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Inefficient Force Generation in 3-D Printed Prosthetics

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Abstract

The process of 3-d printing prosthetic hands has been used to make prosthetics more widely available by lowering the cost. However, many of these devices are not mechanically tested once they are constructed and they may not achieve their intended function. This study quantifies the efficiency and magnitude of mechanically activated grip strength in a 3-d printed prosthetic hand. A rig stabilized the hand on a dynamometer at an angle such that added weight created a constant downward force and engaged the grip. We tested the hypothesis that the presence of the hand would act as a friction device and propagate less force on the dynamometer when engaged than weights alone. The results supported the hypothesis and can aid in classifying the function of the hand for certain tasks such as holding a cup. This study can inform new designs to improve the efficiency of grip strength in similar devices. Furthermore, quantitative data on the strength of the fingers can better inform how custom hand devices will be suited to specific tasks.

Introduction

Additive manufacturing technology has been used for several decades in industrial applications, though the recent availability of 3-d printing technology for consumers has been a driving force in the recent 'maker' movement [1]. In 2013, Jon Schull and Skip Meetze out of RIT co-founded the 501(c)3 organization, Enable Community Foundation (ECF), which has now merged with the Victoria Hand Project [2]. This movement supported the printing of customized prosthetic devices through community action. In 2014, another 501(c)3 born out of UCF, Limbitless Solutions [3] generated significant public hype for these devices through PR involving actor Robert Downey Jr. donating one of their myoelectric arms to a 7-year old boy [4].

Behind the scenes, companies like MakerBot, originally founded in 2009, were supporting the public through open source design sharing platforms like Thingiverse [5]. The availability of information through social media, instructibles and youtube expanded the access to designs for enthusiasts to be able to print and build prosthetic devices. At the University of Florida, a 3-d printing program began at the Marston Science Library and a student group quickly formed with the goal of providing 3-d printed prosthetics to local children just like Iron Man. Jessica Bergau, a zoology major, and Matthew Elias, an industrial engineering major, established Generational Relief in Prosthetics (GRiP) and connected with Hands to Love (H2L) to deliver devices to kids at the annual H2L Hand Camp event.

Despite the intentions of the students involved, the functional limitations of the currently available open source devices became apparent. The lack of engineering design and guidance from licensed prosthetists and occupational therapists relegated hands to become aesthetic gifts rather than to provide any functional benefit. They did not fit properly, or were uncomfortable, too long or too short, too heavy or too bulky, and sometimes they required the recipient to be stronger to engage the grip of the device either by wrist or elbow flexion. Also, there was not an infrastructure for follow-up to fix damaged or non-functional devices, or to provide instructions for recipients to habituate to their device. GRiP began to reexamine the cycle of care and design for the devices they were printing and has recently diverged to focus on task-specific devices for individual recipients [6].

This study assesses the functionality of a 3-d printed prosthetic hand device (the Raptor Reloaded) by testing the grip strength generated at fingertips once the device is mechanically engaged. Grip strength was quantified using a custom-built rig to secure the device and a dynamometer to measure applied force. The hypothesis is that engaging the grip of the hand device would generate less force on the dynamometer than weight directly applied to the dynamometer. The results supported this hypothesis and identify possible design improvements that would increase the efficiency of force transfer in the prosthetic hand device.

Methodology

Rig Assembly

To hold the hand in place on the dynamometer, a specialized rig was necessary. The first prototype is in the Figure 1 below. For this prototype, the elastic used to secure the hand on the dynamometer did not properly hold the hand in place and would get stretched out easily. The final system, in Figure 2, fixed a lot of those initial issues: the casters on a gas cylinder cart were removed, and a wooden cylinder was secured with zip ties across the wheel brackets to secure the hand in place without any downward movement. The hand was placed on the dynamometer such that the fingers pulled on the dynamometer when force was applied to engage the grip. The center of the hand was screwed onto the wood cylinder to stabilize the hand in place. The rig was tilted so that the weight applied would be pulling the string in line with gravity, which can be seen in Figure 3.

Figure 1. This is the original prototype rig. It holds the hand against the dynamometer but does not hold the hand in place properly.

Prosthetic Hand Assembly

This study uses the Raptor Reloaded hand design provided by Enabling the Future (http://enablingthefuture.org/upper-limb-prosthetics/raptor-reloaded/). For this rig, the grip created by four fingers was tested (not including the thumb). The device was 3D printed using a MakerBot Replicator 5th Generation 3D printer (MakerBot Industries, LLC, Brooklyn, NY) and used HATCHBOX PLA filament that has a diameter of 1.75 mm and a tolerance of +/- 0.05. It was printed at a temperature of 230 degrees F using the auto support settings. The device was removed from its raft and the support material was removed from the device. The assembly directions below are provided by a Guide from E-Nable. The fingers were assembled first. The finger's pieces were lined up at the joint and then a pin was pushed through. This was repeated for the other three fingers. The string was then attached to the fingertip by using a clinch knot and two half hitch knots. The string was left very long. The tensioner elastic was not needed for this study. The fingers were attached to the palm shell and the string was routed through the holes. Extra string (100% braided PE fiber, JOF, Japan) was kept, so that if the original string was getting worn out it could be easily replaced [7].

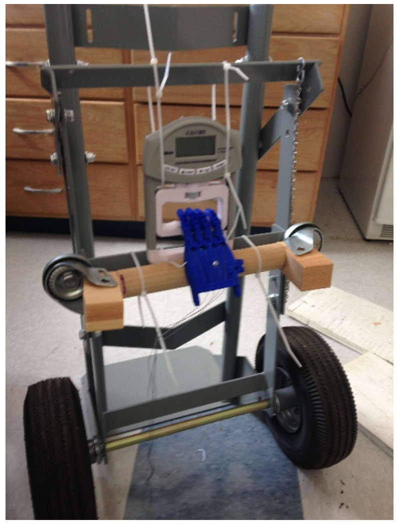

Figure 2. This shows how the hand is stabilized on the dynamometer. This is the rig used in testing the prosthetic hand device.

Figure 3. The string is seen to go straight down, and the rig is held in place by the desks.

Testing Process

A tilted rig was built to stabilize the hand against the dynamometer. The tilt needed to align the strings hanging straight down out of the hand. The dynamometer at its most sensitive settings. This study uses a Camry 200 lbs / 90 kgs Digital Hand Dynamometer. On the weights, the position of each string was marked so it could be re-tied in the same location for different trials. The position of the fingers on the dynamometer was recorded. For the control group the strings should be tied in those same spots.

The dynamometer was turned on and weight was slowly applied. The highest weight read by the dynamometer was recorded when the system was still. This process was repeated three times for each weight applied. There were four total weights applied, 8 lbs (3.64 kgs), 10 lbs (4.55 kgs), 11 lbs (5.00 kgs), and 13 lbs (5.91 kgs). The weight is converted into kilograms since the dynamometer produces it's result in kilograms. The rig was stood up (straightened) and the hand was removed. The strings were tied on to the dynamometer where the fingers were placed prior. The dynamometer was turned on and weight was slowly applied in the same manner. The highest weight for all three trials was recorded, when the system was still.

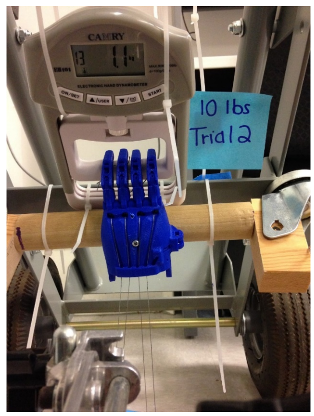

Figure 4. This is one of the trials when testing the prosthetic hand device on the dynamometer. The fingers push down on the dynamometer as the weight is applied.

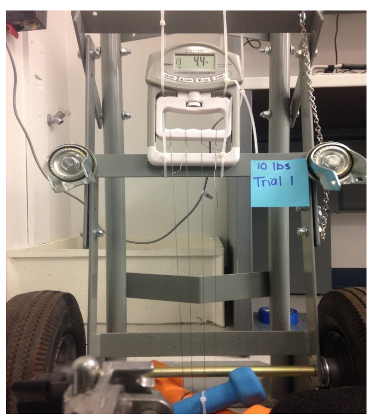

Figure 5. This is for the control group. The string is tied directly onto the dynamometer, so the only force lost would be due mostly to tension. The rig is no longer tilted so that the force applied will still be pulling in the downward direction.

Results

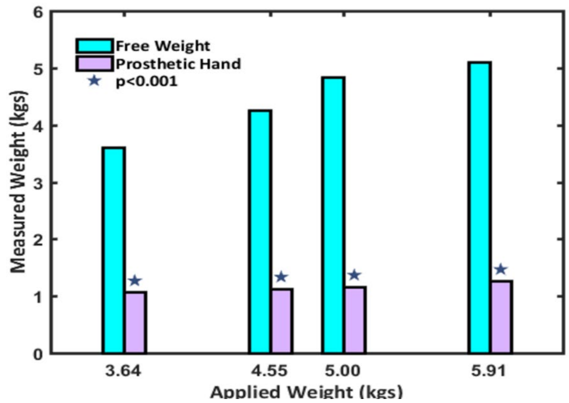

Figure 6. Measured Weight(kgs.) vs. Applied Weight(kgs.)

Figure 6 shows the measured weight between the two conditions. In each case, the grip of the hand was less efficient than weight alone acting on the dynamometer. A one-tailed student's t-test using an alpha level of 0.001 was performed to analyze the significance of each testing condition. The weight measured by the dynamometer under the control conditions versus the hand were significantly different in each case. For the control group, the amount of weight applied was close to the weight read but it did not exactly match. The hand device's measured weight was much lower than the applied weight.

Discussion

The 3-d printed prosthetic devices are more cost effective than traditional ones. They are extremely beneficial for kids who grow rapidly and would therefore need to be refitted for different devices very often. It's important to begin testing these devices to create a more efficient design. Once one can understand what is happening within the device they can begin to improve it. Children do not have has much upper body strength as adults do so it's important to create a device that has the most efficient generation of force so that the devices are easier for them to use.

The dynamometer has a minimum threshold value of weight that must be applied for it to work. The hand device barely surpassed that detection limit which could be causing some error. A more sensitive dynamometer would help eliminate this accuracy issue. The dynamometer also has spots made for people's fingers to be placed in ideally. The hand device's fingers did not fit within those spots at all which may be another source of error. A dynamometer without those would likely improve the accuracy of the reading.

The control group's weight read by the dynamometer did not exactly equal the weight applied. This may be because of the accuracy of the dynamometer. It may also be a slight error with converting the units of the pounds of applied weight to kilograms. The force of tension may also be causing some issues. Future testing should probably focus on the force generation of one single finger and would require a more accurate dynamometer or similar measurement instrument with a higher sensitivity (lower detection threshold).

The forces present are gravity, normal force, tension, and friction. The force of gravity on the mass attached is the force pulling downward on the string. The string is pulling at the center of the finger to curl the fingers down and around the dynamometer. The force of tension is acting on the string. There is also a force of friction pushing the string in the opposite direction from the movement of the string in the hand. The initial friction when the weight applied is kinetic, but the measurements are taken when the weight stopped moving so the recorded effect is static friction. The static friction pulls up on the string that is on laying on the hand against the pull of the applied force. This force of friction depends on the normal force in this system. There may also be a lever effect since the string is pulling in the center of the finger and the readings on the dynamometer are taken as the ends pull down [8].

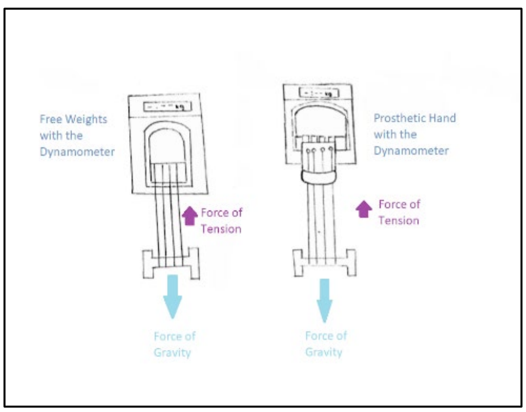

Figure 7. This is the free body diagram for the forces when the test device is placed on the dynamometer. It shows the tension pulling the string up against the weight, which is being pulled down by the force of gravity.

The data represent two cases: weight being pulled downward mediated by either the hand or by the string alone in the control group. The control data demonstrate effects from the force of tension in the string. This also set a baseline for how much force is lost within the hand. The control data shows how the force of tension in the string does not have a large effect on the downward weight read by the dynamometer. Figure 7 shows the free body diagram for the control group and the hand as it applies to the force of tension in the strings. The next free body diagram in figure 8 shows the general forces acting on the rig. It shows the direction the hand pulls down on the dynamometer, the normal force as well as the direction the weight is pulling down on the hand. These are some of the more general forces that occur when a user is wearing the hand. The force of gravity would be replaced by the force the user puts on the hand to get it to open and close by flexing their wrist or elbow.

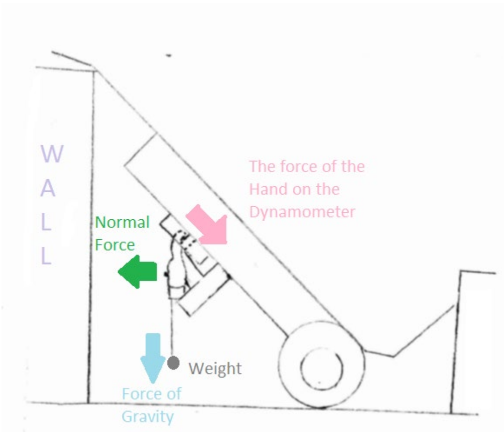

Figure 8. This is the free body diagram of the whole system. It shows where the hand pulls down on the dynamometer.

The fingers themselves could also be causing some discrepancies. There are many corners that the string must travel around as shown in the figure 9 below. These joints that the string must go around may be causing some of the force to be lost. To fix this one could try adding lubricant to the string so that it slides over all these corners easier. One could also design a finger with pathways that lessen the force of friction around these joints. One can also see how the string is tied to the center of the finger. That may be causing some issues with a bit of a lever affect since the dynamometer reading was done at the tips of the fingers.

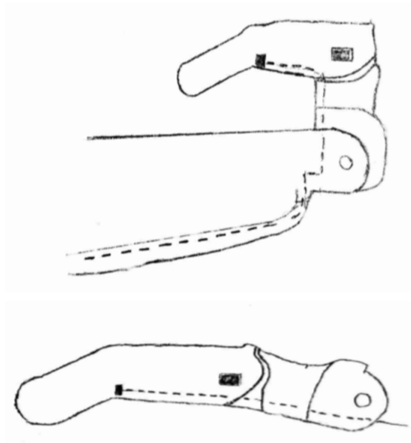

Figure 9. The Diagrams of the finger movement and the edges/angles the string must navigate around. The string is the dotted line. The first image is when force is being applied and the fingers curls up. The second image is a finger relax. The tensioners pull the fingers back into the second image position when no force is applied but those were left off for this experiment.

The string is not pulling at the center of mass which may be causing some force to be lost. One could alter the placement of the notch for the string. If it is moved closer to the tip, it may help transfer more of the force.

This study showed that there are many different forces within the hand working against the adequate transfer of the force. The design of this prosthetic hand device is not the most efficient which can be seen by all the force being lost within the hand. Further testing will show which forces within the hand have the largest effect. Once these forces are isolated, one can create a solution to begin getting rid of these inefficiencies. This research will help create more task specific prosthetic designs that can apply different amounts of force. Understanding how all the different forces interact is vital in understanding how to improve the design to transfer the force inputted to the outputted force. The next step would be to deconstruct the hand further and test the individual components, starting with the fingers and their joints. Another important aspect to consider is the material type of the string and of the actual hand. These materials may be increasing the force of friction against the hand.

Conclusion

The availability of 3-d printed prosthetics devices is a welcome alternative to more expensive prosthetic hands, especially for children who are constantly growing. As 3-d printed hand devices become more commonly used it is important to create more efficient designs that accomplish desired tasks safely. This study began the process of exploring some of the inefficiencies that exist within 3-d printed prosthetic devices. By understanding how the force is being lost in the hand device, one can apply that knowledge to improve on the design of the device. Future directions for this work should include guidance from licensed professionals, including orthotists, prosthetists, occupational therapists and physical therapists. By including design inputs about the range of motion and strength of persons with missing limbs, the mechanical considerations can be maximized to ensure the safety and functionality of customized 3-d printed prosthetics devices.

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