LOW-COST, COMPLIANT CONTACT SENSOR FOR FRAGILE GRASPING WITH REDUCED COGNITIVE LOAD

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INTRODUCTION

Myoelectric prosthetic hands have a long history of impressive technological development but low functional utilization and acceptance [1]. Substantial research has gone into the development of technologically advanced prostheses; but while costs of care have skyrocketed over the decades [2], no observable progress has been made in improving the practical functionality of these devices, their user satisfaction, or quality of life for their users [3]. Before adding even more technology, it is important to understand problems that lead to this unsatisfactory situation:

1. Operating a myoelectric hand requires a lot of mental effort, especially for tasks requiring precision (e.g. grasping delicate objects); variance in performance in these tasks creates a lack of confidence in the hand's performance.
2. Adding technology makes any device more complex, hence expensive and prone to breakage.

To be successful, new technologies must address problem 1 without adding to problem 2. Problem 1 arises from the limited sources of command signals that can be used to control a prosthesis. As prostheses become more anthropomorphic with multiple degrees of freedom (iLimb, Touch Bionics; BeBionic, RSL Steeper; Michelangelo, OttoBock; etc.), the limitation in command signals becomes a bottleneck in their functional utility, with little improvement in performance seen over simpler devices [4]. Targeted muscle innervation to expand the number of command signals shows substantial promise [5], but may prove to be too costly and invasive for widespread adoption, particularly in less-severe amputations. As it has been reported that acceptability of prosthetic hand technology is more dependent on the required attention than the success in grasping [6], making prosthetic devices more intuitive to control should remain a primary objective.

Fragile and precise grasping are among the most difficult and cognitively demanding tasks for prosthetic hand users. With currently available technologies, even inconsistent performance handling fragile objects requires substantial patience and visual attention, resulting in high cognitive load. To perform well, EMG signals must be precisely timed when grasping these objects; even small errors can result in incomplete grasps or undesired high stalling forces when the fingers close. Consequently, unilateral amputees prefer to use their intact hand for most tasks, especially those involving fragile objects. Able-bodied subjects have no difficulty in grasping fragile objects due to the wealth of tactile feedback available during these tasks [7], [8]. Conversely, even the fully intact human hand with its high level control is almost useless in the absence of tactile feedback [9]. Various sensing technologies have been developed to bring human-like tactile sensing to robotics [10]-[12], yet few sensors meet the unique specifications demanded in prosthetic applications. This study presents a biologically inspired method to enable fragile grasping of objects by combining compliant tactile sensors with a biomimetic contact detection reflex.

METHODS

Figure 1: Left - a BioTac® tactile sensor; Right - a low-cost NumaTac® prototype tactile sensor.

In previous work we had explored the benefits of human-like tactile sensing in prosthetic hands for reflexive grip control [13] and tactile perception [14] with the BioTac sensor (Figure 1, SynTouch LLC, Los Angeles). The BioTac is a finger-like compliant tactile sensor capable of sensing much of what human fingertips can sense: normal and shear forces [15], [16], point of contact [17], vibrations [18], [19], and temperature [20]. While the complexity and cost of this device make it poorly suited for a commercial prosthetic hand, it was useful as a research tool to identify which of these sensory modalities could enhance prosthetic hand function. Our findings indicated that the performance and reliability of grasping fragile objects could be greatly improved while simultaneously reducing the cognitive load (addressing problem 1 as stated above) using only a small subset of the BioTac's capabilities (compliance and sensitivity to contact) [13]. To address problem 2, we developed a simplified version of this sensor to provide these specific capabilities.

The NumaTac Sensor

The NumaTac (Figure 1) is a low-cost and compliant tactile sensor that provides sensitive contact detection. It consists of a rigid bone-like core covered with open-cell reticulated foam. The foam is self-skinning and sealed with a polyvinyl fluoride to trap the air inside the sensor. A pressure sensor embedded into the core and sealed with a silicone gasket records the pressure inside the foam. When the sensor makes contact with an object, the sensor detects the resulting pressure increase inside the foam. The NumaTac possesses similar sensitivity to contact as the human fingertip and the BioTac [18], but cannot resolve the location or direction of contact. It can also be molded into almost any desired shape.

Contact Detection Reflex

Humans are capable of quickly grasping objects without excessive forces. This is enabled by specialized cutaneous receptors and spinal circuitry that can detect contact and inhibit further activation of the muscles closing the fingertips [7]. Excessive forces are typically not a concern to prosthesis users when handling rigid non-fragile objects (operators typically send large EMG signals, letting the motors stall on the object). When handling fragile objects, however, the user must close the fingers slowly with small EMG signals until stable contact can be confirmed visually. Relatively large command signals may be required to overcome friction and the amplitude of the user-generated EMG signal tends to be noisy, making this process slow, difficult to control, and heavily reliant on visual feedback and attention. This can be greatly simplified by artificially mimicking the above-described inhibitory reflex [13].

To achieve this desired reflexive behavior, a state change was implemented to reduce the gain of the EMG signal delivered to the prosthetic controller upon sensing contact in opposing fingertips (Figure 2). Fluid pressure was used to detect this contact for each sensor (liquid in the BioTac, and air in the NumaTac). When there was no contact, control signals had unity gain to make the hand more responsive and easier to close at faster speeds. After contact was detected, this gain was reduced to 0.3 (determined by user preference). For low EMG levels this would cause the motor to stall on the object with low but predictable force, dependent on the EMG level, closing speed before contact, a small delay in the feedback loop and the compliance of the fingertips. As EMG signals were not abolished upon contact, the prosthesis operator maintained full control over the stalling force and was capable of closing with high forces with elevated EMG signals. While simplistic in nature, this approach was found to dramatically improve speed and reduce performance variability in repeated tasks [13].

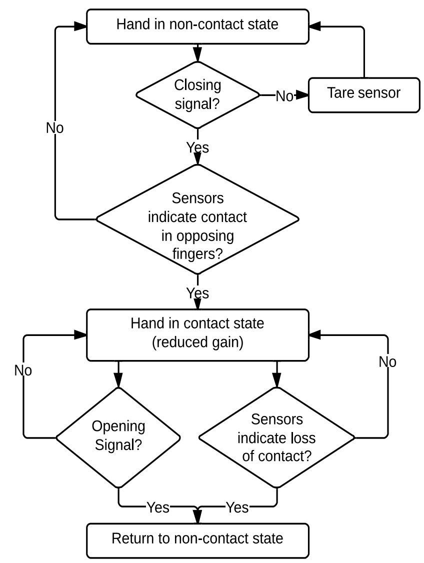

Figure 2: Control algorithm with contact detection

Hardware

Similar methods to those described in [13] for evaluating the BioTac in fragile grasping performance were used to also evaluate the NumaTac sensor in this study. Relevant aspects of these methods are summarized herein.

In previous work, specialized mechanical adapters were fabricated to install the BioTacs onto a commercially available 1-DOF myoelectric hand (MC Hand, Motion Control). Fixtures to attach the NumaTac sensors to these same adapters were made to facilitate switching between sensors. In all tests a sensor was placed in the thumb and index finger to detect opposing contact. The cosmesis was removed along with the passively coupled ring and pinky fingers and a non-functioning fingertip was installed on the middle finger, although if desired another sensor could be used with no major changes to the algorithm.

EMG signals were taken directly from the pair of electrodes in the subject's prosthetic socket used to control his regular prosthesis (13E200 MYOBOCK® Electrode, OttoBock). The electrodes have adjustable gain and filtering developed by OttoBock, designed to provide a DC voltage in proportion to muscle activation to control the prosthetic hand. The contact detection algorithm, previously developed in computer software, was programmed onto an electrical board to improve portability and reduce latency.

Experimental Comparison

Three 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 our subject. A fourth experiment was designed for evaluating performance when handling rigid objects to evaluate whether this controller might impede non-fragile grasping tasks. The following tests were performed (Figure 3):

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 importance placed on 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 eggshells between cartons as quickly as possible. Broken eggs (~25N) did not count towards the total. In a variation with distraction, the subject was asked to simultaneously spell a series of words.
iv. Grasp and move ten unopened soda cans across a table as quickly as possible. This activity was designed to compare performance on rigid grasping.

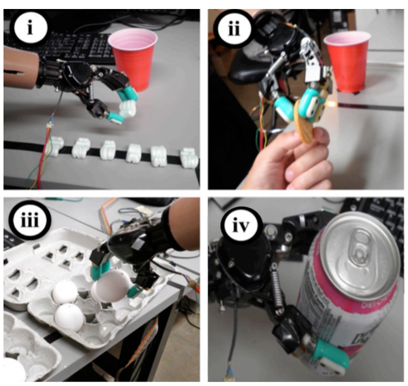

Figure 3: Grasping Experiments

Performance was tested with one subject, a 22 year-old male, congenital, unilateral, trans-radial amputee and myoelectric prosthesis user. The subject was compensated for his time during testing and development. Each task was performed by the subject with 1) his own prosthesis (VS, VariPlus Speed, OttoBock), 2) the BioTac-equipped hand with contact detection algorithms (BT), 3) the NumaTac equipped hand with contact detection algorithms (NT), and 4) his intact contralateral dominant hand (DH). For each experiment, the subject was allowed to train until his performance became steady, then 5 trials were recorded.

RESULTS

In every timed fragile-grasp task (i-iii), the subject's personal prosthesis without compliance or tactile sensing (VS) had the worst performance (Figures 4-6). The BioTac equipped hand with contact detection (BT) and the NumaTac equipped hand with contact detection (NT) were always better than the subject's personal prosthesis and neared the performance of his dominant hand (DH).

A. Performance on Timed Grasping Tasks

The performance index normalized by the time to complete the task with the subject's dominant hand (DH) is presented in Table 1. The subject's personal prosthesis (VS) scored as poorly as 4.82 times slower than the dominant hand and was never better than 2.45 times slower at fragile grasp tasks. Additionally, the subject repeatedly broke objects with his personal prosthesis (VS): 1.2 foam peanuts per trial, 2.8 crackers per trial on the speed test (and 12 failed trials on the accuracy test), and .4 eggs per trial both with and without distraction.

Compliant sensors with contact detection brought performance closer to biomimetic performance, with one trial requiring only 1.25x the time for the dominant hand.

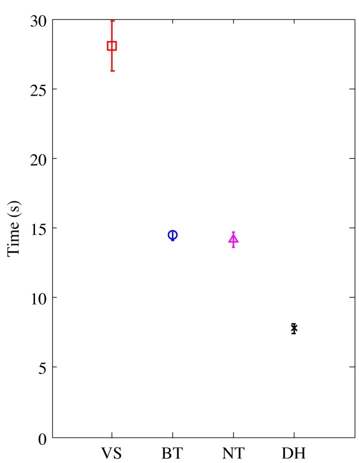

Figure 4: Foam Experiment

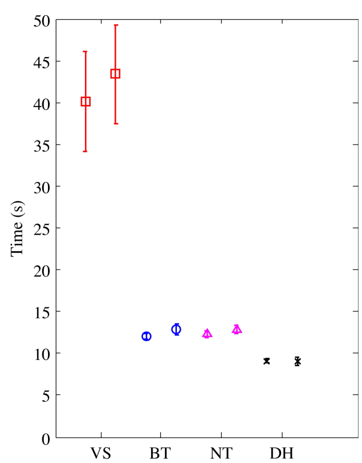

Figure 5: Cracker Experiment. Left = speed trials, Right = accuracy trials

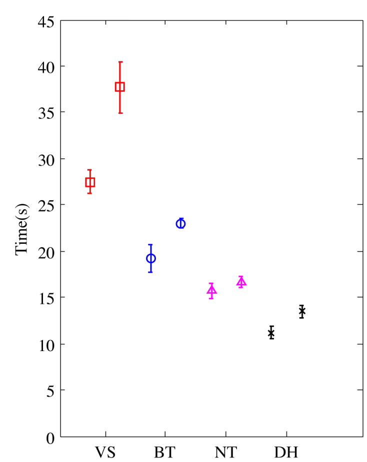

Figure 6: Egg Experiment. Left = trials without distraction, Right = trials with distraction

Additionally, the variance in the subject's performance was much lower with contact detection than without for all fragile grasping tasks using both the BioTac and the NumaTac sensors. With contact detection, the subject broke only one object during testing (a cracker, using BioTacs).

A one degree-of-freedom ANOVA test was carried out to verify the improvements each method provided. Both methods of contact detection outperformed the VariPlus Speed hand at a high confidence level ($P<0.01$) for every timed fragile-grasp task. None of the tested prosthetic systems were significantly different ($P>0.10$) on the soda test, suggesting that no performance was lost with either sensor on rigid grasping tasks.

Table 1 – Summary of Results

	VS	BT	NT	DH
Foam	3.59	1.85	1.82	1
Crackers - Speed	4.41	1.32	1.36	1
Crackers - Accuracy	4.82	1.43	1.43	1
Eggs - No Distraction	2.45	1.71	1.40	1
Eggs - Distraction	2.79	1.70	1.24	1
Soda	1.86	1.86	1.76	1

DISCUSSION

Compliant contact detection sensors not only provided significant speed improvements when compared to the subject's regular prosthesis, but also reduced the variance of performance to levels near that of the subject's dominant hand. Variance is an important factor as a hand with inconsistent performance reduces operator confidence. The subject reported that the compliant sensors made stable grasps much easier to achieve due to the reduced need for precision and the mitigation of force overshoot. Because of this, he felt confident to move more swiftly during grasping activities after minimal training.

The results of the distraction task show that the cognitive burden of the subject was greatly reduced by our contact detection algorithm. While his performance worsened on all four control strategies (evidence that he was distracted), with his own prosthesis the relative performance change was drastic and the variance became much greater, while with contact detection the amount of performance loss and the variance were similar to that of his dominant hand (Figure 6). This suggests that using the prosthesis with contact detection substantially reduced the cognitive burden of the operator when compared to his personal prosthesis.

Despite its simplicity, the NumaTac sensor proved to be a good substitute for the BioTacs. The performance with NumaTacs was significantly better than with BioTacs on both egg grasping tasks and statistically the same on other tasks. The difference in performance between the sensors may be due to their physical properties. It was observed that the fluid-filled BioTac has a short range of very high compliance that decreases abruptly after the skin contacts the rigid core; the foam-filled NumaTac has a larger range in which the stiffness slowly increases as the foam is compressed. Further studies will be needed to evaluate.

Too little progress has been made on facilitating prostheses' most important task – grasping objects. Here we have presented two simple ideas that appear to offer a real improvement in the usability of prosthetic technology. Compliance is a biomimetic property that can easily be applied to nearly any existing prosthesis, at a significant gain of function. Contact detection reflexes similar to biological reflexes can also be used to improve performance and consistency during everyday tasks, allowing the prosthetic hand to be both quick and delicate as well as intuitive and natural for the user. These principles can also help make prosthetic technology more affordable by providing superior functionality with inexpensive actuator technology and avoiding the need for tactors or haptic displays. In a low-cost prosthesis, we were able to obtain performance that is unattainable to date in many expensive research hands. Next steps will be to attach a smaller version of the NumaTac directly to the metal skeleton of the prosthesis under the cosmesis so that it can be tested under normal field conditions by a larger number of subjects.

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