia and speed of the hand help cause the hand to close with a high grip force before the contact state is enabled. However, when grasping fragile objects, relatively small EMG signals were produced by the subject, so the algorithm minimized overshoot and produced a lower stopping force. This property helps produce forces that are closely aligned with the intent of the user and prevents the algorithm from interfering with rigid grasping tasks.

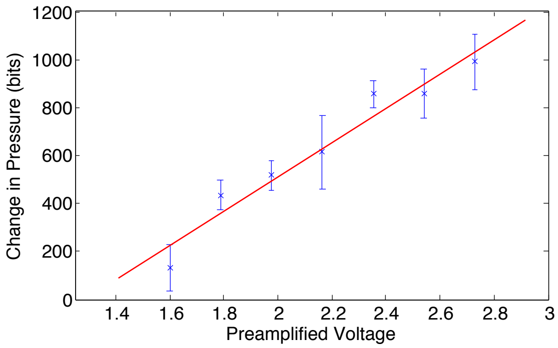

Figure 11 - EMG signal (Preamplified Voltage) vs. final stopping pressure. The final resting pressure of the BioTac (1bit = 0.01N) was found to be proportional to the EMG command signal to the system. Modulating this control signal has a direct effect on overshoot and final stopping pressure.

D. *Conclusions*

Much of the research currently being done on prosthetic hands is focused on making hands with multiple degrees of freedom or programmed prehension patterns that enable the hand to assume a variety of positions but are difficult to control. Far less progress is being made on improving performance on prostheses' most important task: grasping objects. In this paper we have presented two simple ideas that appear to create a marked improvement in the usability of prosthetic technology. Compliance is a biomimetic property that can easily be applied to existing prosthetic technology, at a significant gain of function to the user when grasping fragile objects. Contact detection reflexes can also be used to improve the performance of prostheses during everyday tasks, allowing the prosthetic hand to be both quick and delicate as well as more intuitive and natural for the user. These two principles can also help make prosthetic technology more affordable by providing superior functionality with less expensive actuator technology and avoiding the need for tactors or other haptic display technology. In a low-cost prosthetic hand, we were able to obtain performance that is unattainable to date in some of the most expensive research robot hands. Future research in this area will include integrating the technology within the power and weight constraints of a wearable prosthesis, and developing a simpler and cheaper tactile sensor intended specifically for contact detection.

V. Acknowledgement

The authors would like to thank Vikram Pandit for his help on the project, Raymond Peck for designing the adapters and various fixtures for these tests, Gary Lin for assistance with electronics and programming, and the rest of the team at SynTouch for their support. This work was supported in part by the Eunice Kennedy Shriver National Institute of Child Health & Human Development of the National Institutes of Health Grant 5R44HD061165-03.

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