Design Principles and Accessibility of Open-Source Prosthetics

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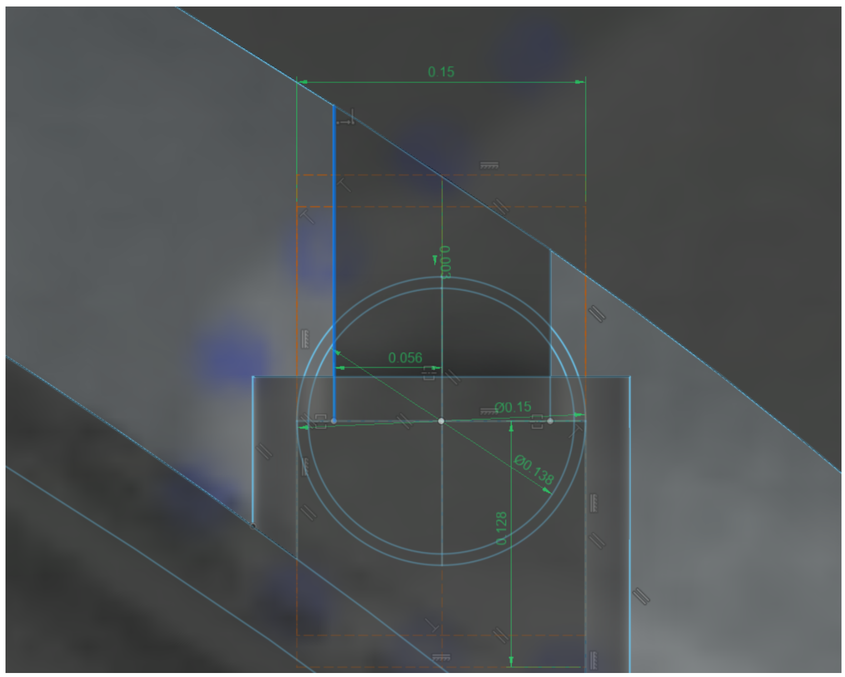
Without insurance, the average patient suffering from upper limb loss in the United States can expect to need to pay $5,000 for a silicone cosmetic limb resembling the original section pre-amputation or trauma. This cost climbs dramatically as functionality increases, with functional hook prosthetics costing $10,000 to $50,000 and the latest myoelectric technologies costing anywhere between $20,000 to $100,000 (MCOP). This cost can be great in industrialized nations, let alone in developing ones, creating a barrier that can exclude functional prosthesis as a pricey luxury to many Americans living without health insurance or in low-income circumstances. This poses an especially significant problem to the United States and Mexico, both of which are nations that are plagued with high rates of diabetes and therefore potential amputation due to complications from this and other comorbidities (Beaubien). With the rise of affordable, at-home CNC machining capabilities such as additive 3D printing, multiple organizations as well as individual engineers have attempted to fabricate prosthetics with these technologies. However, these prosthetics typically do not approach the level of functionality of commercially-available ones, with their core design revolving around hook-based or tensioned string mechanics. Therefore, to even a middle-class citizen living with limb loss, a fully-functioning upper limb prosthetic can be an exorbitant expense, on top of any other medical treatments required regarding the circumstances of the loss. It is my intent to bring to the prosthetic development community a versatile prosthetic whose only associated cost is attributed to relatively inexpensive additive CNC equipment, the associated additive materials, and electronics such as motors. To accomplish this, I needed to conduct research into which design parameters are considered in the creation of a prosthetic, the current accessibility rate of said prosthetics, and the specifics of developing and sharing a publicly-available prototype of a prosthetic. To accelerate development, the exact technical specifications, as well as computer code, will be widely accessible to the interested community through the internet.

ACCESSIBILITY:

While children outgrow their prosthetics, adults also tend to wear down their prosthetics, so a cost-effective method of producing these artificial limbs more than once is necessary. The possibility of using 3D printing for prosthetic applications has already been considered and implemented, with varying degrees of success (Frost, Ben-Achour). This approach is promising, due to the greatly reduced cost of fabrication of 3D printed parts compared to other methods. Entry-level 3D printers are accessible in the United States for prices under $500, with plastic material, known as filament, typically accessible for under $50. Organizations such as Limbitless and Quorum Prosthetics already utilize additive methods for production. However, these solutions are only clinically available, meaning a patient must have access to healthcare to obtain a prosthetic. Along with creating a public version of the physical design of these prosthetics, the software which would control the motorized aspects of the prosthetic must also be considered. Software that is generally accessible to the public with support of community development is often referred to as open-source. This kind of code is a key component of modern computing, acting as the backbone of development from microcontroller code for motors to Linux operating systems to even cryptocurrency mining (Free Software Foundation). The general intent of creating open-source code is to increase its accessibility as well as crowdsourcing efforts to develop it. Open-source projects are typically free to download and access to the end-user, and encourage development from the associated community. This approach is separate from that of common prosthetics, which require healthcare and funds to access, and allows room among the community necessary to encourage crowd-sourced development.

TECHNICAL SPECIFICATIONS:

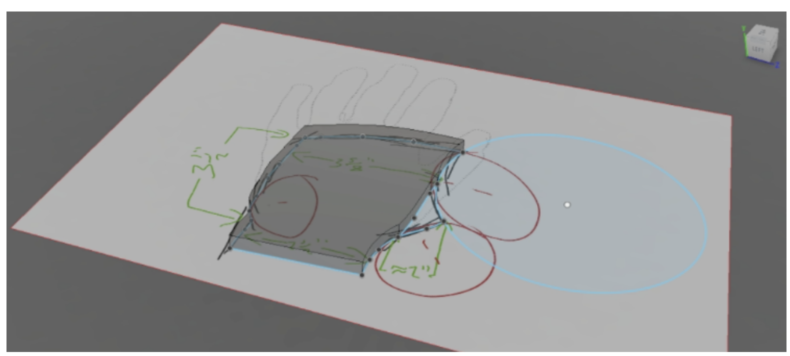
With the underlying philosophy of the prosthetic's design explained, its production in technical detail can now be examined. In most modern projects requiring highly technical manufacturing, computer-assisted drawing software, or CAD, is typically used. In this software, users can create two or three dimensional schematics of their intended product for manufacturing and prototyping purposes. The model is tuned to specific technical dimensions per its functional requirement. In the case of prosthetics, a model will require the appropriate specifications to properly fit the patient. This is often accurately accomplished by prosthesis designers by creating a cast of the residual limb using shape-retaining chemicals such as alginate. This model can also be accomplished by using infrared scanning of the residual limb into a computer application.



DEVELOPMENT:

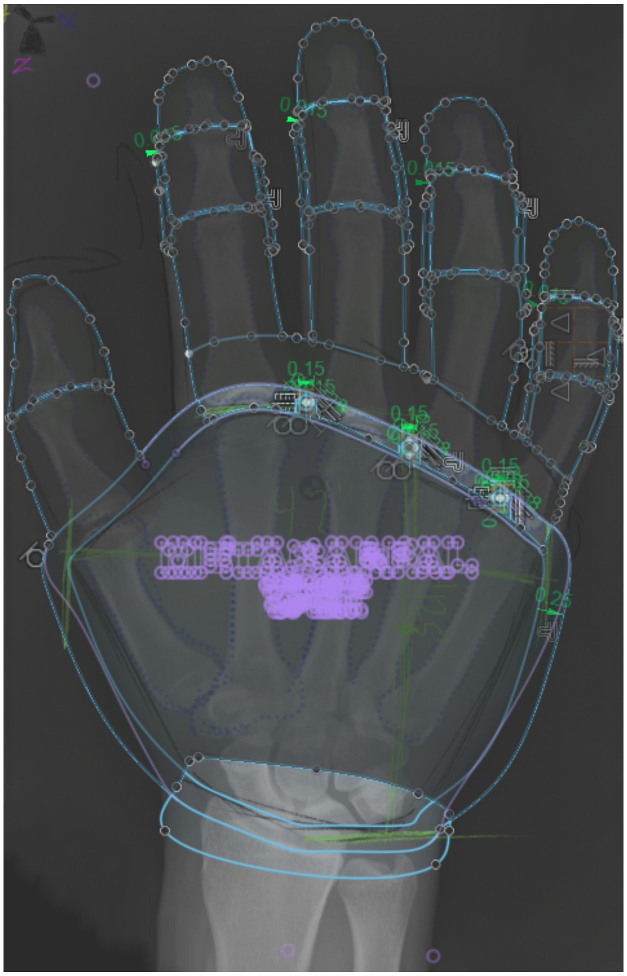
Developing an accurately dimensioned prototype requires the aforementioned CAD software, as well as other technologies in the realms of both software and hardware. The procedure of obtaining suitable measurements was the primary focus of my research, as I delved into the specifics of tuning a conceptual model to a physical patient's needs. Primarily, the circumference of residual limb and its initial length, usually taken from a remaining limb, are key measurements which contribute to a prosthetic's functionality. In the absence of these measurements, generalized parameters can still be used to produce a functional prosthetic. Many patients tend to prefer a prosthetic which provides separate or limited functionality compared to an original limb as they transition into living with limb loss, and others may prefer no prosthetic at all.

To gain a sense for the approximate dimensions a prosthetic would require, I used x-ray images of human hands and arms to form an approximately accurate 2D sketch of the intended area, then scaled the sketch to usable proportions using dimensions of my own palm and fingers. These dimensions, as well as the height of the prosthetic, will ideally be largely up to the end-user in parameterization but are based on anatomically accurate measurements.

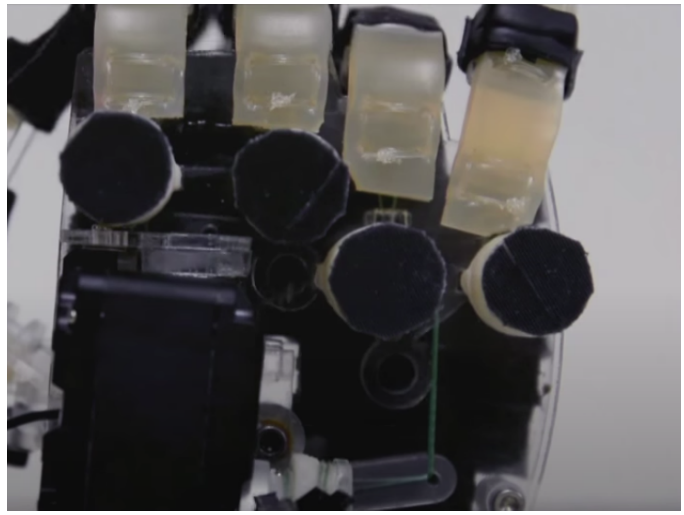


CONTROL METHODS:

The main focus of a prosthetic is mechanical endpoint control, or the ability to actuate a component through motion. In prosthetics, the patient may be able to control their prosthetic appendage in a similar way one would control a limb. Though their design is beyond what I am currently capable of replicating, I was able to learn about more advanced prosthetics during my interviews with prosthesis specialists.



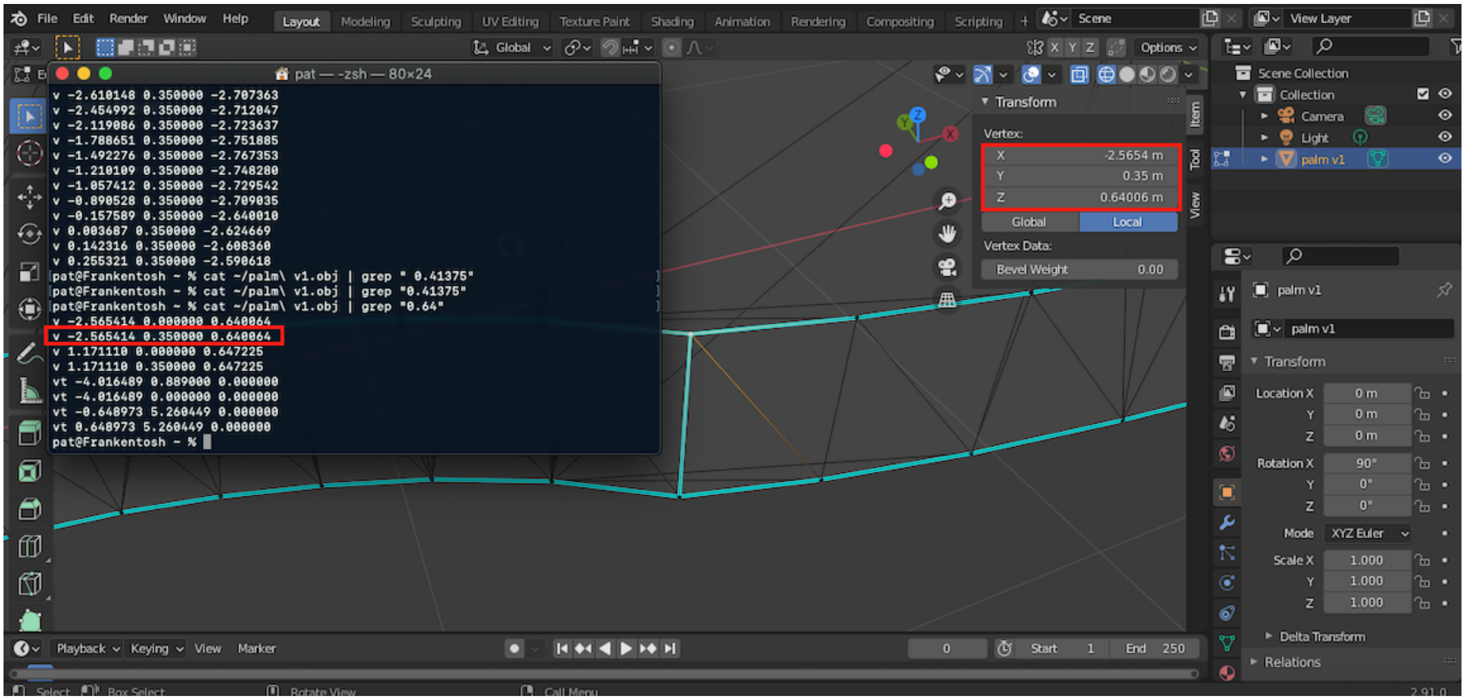
Higher-grade models of upper-limb replacement prosthetics may use electrical components such as motors which actuate based on detected intended movement from the patient, or some may interface with muscular nerve endings on the patient's residual limb to intercept electrical signals to use in controlling electronics on the prosthetic. Prosthetics of this type are referred to as myoelectric prosthetics, and tend to raise a far higher price for the end-user in the healthcare market. On top of the increased cost burden of a myoelectric prosthetic, the interviewed specialists have noted that these types of devices may be excessive or overly-complicated for the end-user. Myoelectric prosthetics rely on active nerve endings to control electrical components, but in the event some of these nerve endings are absent from the residual limb, it may be necessary for the prosthetic to be mapped to alternate ones. For example, if a nerve ending which stimulates motion in an arm is absent, but one which stimulates motion in a finger is present, the portion of the prosthetic which emulates arm motion may be controlled with the finger nerve ending. Thus, a patient with limb loss would act as if they are moving a finger to control the prosthetic. Many patients find this to be highly counterintuitive, and some prefer to have a non-controllable prosthetic or none at all.



A separate method of prosthetic development, known loosely as "body control," has existed far longer and is seen by many as a more intuitive approach than myoelectric applications. In body-control prosthetics, the prosthetic will contract more as the patient actuates their residual limb. This is usually accomplished with a combination of elastic material like thermoplastic polyurethane (TPU) or elastic string, and a rigid shell which constrains and manipulates this material as it is controlled along its axis of motion. As the patient moves the limb, the elastic material is constricted, pulling the endpoint of the prosthetic. This creates a proportional relationship between the user's motion of their residual limb and the motion of the endpoints of the prosthetic, allowing for an intuitive experience. (TEDx Talks and Liarokapis).

MODELLING:

Upon completion, a model will be converted from a format which can be interpreted only by the CAD software to triangulated data points which compose a three-dimensional space interconnected by polygon faces. This is the most common type of model format, and is known as a face-vertex mesh model. The end-user will download and manufacture this model, as it



represents the final iteration of the prosthetic's design of that version. In a filesystem, these models commonly take the file formats of OBJ and STL, as well as multiple other types. In triangulating the data of a model, the computational resources required to process it become lower, but the accuracy of the model's dimensions to its original intent also decreases. This should not be an issue for most modern computing systems as 3D rendering power has become more accessible, but this potential loss in quality should still be considered (Smith).

As shown, a point stored with plain-text data in an OBJ model is translated to a vertex point in 3D modelling software, which depicts the vertices with interconnected faces. OBJ files contain data for these vertices, the faces which connect these points, and other data such as higher-level curves and bevels (Smith). Below is a fragment of data from the palm model with vertex and face tags compared side-by-side. Face tags are represented as references to vertex points. The data following the "f" in a face tag is known as its parameters, which can be compared to variables in a function, and affect the behavior of the line of code in the OBJ file. In

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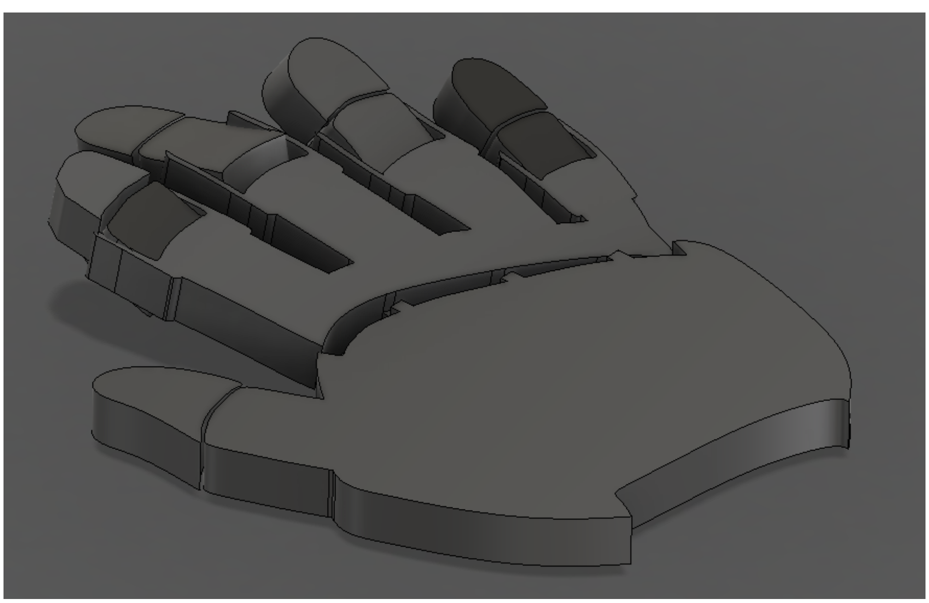
v -2.565414 -0.000000 0.961388     |      f 1/1/1 2/2/2 3/3/1
v -2.321037 -0.000000 1.021000     |      f 3/3/1 2/2/2 4/4/2
v -2.565414 0.350000 0.961388      |      f 4/4/2 2/2/2 5/5/3
v -2.321037 0.350000 1.021000      |      f 4/4/2 5/5/3 6/6/3
v -2.037710 -0.000000 1.070473     |      f 6/6/3 5/5/3 7/7/4
v -2.037710 0.350000 1.070473      |      f 6/6/3 7/7/4 8/8/4
v -1.719183 -0.000000 1.109973     |      f 8/8/4 7/7/4 9/9/5
v -1.719183 0.350000 1.109973      |      f 8/8/4 9/9/5 10/10/5
v -1.380272 -0.000000 1.141229     |      f 10/10/5 9/9/5 11/11/6
v -1.380272 0.350000 1.141229      |      f 10/10/5 11/11/6 12/12/6
v -1.048570 -0.000000 1.167929     |      f 12/12/6 11/11/6 13/13/7
v -1.048570 0.350000 1.167929      |      f 12/12/6 13/13/7 14/14/7
v -0.755080 -0.000000 1.194360     |      f 14/14/7 13/13/7 15/15/8
v -0.755080 0.350000 1.194360      |      f 14/14/7 15/15/8 16/16/9
v -0.630244 -0.000000 1.208555     |      f 16/16/9 15/15/8 17/17/10
v -0.630244 0.350000 1.208555      |      f 16/16/9 17/17/10 18/18/10
v -0.522028 -0.000000 1.223723     |      f 18/18/10 17/17/10 19/19/11
v -0.522028 0.350000 1.223723      |      f 18/18/10 19/19/11 20/20/11
v -0.430813 -0.000000 1.239951     |      f 20/20/11 19/19/11 21/21/12
v -0.430813 0.350000 1.239951      |      f 20/20/11 21/21/12 22/22/12
v -0.356560 -0.000000 1.257261     |      f 3/23/13 23/24/14 1/25/13
v -0.356560 0.350000 1.257261      |      f 1/25/13 23/24/14 24/26/15
v -2.755667 0.350000 0.523333      |      f 24/26/15 23/24/14 25/27/16
v -2.755667 -0.000000 0.523333     |      f 24/26/15 25/27/16 26/28/16
```

the same way, the data following the “v” in a vertex tag are parameters to a vertex. Where vertices take three-dimensional coordinates as parameters, however, faces take three vertex objects as parameters in the form “f v1/v2/v3.” Rather than using the coordinates of each vertex, the vertex points are instead referred to by line number in the file. Because of this, vertex points can be dynamically moved while preserving faces. This is crucial, as it allows for the user to add in custom parameters to resize the prosthetic to their needs. Considering the formats “v x y z”, “v x' y' z'”, “v x'' y'' z''” and “f 1/1/1 2/2/2 3/3/1,” each on separate lines, three-dimensional coordinates could be substituted for x, y, z, x', y', z', x'', y'', and z''. The result would be an OBJ-style model with three vertex points and an interconnecting face. Giving the user the opportunity to plug these values in for themselves allows for a resizable model that can conform to necessary parameters.



With an OBJ-style model produced, the process of manufacturing it for the end-user can be conducted. This requires that the user has a 3D printer and filament, or an alternative method of acquiring a product from a 3D model. In most setups, a model must be converted to printer-readable code, or “sliced,” before being printable. Applications which can do this are known as slicers, and are widely available from free to paid solutions. The goal of these slicers is to produce “G-code,” or code which is read, usually from an external media like an SD card, by a printer and converted into specific instructions for motor movement. These instructions are interpreted by software that is permanently programmed to the printer, or firmware, and is located onboard in non-volatile flash memory, or EEPROM. Most printers, both open-source and commercial, use the open-source Marlin firmware, making slicers and the G-code they produce widely universal (Marlin Firmware).

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