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Continuous Hold Modification for e-NABLE Hand Prosthetic

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ABSTRACT

Introduction

There is a need for low cost hand prosthetics in the developing world. Organizations, such as e-NABLE, have created open source, 3D printable prosthetics to meet this need. However, current models create a closed fist position in the prosthetic using wrist flexion, which causes forearm fatigue with continuous use. The purpose of this study was to develop a locking mechanism modification for an existing eNABLE device to reduce muscle fatigue in the user.

Methods and Materials

The Raptor Reloaded prosthetic model was chosen for this project because it is a commonly used model for partial hand amputation. The palm piece of the prosthetic was modified to incorporate a clamp locking mechanism over the tensioner cables, thus allowing the user to maintain a closed fist position without wrist flexion. The design requires the use of an unaffected hand to enable and disable the clamp. The hand was 3D printed using polylactic acid (PLA), and functionality was assessed through a series of grip strength and clamp failure tests.

Results

There was no statistically significant difference found in the maintained grip force held by the locking mechanism between the three different object geometries tensioned with both 20N and 40N. An exponential decay was observed in the grip force measured over a period of 5 minutes with relatively low average grip forces ranging between 2.1 and 4.4N. The clamp failure testing showed string slippage occurring at upwards of 30N at each finger tension cable with the larger 3mm diameter string. A clamping force distribution was also noted but varies depending on the diameter of the string and print size of the clamp.

Conclusions

The new Raptor Locked and Reloaded is able to maintain a low amount of force for objects being gripped against the palm. This large difference from the tension applied does not appear to be from string slippage through the clamp. A single tensioner cable was found to be able to hold almost the entire applied tension however the exponential decay was still observed. Following these tests, an observation was made that even when the tensioner cables are taught there is still a small amount of free movement in the fingers. This accentuates a more fundamental problem with the raptor reloaded's gripping mechanism however the tensioner cable clamp is still a viable idea for future iterations of the Raptor Reloaded and other eNable designs.

INTRODUCTION

Loss of limbs from landmine accidents is common in war-torn countries, causing approximately 26,000 amputations each year.[1] Limited access to health services compounds this issue, furthering the number of amputees in the developing world. Prosthetic devices remain monetarily and geographically out of reach for these amputees, with the average cost of a prosthetic in the United States ranging from $5,000 to $15,000.[1] Moreover, if a prosthetic can be obtained, it must be replaced with an unrealistic frequency for those who are economically disadvantaged. On average, adults require a new prosthetic every 3 to 5 years, while growing children must replace their prosthetics every 6 to 12 months.[1] Therefore, there is a significant need for low-cost, durable, and functional prosthetics, particularly for people in third world countries.

e-NABLE is a community of volunteers dedicated to serving people in need of low-cost prosthetics. To date, over 10,000 volunteers have assembled and delivered almost 3,000 prosthetics to over 90 countries.[2] Currently, all e-NABLE prosthetics for partial hand amputation operate using the same closing mechanism: wrist flexion tightens flexor cables attached from the tips of the fingers to the back of the wrist, thus closing the fingers of the device. The simplicity of the design enables device costs to remain low, ranging from $12-20. However, the design can also cause long-term injury. Continuous holds are maintained using constant wrist flexion, resulting in muscle fatigue and potential overuse injuries, such as carpal tunnel and tendonitis.[3] This project aimed to resolve these potential issues by creating a locking mechanism to hold the prosthetic in a closed grip position.

METHODS AND MATERIALS

The Design

The final prototype (Figure 1) features a modification of the original raptor reloaded palm piece in which the clamp is integrated onto the proximal end of the palm piece, nearer to the wrist. The extensor cable attachment sites were moved distally in order to make room for the grooves of the clamp, tensor cable guides were slightly rerouted in order to run through the clamp, and attachment sites for the other clamp components were added along with other minor modifications to the original palm piece. This prototype uses bolts as pins sourced after 3D printing. The clamp itself uses the ‘smooth’ teeth geometry discussed below in preliminary clamp testing and operates via a mechanism similar to a draw latch in which the geometry of linkages within the clamp hold the clamp in position.

The locking mechanism for this design consists of a clamp on the proximal portion of the palm piece that prevents movement of the tensor cables. To use this device the user must first flex their wrist, thereby adding tension to the flexor cables and closing the fingers. The clamp can then be lowered over the cables resting on the back of the palm (Figure 1). The placement of the clamp thus allows the user to extend their wrist after locking the cables in place since the tension in the cables will be maintained. The hand clamp design operates on the assumption the user has one unaffected hand to operate the locking mechanism.

Figure 1: Photos of the Raptor Locked and Reloaded with the clamp open (left) and the clamp engaged (right).

Maintained Object Grip Force Testing

The capabilities of the Raptor Locked and Reloaded was assessed through maintained grip force of various shapes against the palm over a period of 5 minutes. These tests were done on a 120% size hand with 0.41mm 60lb fishing line. Load cells were placed in a holder secured to the inside of the prosthetic and calibrated to the various shapes placed on top. The prosthetic was tested with three different geometries: a hemisphere, block, and cylinder (Figure 2). Three trials were recorded with an Arduino for each shape and tension. The tensioner cables were tightened to either 20 or 40N, and to minimize variations between tests the fingers were wrapped around the object each time. The base and top test pieces were taped together very lightly so they would stay in place for proper data acquisition. Gel fingertip grips were attached to the fingers (a common ENABLE practice) to increase friction.

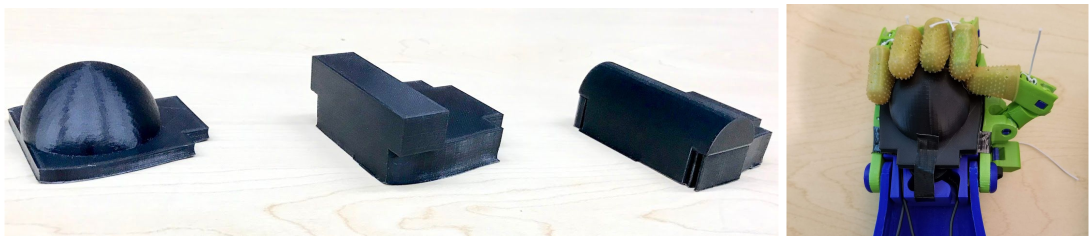


Figure 2: Left to right hemisphere, block, and cylinder used for the maintained object force testing. Image on far right shows an example of the data acquisition set up for the hemisphere.

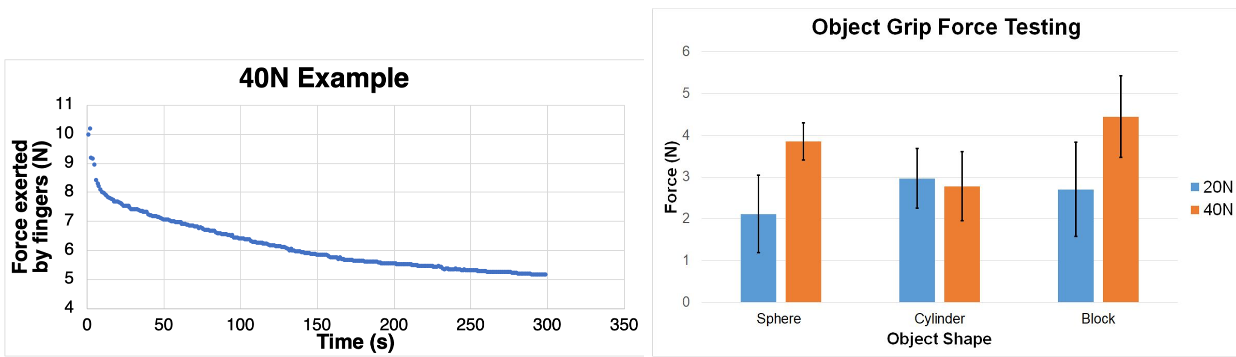
Clamp Failure Testing

Clamp Failure Testing was performed using a 15lb force gage. Two strings, a 0.41mm 60lb fishing line and a 3mm string, and two hand sizes, 120% and 150%, were tested. A single string was placed into the clamp at each of the finger locations. The clamp was enabled and the string was pulled with the force gauge until it began to slip. The force required to make the string slip was recorded as the force of failure. Three trials were performed at each finger location with both string types in both hand sizes.

RESULTS

Maintained Object Grip Force Testing

To evaluate how the clamp maintains closed grip over time, Maintained Object Grip Force Testing was performed. In this test, 3 load cells were placed in the palm of the 120% hand and used to measure the force of the fingers on the palm over a period of 5 minutes. Gel fingertip grips placed onto each finger reduced the effect of finger slip on the measured grip force. Each of the 3 grip geometries (hemisphere, block, and cylinder) were tested over 3 trials using both a 20N and 40N initial pull force on the strings. The data show an exponential decay in the object grip force that reaches a steady state value much lower than the initial force (figure 3). To quantify the rate of initial force change, time constants were averaged between trials (figure 3). These values ranged between $4.8*10^{-4}$ and $1.9*10^{-3}$, signifying a very rapid initial drop in force. Time constant values were not found to be statistically different based on a two-way ANOVA test. The average grip force ranged from 2-4N, compared to the 20N or 40N applied to the tensor strings (figure 3). After running a two-way ANOVA on the average forces no significant difference was found in the maintained grip force held by the locking mechanism between the three different object geometries tensioned with both 20N and 40N.



	20N	40N	20N	40N	20N	40N
	Sphere		Cylinder		Block	
Time Constant	-0.000863	-0.00092	-0.00161	-0.0019	-0.00072	-0.00048

Figure 3: Results of maintained object force testing. The upper diagrams depict the force measured in the load cells over time (left) and the average grip force for each geometry (right). Average time constants are shown in the lower diagram.

Clamp Failure Testing

Clamp failure testing was performed to determine the operational parameters of the Raptor Locked and Reloaded. Two commonly used hand sizes, 120% and 150%, were tested with two string sizes, 0.41mm fishing line and 3mm string. In the 120% hand, the fishing line failure force ranged from 22.5-34.1 N (Figure 4a). A distributed force was observed, with the lesser force applied to the thumb and increasing force values as the string got closer to the clamp hinge at the pinky. The string failure force was higher than the fishing line at every location except for the 4th finger. This string failure force ranged from 31.7-45.8 N (Figure 4a). Surprisingly, the string clamp force distribution did not mirror the fishing line distribution. Instead, the string distribution was highest in the middle (2nd finger) and lower at the outer extremities (thumb and 4th finger).

In the 150% hand, the fishing line failure force ranged from 15.4-16 N (Figure 4b). Notably, no clamp distribution was observed in this configuration. Similar to the 120% hand, the string had a higher clamping force than the fishing line. The string failure force ranged from 44.1-69 N in the 150% hand (Figure 4b). However, dissimilar to the 120% hand, the force distribution was not highest in the center of the clamp. The force was lowest on the thumb and became gradually greater as the location neared the hinge of the clamp at the 4th finger.

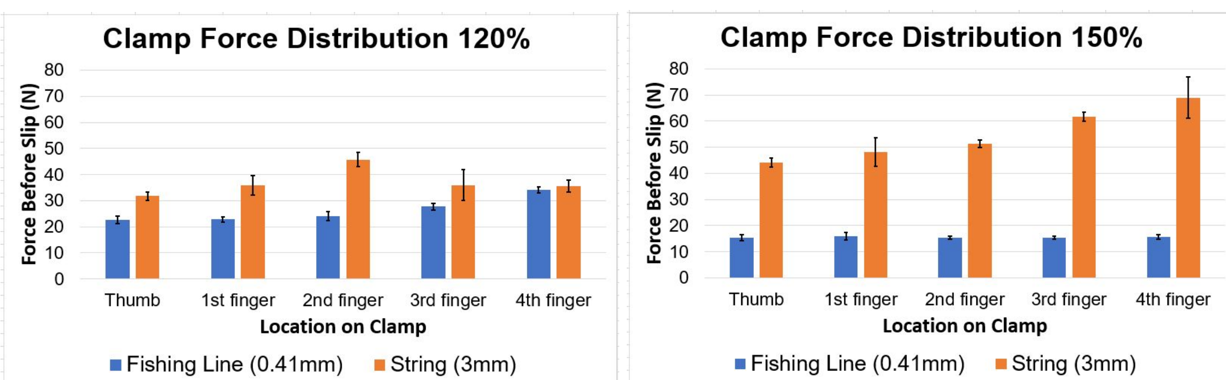


Figure 4: Results of clamp failure testing for a) the 120% size hand and b) the 150% size hand. No statistics performed.

DISCUSSION

The results of clamp failure testing indicates there is an uneven force distribution across the clamp that is dependent on both the print size and string diameter used. The 3mm string in both sizes resulted in larger failure forces. This is likely because the increased diameter made it easier for the clamp to grip, and hold, the flexor cables. The fishing line used in the 150% hand had a greatly reduced force of failure compared to the 120% hand. This may be because the increase in hand size increased the space between the clamp, allowing the smaller fishing line to slip through. This data shows that there are optimal string diameters when scaling up the Raptor Locked and Reloaded clamp. While the data shows it is not detrimental to oversize the string, undersizing will reduce the maximum force the hand can maintain. In the future it might be best to test more hand sizes and string diameters to truly optimize the operational parameters.

The object grip force testing showed that the force generated by the fingers to hold an object against the palm of the hand is much less than the force applied to the strings at the time of clamp closure. The data also shows the clamp does not perform differently when gripping different shapes, and the grip force did not statistically change when the initial string tension doubled from 20N to 40N. The former implies that the clamp will hold multiple shapes equally well. The latter implies that, at a certain point, the force the user applies will not alter the output grip force.

The very small time constants obtained from fitting an exponential curve to each data set are preferable over larger numbers because of the inherent use of the device. It is likely safer to have the force decay rapidly and level off than to have it decay more slowly over a long period of time. If the decay was slow, things may slip out of the grip unexpectedly. When the hand is initially being used, the user is likely more attentive to how the prosthetic is holding an object. So if the object slips in the first 30 seconds, the user may still be wary enough to observe this force reduction and make adjustments as needed.

The time constant data, along with the force data it originates from, help to uncover a potential underlying problem with the hand. The clamp failure testing data indicate that the clamp can hold the forces applied to the hand during the object force testing. Despite this, the force applied to the object by the fingers decreases over time. This may be attributed to the design of the fingers and hand itself, rather than clamp slippage. When the hand is closed without clamping the strings, the fingers can still loosen on the object. This shows there is an inherent flaw with how the hand operates. This paper may serve as a starting point for testing new hand designs that should limit the movement of the fingers while the clamp is engaged in order to make the best use of the clamp's capabilities.

CONCLUSION

The Raptor Locked and Reloaded clamp is a viable locking mechanism that may help reduce forearm fatigue of users. The clamp has varying operating parameters, depending on the size of the hand and flexor strings. The device can hold objects with different shapes equally well, however finger slippage over time appears to be an issue with this, and potentially other, eNABLE devices.

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