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Creating Custom Prosthetic Arms Using Fusion 360's Solid and Mesh Modeling

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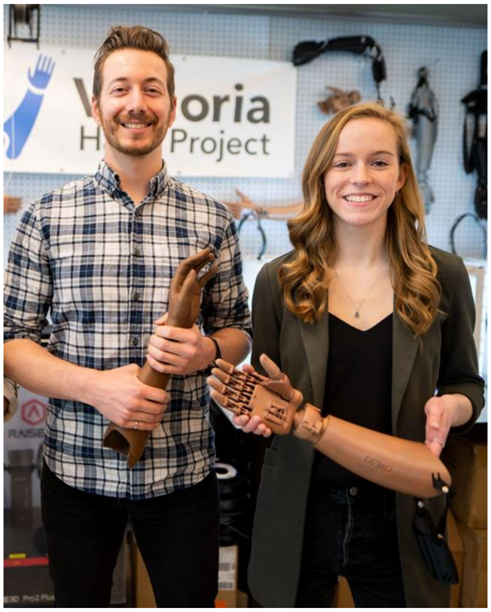
Learning Objectives

- Create custom healthcare devices by combining 3D scanning and CAD tools
- Implement custom product design workflows using the Fusion 360 API
- Combine 3D scans and solid bodies using both Solid and Mesh Modeling in Fusion 360
- Integrate Fusion 360 in clinical settings to improve productivity

Description

Victoria Hand Project (VHP) is a charity that designs and deploys low-cost 3D printed prosthetic arms in resource-poor areas of the world. VHP provides clinicians in these regions with the tools and training to create custom prosthetic arms, including in-house developed software that utilizes Fusion 360 to create these devices. In the past, VHP has struggled to create prosthetic devices for upper-arm amputees (i.e. above elbow), due to the complex geometry of the 3D scans, and the in-depth knowledge/workflow required by the clinicians to make the devices. By combining both Solid Modeling and Mesh Modeling, VHP has been able to improve the workflow for creating upper-arm prosthetic sockets. This workflow allows for further automation of the prosthetic socket creation through VHP's software, which integrates with the Fusion 360 API. This empowers VHP's in-country partners to create custom upper-arm prosthetic devices quickly and easily, allowing for improved access to prosthetic care.

Speaker Information



Michael Peirone is the Chief Executive Officer (CEO) of Victoria Hand Project (VHP); a Canadian charity organization with a mission to provide prosthetic care to low-income communities around the world. Michael has been a core member of VHP since its conception in 2015; assisting with the research and design of the first Victoria Hand, a low-cost, 3D printed prosthetic device. As CEO, Michael oversees the day-to-day operations of VHP and assists with the long-term vision of the organization. With extensive experience in 3D printing, engineering design, and the orthotic and prosthetic industry, Michael has trained many of the VHP's partners around the world on manufacturing and fitting the Victoria Hand. His expertise and passion for making a difference has driven the success of the project over the years, and he continues to be closely involved with innovation and design improvements.

Kim Arklie is a Mechanical Systems Designer with VHP. As Mechanical Systems Designer, Kim works directly on the research, development, and testing of VHP's prosthetic devices. She specializes in 3D print optimization, computer-aided design for additive manufacturing and rapid prototyping, and project management. Kim first got involved with VHP in 2018 during her undergraduate degree in Mechanical Engineering at the University of Victoria, where she volunteered and completed co-op work terms. Since joining the engineering design team at VHP she has assisted with the development of new low-cost prosthetic hand models, and prosthetic socket designs.

Introduction

This industry talk will provide a case study on how the Victoria Hand Project (VHP) uses Autodesk Fusion 360 to efficiently create custom prosthetic arms for amputees with above-elbow limb loss using a new and optimized workflow. VHP's original workflows for creating the custom upper-arm prosthetic sockets were time-consuming and required many user input steps. Additionally, the resulting prosthetic sockets did not have a nice cosmetic appearance, which could lead to users not wanting to wear the device.

Prosthetic Care in Resource-Poor Communities

The World Health Organization (WHO) estimates that 80% of amputees live in developing countries, yet only 5% have access to prosthetic care[1]. Healthcare systems in many developing countries do not receive proper support from their governments and are not able to provide amputees with sufficient care. This is due to a variety of factors, such as the high costs of prosthetic devices, a lack of infrastructure to manufacture the devices, and a scarcity of trained prosthetists to help provide these devices to patients.

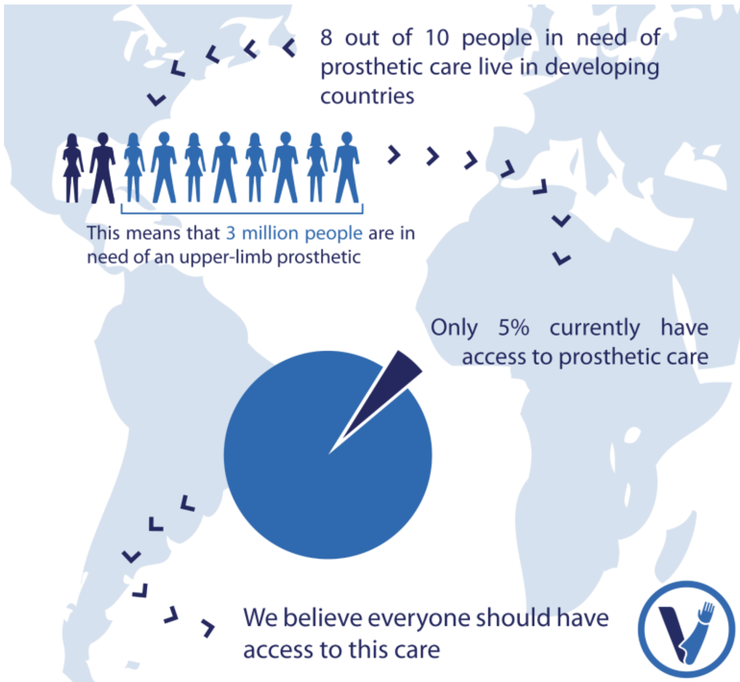


Figure 1: Millions of amputees around the world do not have access to proper prosthetic care.

This means that many amputees end up going without a prosthetic device. In some developing countries, the loss of the limb can have a stigma associated with it and can lead to low self-esteem and social exclusion from their community. Limb-loss may make it difficult for amputees to find and maintain sufficient employment. There are also many daily hardships associated with limb loss, including difficulties with eating, taking transportation, and dressing. These are all things that able-bodied individuals take for granted.

Victoria Hand Project Background

Victoria Hand Project (VHP) is a Canadian charity organization with a mission to provide low-cost, 3D printed prosthetic care to amputees in developing countries and low-income communities. VHP is currently providing the Victoria Hand in 8 developing countries and is beginning expansion to remote and under-served areas of Canada and the United States. VHP uses 3D printing and 3D scanning technologies to create custom prosthetic devices for low-income communities around the world.

Figure 2: Countries where VHP operates.

Figure 3: The three key aspects to VHP's deployment model.

VHP partners with healthcare professionals and technology experts in developing countries, and trains them on how to manufacture and fit the Victoria Hand prosthetic devices themselves. By 3D printing the prosthetic devices in the communities where they are needed most, amputees can receive their custom prosthetic arms in less time than compared to conventional devices. This also helps create high-tech jobs using advanced skills, such as computer aided design (CAD) and 3D printing. Clinicians using these tools to make devices for their neighbors helps foster a sense of pride in the community and leads to a sustainable, on-going care and deployment model.

Figure 4: Recipients of the Victoria Hand.

The clinicians VHP works with are incredibly busy and are not able to dedicate time to properly learn CAD programs. They want to use cutting-edge technologies to increase their clinic's capacity and help as many people as possible. The desire to enable VHP's partners to maximize their impact is what drove VHP to develop software using the Fusion 360 API (Application Programming Interface) to ease the workflows for creating custom prosthetic sockets.

The Fusion 360 API

The Autodesk Fusion 360 API is a simple way to control functions and features within a design and streamline workflows. An API is an intermediary that works between two programs or applications. In this case, the API works between a script (i.e. a software script) and Fusion 360. A developer will write a script to add the sketches, functions, or features into a Fusion 360 design. The API will read the script and add these sketches or features into the model in Fusion 360 with little or no user input.

> A chart showing the object models that can be added into designs by using the Fusion 360 API is shown here: https://help.Autodesk.com/cloudhelp/ENU/Fusion-360-API/ExtraFiles/Fusion.pdf

The Autodesk site contains extensive documentation on how to get started with the Fusion 360 API, the programming syntax, and coding examples. The Fusion 360 API Scripts and Add-ins were previously written in both JavaScript and Python. However, after a recent update, the Scripts and Add-ins need to be done in Python or C++.

Further information about the Fusion 360 API.

- Introduction to Fusion 360 API: https://help.Autodesk.com/view/fusion360/ENU/?guid=GUID-A92A4B10-3781-4925-94C6-47DA85A4F65A
- Fusion 360 API GitHub: https://Autodeskfusion360.github.io/#section_welcome
- Fusion 360 API Sample Code: https://help.Autodesk.com/view/fusion360/ENU/?guid=GUID-DE98632B-3DC0-422B-A1C6-8A5A15C99E11

Additional information about how VHP utilizes the Fusion 360 API, and steps on implementing the Fusion 360 API, can be found on VHP's 2021 AU presentation page.

Features of the Victoria Hand

The Victoria Hand is a low-cost, highly functional, 3D printed prosthetic arm, which recipients use for tasks at home, work, and school. This hand allows amputees to gain back their independence in their day-to-day lives, and also feel more confident in public. VHP's international partners make each of these arms custom-made for each user, to create a more comfortable fit, and a natural looking prosthetic device. The shape of the patient's limb is captured using 3D scanning (described later) and is used to digitally create a custom prosthetic socket, which is then fabricated using 3D printing. The entire end-to-end process is completed by clinicians and technicians in the world's poorest communities, getting these devices to the people who need them most, close to home.

The Victoria Hand is a body-powered device, and does not contain any electronic components, such as myo-electric sensors, motors, or batteries. The reason VHP does not implement electronic components is because it keeps the overall cost of the device low, allows for easier assembly and repair in resource-poor communities, and it is much safer for use in a variety of environments. The entire cost of materials for a trans-radial Victoria Hand (described below), including 3D print material, metal components, harnessing, and paint is only $100 USD. The Victoria Hand can get wet during use and there will not be a risk of electronic components being harmed. Also, users can wash the hand with soap and water to keep the surfaces free from bacteria.

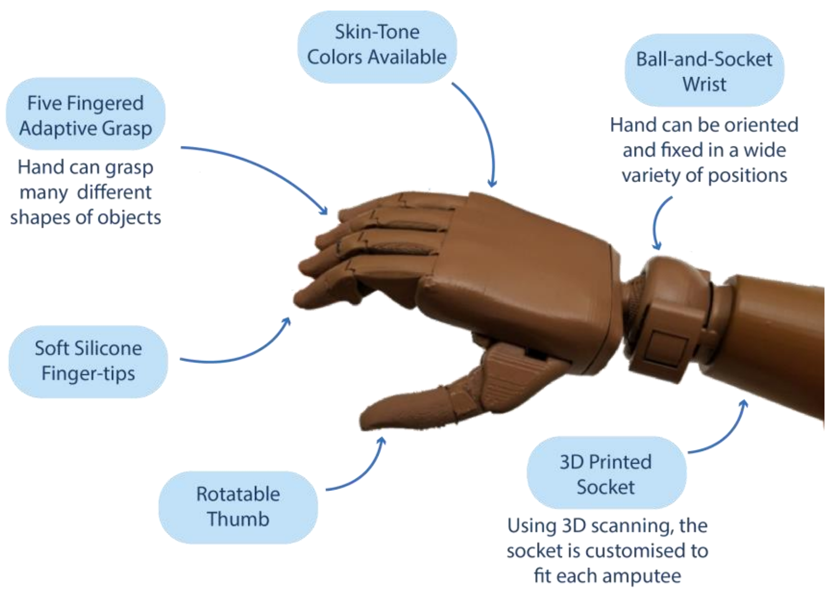


Figure 5: The features of the Victoria Hand.

Although the Victoria Hand does not contain motors and actuators, VHP's design team has built in a lot of useful features, allowing the user to perform a variety of tasks.

- Rotatable Thumb: The thumb can be rotated (adduct/abduct) by the user, to achieve different positions allowing for many different grasps. This includes a one-finger pinch, a two-finger pinch, a power grasp, or a lateral grasp.
- Backlock Mechanism: This lets the user lock the hand closed, for tasks such as carrying bags, or maintaining a constant grip onto objects.
- Rotatable Wrist: The wrist contains a ball-and-socket mechanism that allows the user to change the orientation of the hand quickly and easily. This wrist can rotate the hand up to 360 degrees, while simultaneously being flexed or extended by 25 degrees.
- Adaptive Grasp: The Adaptive Grasp mechanism allows the fingers to conform around the shape of irregularly shaped objects making them easier to grasp and hold.
- Silicone Fingertips: These fingertips improve the grip of the hand since the rubber will be able to better hold a variety of objects that are smoother.
- Metal Links: VHP implemented laser cut stainless steel links into the fingers and other areas of the hand to help with improving the strength and durability of the device.

Making the Custom Socket

VHP has specialized in custom trans-radial (below-elbow) prosthetic sockets since 2014. Each custom-made prosthetic socket uses the patient's anatomical dimensions to create a prosthetic device that is anatomically correct and comfortable. Over the years, VHP has fit over 200 amputees with their own prosthetic device, some of whose stories are shared online.

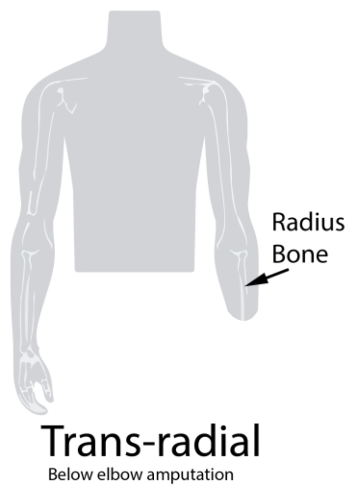


Figure 6: A trans-radial amputation is through the radius bone.

When a patient visits the clinic, the clinician will record the patient's anatomical measurements, including limb circumference and limb length, and create an exact replica of the limb using Plaster of Paris, called the 'limb positive' (shown below). The limb positive is 3D scanned to create a digital model of the patient's limb. The limb positive, also called the plaster impression or limb impression, is 3D scanned in Autodesk ReCap Pro using a technique called photogrammetry. Photogrammetry is a process which uses numerous photos of an entire object, to generate a 3D replica of the object on the computer. The reason VHP uses this method for 3D scanning, rather than using other 3D scanning methods, is because it is much lower cost and it provides very accurate scans with true color information (i.e. the color information from the photos, as shown below). Additionally, it is easy to use this scanning technique in the field, without needing to transport a large 3D scanner, or a high-power laptop for processing the 3D scan. When the technician returns to the clinic, they can transfer the photos from the camera to the computer and go through the photogrammetry process to make the 3D model.

Figure 7: Taking images of the limb positive with a digital camera (left). Using photogrammetry in Autodesk ReCap Pro to generate a digital model of the limb positive (right).

Using the patient's dimensions, a custom-sized limb socket is made using VHP's software solutions. Previously, VHP had to create a database library of pre-made sockets of various sizes that clinicians would select from to choose the socket that is closest to the patient's size. This was tedious and time-consuming for clinicians and may require them trying a few different sizes of socket to find the best fit. Recently, VHP's developers created a program that integrates with the Fusion 360 API to customize socket sizes. When a clinician enters the patient's limb dimensions into the VHP software program, the measurements will be pushed to a parametric model in Fusion 360 to scale it to the desired size. This custom size socket is quickly updated and exported from Fusion 360 as a .stl or .obj mesh file.

The 3D scan and socket are loaded into a program named Autodesk Meshmixer. Meshmixer, shown below, is a free Autodesk mesh program for working with triangle meshes (i.e. .stl and .obj files formats). The 3D scan is aligned in the custom socket in Meshmixer, according to the clinician's expertise and the patient's needs. The digital model of the limb is cut out from the socket using a Boolean Difference operation, to leave a cavity the exact shape of the recipient's limb. After cutting out the limb shape, the socket is smoothed out to remove any rough edges and the socket is 3D printed in the clinic. This entire process can be done by the clinicians in one day, and the patient can receive a custom socket the following day. In some cases, patients need to wait a few days or weeks to receive their socket when being fit with a traditional prosthetic. A condensed workflow showing these steps in Meshmixer is also shown online.

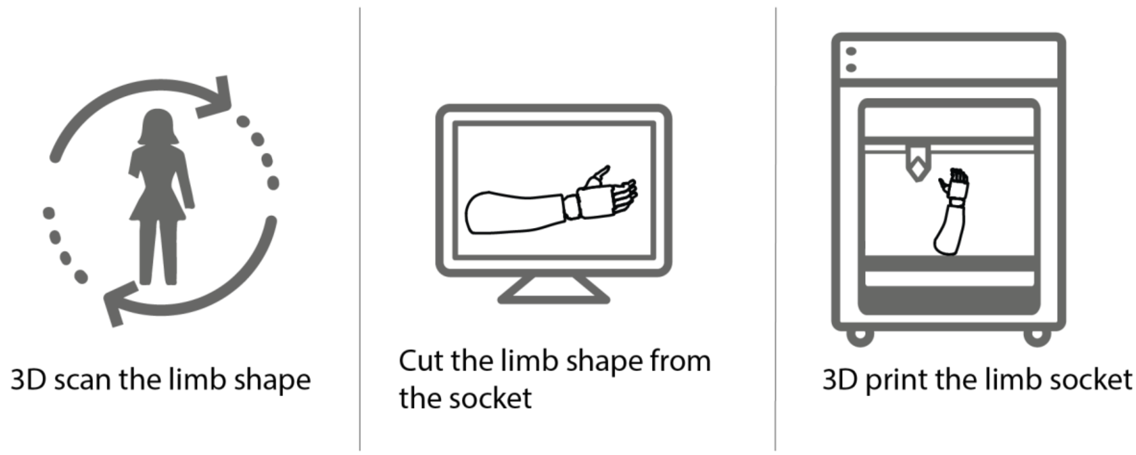


Figure 8: The three simple steps to make a custom socket.

Figure 9: The scan of the limb positive in Autodesk Meshmixer, with true color information from photogrammetry 3D scanning.

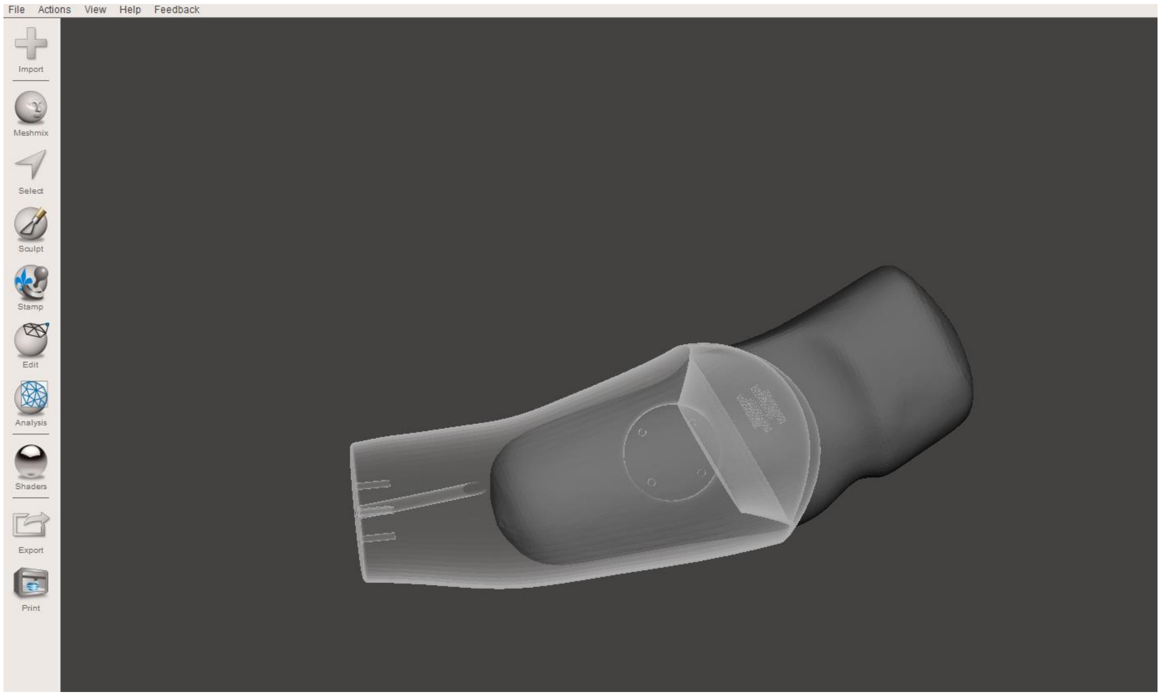


Figure 10: Aligning the limb positive in the socket in Autodesk Meshmixer.

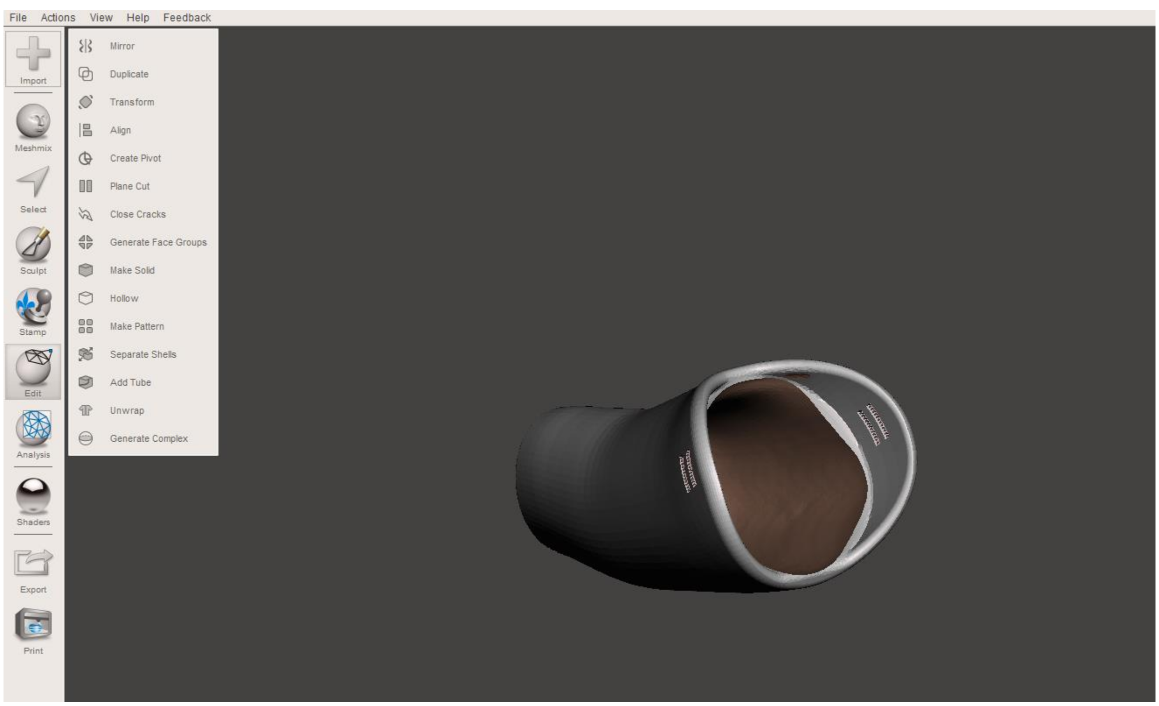


Figure 11: Performing a ‘Boolean Difference’ operation to cut the limb positive shape out of the socket.

Trans-Humeral Prosthetic Devices

VHP has developed and deployed the trans-radial (below-elbow) prosthetic devices since 2014, but throughout this time VHP was approached by many amputees who were missing their arm above their elbow. Unfortunately, these patients could not use VHP's trans-radial device, resulting in many of these patients not having access to prosthetic care. Many trans-humeral amputees (above-elbow amputees) will not receive a prosthetic device since these custom arms are more complicated to make and are more expensive. This showed the need for VHP to design a trans-humeral prosthetic device to help these patients, and many more around the world.

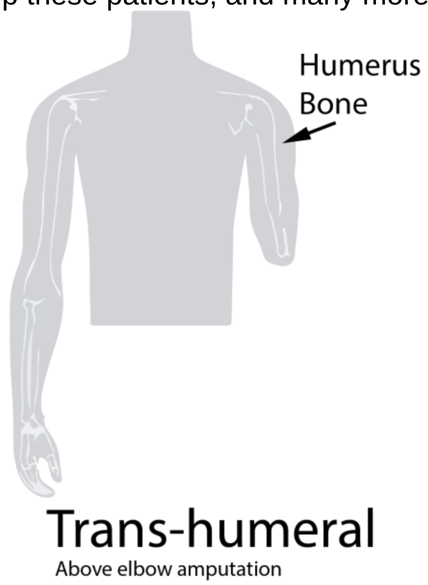


Figure 12: A trans-humeral amputation is through the humerus bone.

In 2017, VHP began preliminary research and development on the design of trans-humeral prosthetic devices. VHP initially had conversations with clinical partners in Canada and around the world about the fit and functionality of trans-humeral prosthetic devices to learn more about the requirements and how these devices should operate. It was also very important to understand how the device should fit on a patient for optimal comfort and mobility. Through these conversations, VHP's design team determined the following design constraints for the new system:

- Good cosmetic appearance: The cosmetic appearance is very important to many users so they can feel comfortable wearing their prosthetic device in public.
- Low weight: Prosthetic devices that are too heavy will be uncomfortable and users will not want to wear them.
- Appropriate fit and range of mobility: The prosthetic socket should be fit properly to ensure that users can properly move the device and it is comfortable to wear for long periods of time
- Functional elbow: A moveable elbow allows the users to lift the hand, and objects being held, to various heights, and use the device for more tasks, such as eating.
- Adaptable workflow: An adaptable and easy-to-use workflow allows clinicians to make these devices quickly and easily themselves.

Using these design constraints as a starting point, VHP's mechanical and biomedical designers began developing prototypes for elbow mechanisms. The original design of the prosthetic elbow involved a ball-and-socket joint that could be locked in any position using friction. This design allowed for more freedom in the elbow range of motion and locking position (as it could be locked at any angle), but through testing it was discovered that the elbow could not hold much weight prior to slipping. After the elbow slipped, it may be damaged and would require repairs or replacement. This was not ideal because it would mean that users would not be able to hold much weight using the hand. From this testing it was concluded that the elbow would need to be redesigned to make it more durable for users before worldwide deployment.

Figure 13: VHP's original trans-humeral socket model with ball-and-socket elbow.

Many different concepts were devised, but the optimal elbow design uses a ratchet-and-pawl mechanism. By making the ratchet-and-pawl mechanism using stainless steel components, the elbow mechanism was determined through testing to be significantly more durable, and users could feel more confident holding objects of various weights.

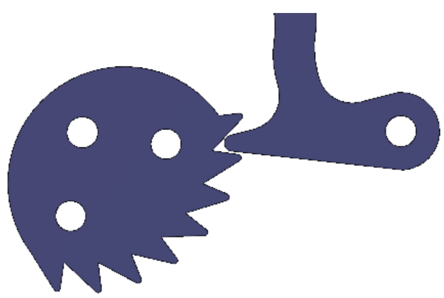


Figure 14: Ratchet-and-pawl mechanism.

VHP's Original Trans-Humeral Socket Workflow

Along with the design of a functional elbow mechanism, VHP needed to develop a workflow to create the custom trans-humeral sockets. The process for creating the trans-radial (below-elbow) sockets is relatively straight-forward, where a modified mold of the limb is 3D scanned and this is cut out of a pre-made socket, as described earlier. This same workflow could not be applied to make the trans-humeral socket due to the unique anatomy of the user's shoulder. Cutting the entire limb scan shape out of a solid socket shape would not feasibly work, as it would result in a very large and heavy socket, which is not desired by users.

Figure 15: Trans-humeral limb impression with desired socket shape outlined.

This resulted in needing to use the unique anatomy of the user's shoulder to create a thin shell that could suspend the socket over the shoulder. Creating this thin shell would be more complicated than the trans-radial (below-elbow) workflow and would require more steps by the technician making the prosthetic socket. It was determined that the workflow to create the custom prosthetic socket would combine two components - the patient's limb impression (to create the thin shell to suspend the socket over the shoulder), and a pre-sized socket to create the lower portion of the socket. To create the thin shell using the original trans-humeral socket workflow that VHP developed, a clinician would highlight the shoulder area on the 3D scan in Autodesk Meshmixer and thicken the highlighted area to create the over the shoulder cuff, as shown below.

Figure 16: Highlighting area for shoulder cuff on the 3D scan in Meshmixer.

The clinician would also select a pre-sized lower trans-humeral socket from a library of sockets and cut the limb shape out of it, similar to the trans-radial workflow described above. The pre-sized lower sockets for the trans-humeral arm change the circumference at various levels, and the overall length, similar to the sockets shown below. The thin shell (upper socket) and the socket with the 3D scan cut out (lower socket) would then be combined and 3D printed. A brief overview of VHP's original workflow to make the trans-humeral devices is shown in this video.

Figure 17: Different sizes of pre-made lower sockets for the trans-humeral workflow.

Issues with Trans-Humeral Workflow

While this workflow allowed VHP's partners to create custom trans-humeral sockets, it still had its limitations and issues. When combining the top socket and bottom socket in Meshmixer, the resulting transition between the top socket and the bottom socket did not have an organic (i.e. life-like) shape, and it would have sharp edges. When trying to mitigate these issues and smooth this transition there may be holes introduced, or it would have a lumpy appearance. Even when no holes were introduced the transition between the two portions of the socket was not smooth, causing the arm to have an imperfect shape, which users of the prosthetic device may not like.

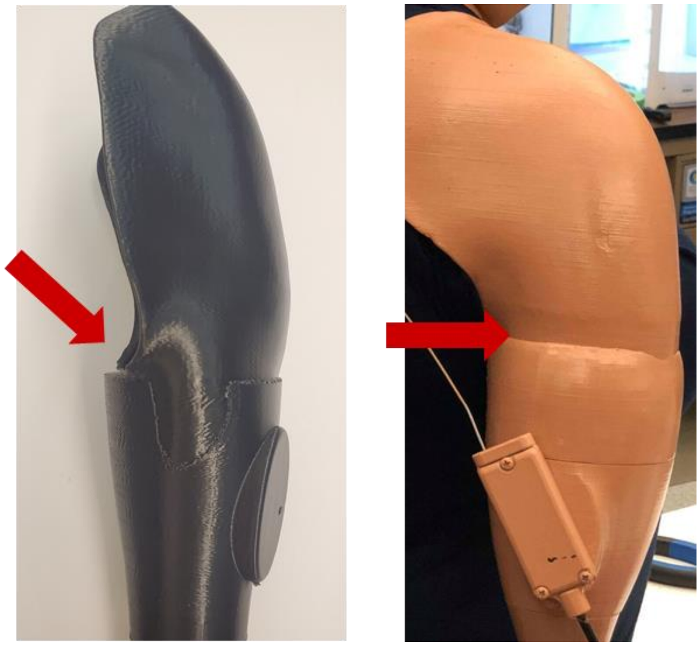


Figure 18: Cosmetic issues resulting from VHP's original trans-humeral workflow in Meshmixer.

By performing this workflow in Meshmixer, there were limitations in altering the size of the lower socket throughout the workflow since the pre-sized lower socket was selected and imported into Meshmixer. If the lower socket was the incorrect size for the patient, it was not possible to resize the socket in Meshmixer without performing the entire workflow again. A new pre-socket of a different size would need to be selected, and the workflow of creating the over shoulder shell would need to be redone, as well as combining the upper socket and the lower socket. It would be burdensome and time-consuming to make minor adjustments to the socket if any errors were determined throughout the workflow.

Finally, the entire workflow required too many user inputs and commands. The workflow in Meshmixer had many manual steps to create the custom device which resulted in a timely and complicated workflow for clinicians. A new way of creating these custom prosthetic devices was needed to reduce user inputs, allow for easier socket size adjustments, and create a socket with a more natural appearance.

Optimizing the Workflow Using Autodesk Fusion 360

Recently VHP began to optimize the workflow to create custom trans-humeral prosthetic sockets to improve the end product and make the production workflow easier for in-country clinical partners. The new workflow was developed using only Autodesk Fusion 360 and utilizes the newly developed Mesh Workspace. Similar to the original workflow, this optimized workflow creates the trans-humeral socket using two components - the upper portion of the socket that will create the over the shoulder cuff, and the lower portion of the socket. The pre-sized lower socket from the original workflow was redesigned in the Fusion 360 Solid Workspace to be parametrically dimensioned (i.e. based on parameters to adjust the size of the design) for improved customization and a better fit on the user. The upper portion of the socket is created solely using the patient's limb impression. The limb impression is imported into Fusion 360 as a mesh and kept as a mesh body throughout the workflow.

The optimized workflow can be broken down into 7 steps to be performed by the clinician creating the socket.

Step 1. Create the lower socket

Size the lower socket by inputting the patient's recorded anatomical measurements into the solid body design parameters of the lower socket model in Fusion 360 using Victoria Hand Project software and the Fusion 360 API. This lower socket model is parametrically dimensioned using user-input parameters on various planes in the medial-lateral and anterior-posterior anatomical directions, as well as lengthwise. This creates a lower socket that is similar in size to the patient's unaffected limb, improving the cosmetic appearance of the device on the patient.

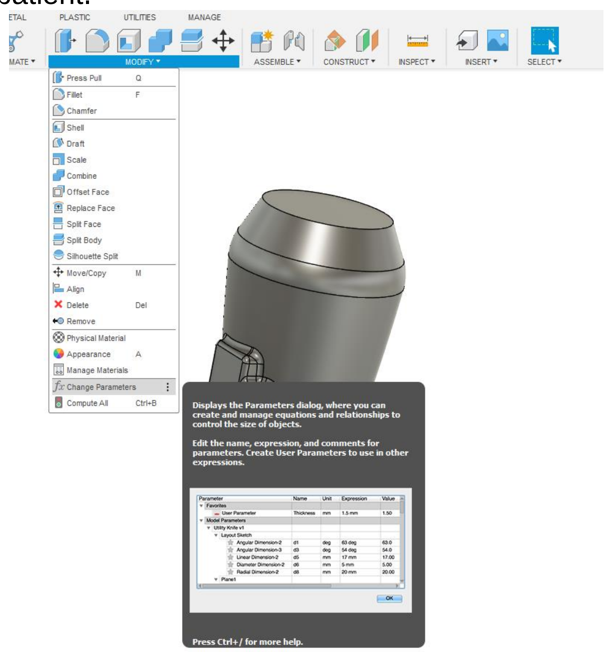


Figure 19: Selecting "Change Parameters" under Modify in the Solid Workspace.

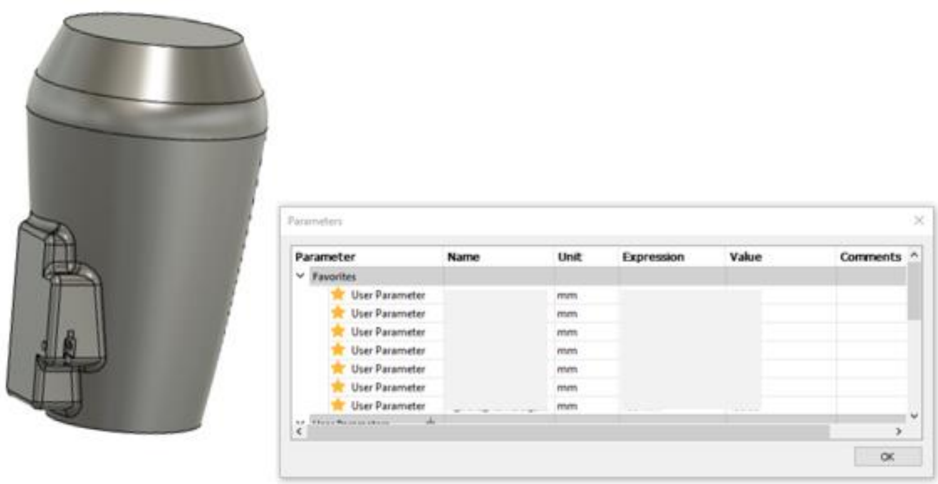


Figure 20: Creating the lower portion of the trans-humeral socket in Fusion 360 using parameters.

Step 2. Import and align the limb impression

Insert the patient’s limb impression into Fusion 360 as a mesh body inside a component. The limb impression will be used to create the portion of the socket that will go over the patient’s shoulder. Since only the limb impression is used to create this part of the socket, it is completely custom to the patient’s anatomy. Once imported, the limb impression is aligned to the lower portion of the socket. To do this, a line is created through the center of the limb, as well as through the center of the lower socket. A rigid joint is then created between those two lines, snapping the components together. This avoids manual alignment of the two components but still allows the clinician to rotate and move the limb impression up and down relative to the lower socket. This minimizes any human error that could occur in aligning the two components together manually, which was previously done in the original workflow. Additionally, the rigid joint can be easily edited to realign the two components if the alignment was not correct to begin with.

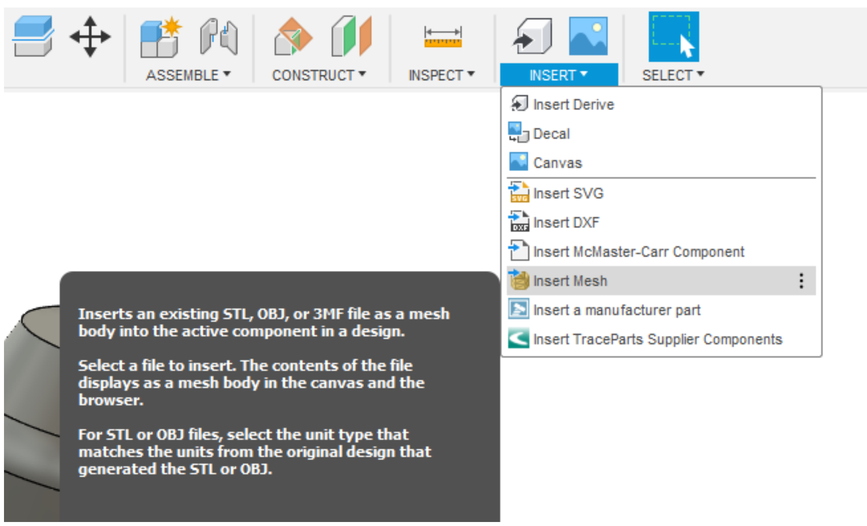


Figure 21: Selecting “Insert Mesh” under Insert in the Solid Workspace.

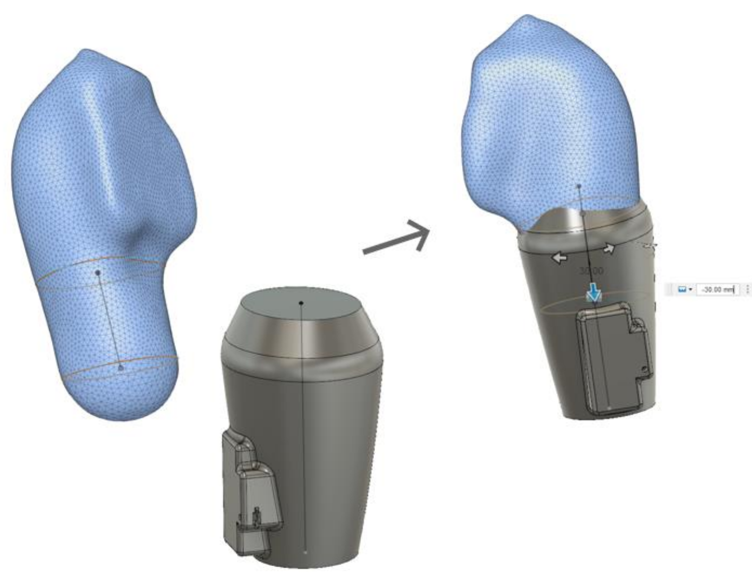


Figure 22: Aligning the patient’s limb impression with the lower socket in Fusion 360.

Step 3. Create the upper socket

Once the limb impression has been aligned with the lower socket, the upper portion of the socket can be created. This is done by duplicating the limb impression and hiding the original copy. The duplicate of the limb impression is then trimmed to remove parts of the limb impression that are not required to create the upper portion of the socket, such as the two ends of the limb impression. This results in an open mesh shell. The open shell is then repaired to create a stitched solid mesh (closed mesh body), and it is then remeshed and smoothed. The solid mesh is then offset 5mm outwards so that once the limb impression is later cut out of this shape, the upper portion of the socket will have a wall thickness of 5mm. For clarification, please refer to the 5mm offset overlapping the limb impression on the right-hand side of the screen in the figure below. This creates an upper portion of the socket that is completely custom to the patient's anatomy and is how the prosthetic device is suspended over the patient's shoulder.

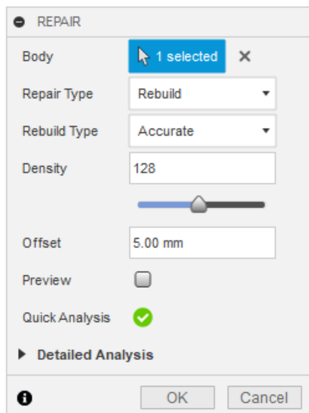


Figure 23: Offsetting the closed mesh body 5mm outwards.

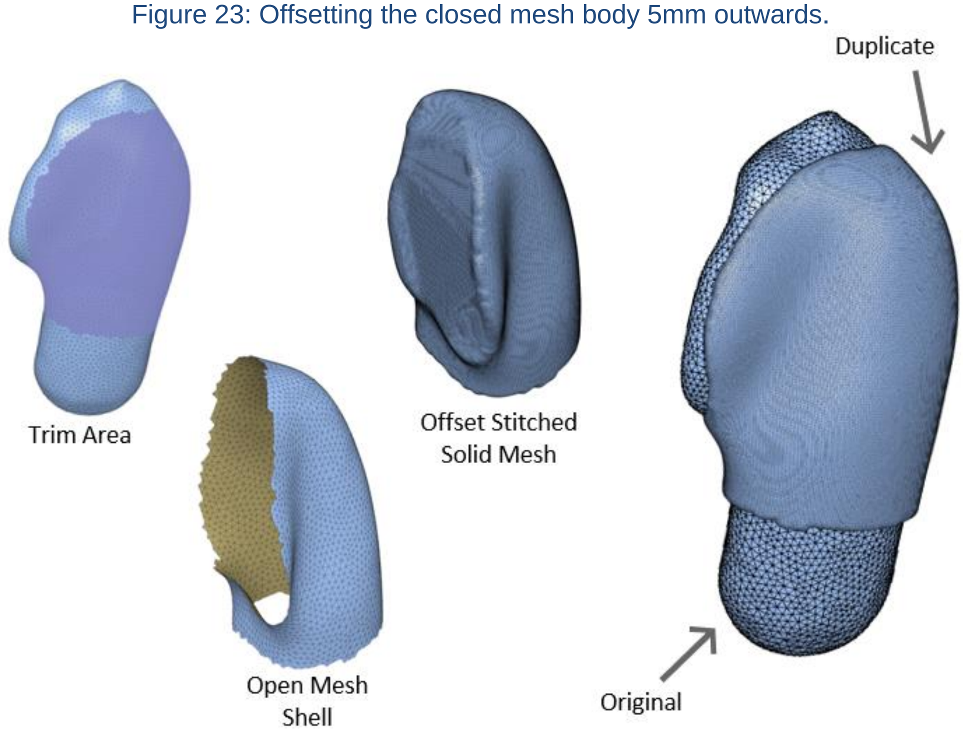


Figure 24: Creating the upper portion of the trans-humeral socket in Fusion 360.

Step 4. Tessellate the lower socket

Once the alignment of the lower socket, upper socket, and patient's limb impression is correct, the lower socket is tessellated to convert it from a solid body into a mesh body to be further edited.

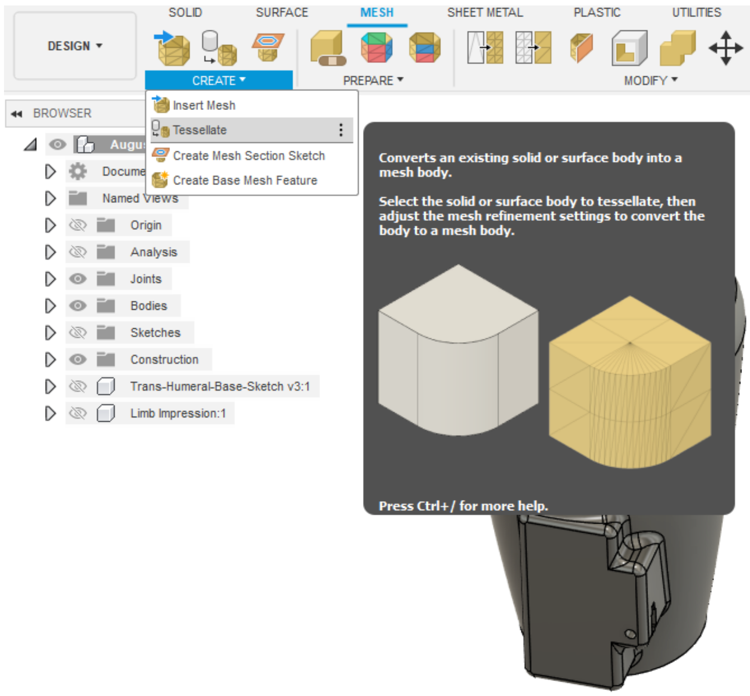


Figure 25: Selecting "Tessellate" under Create in the Mesh Workspace.

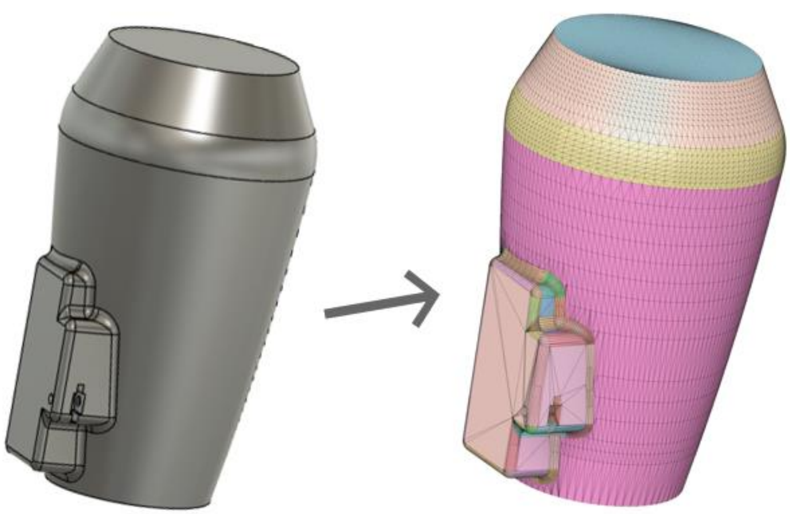


Figure 26: Tessellating the lower portion of the socket into a mesh body in Fusion 360.

Step 5. Boolean Union the lower and upper socket

Now that all components to create the trans-humeral socket are mesh bodies, a Boolean Union operation in the Mesh Workspace can be performed to combine the lower portion of the socket and the 5mm offset upper portion of the socket previously made using the patient's limb impression. This creates one mesh component that can now be further edited.

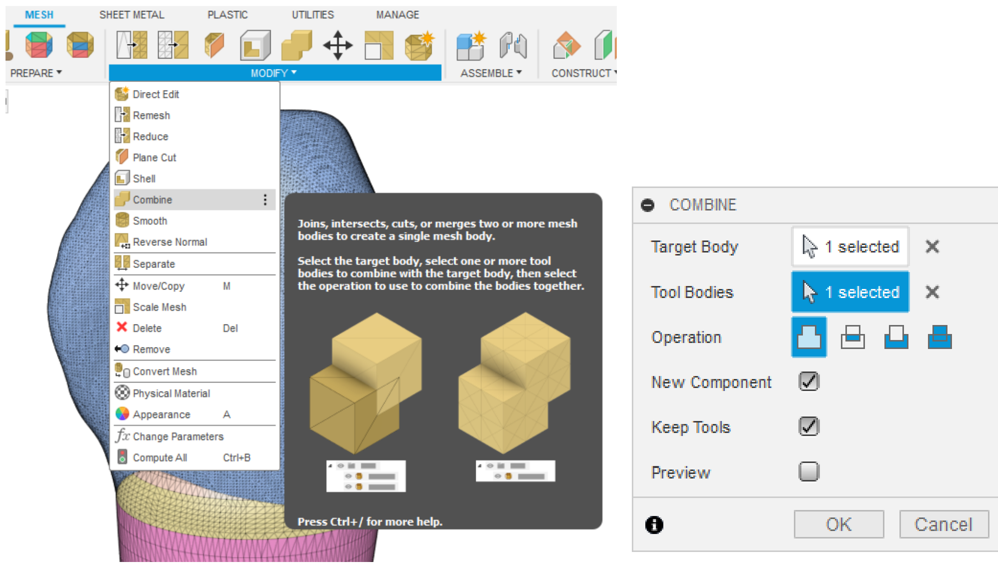


Figure 27: Selecting "Combine" under Modify in the Mesh Workspace and selecting the "Join" operation.

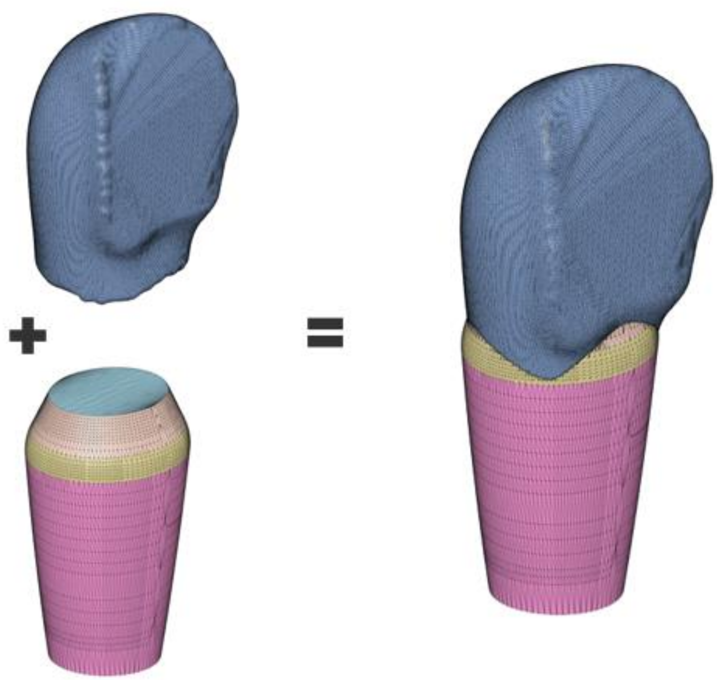


Figure 28: Performing a Boolean Union operation in Fusion 360 to combine the lower and upper socket.

Step 6. Clean up socket transition

Now that the lower and upper portions of the socket have been combined into one mesh component, the transition between the two previously separate components can be cleaned up and smoothed. This is done by direct editing the component and first combining the face groups of the socket body (this excludes the extrusion seen on the exterior of the socket body in the figure below, this is for attaching the Backlock Mechanism feature on Victoria Hand prosthetic systems). The Erase and Fill function can then be used by highlighting the socket transition; the Erase and Fill function will essentially create a mesh surface loft between the two edges that were erased. The socket is then remeshed and smoothed to obtain a desirable surface finish and a seamless transition between the previously separate components of the socket.

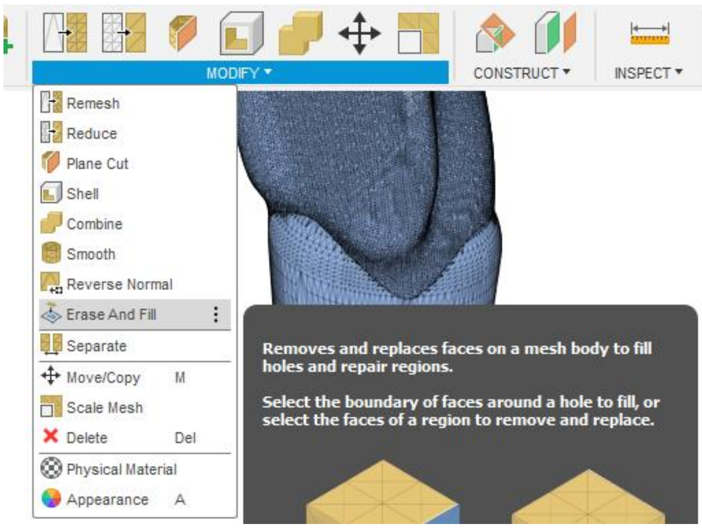


Figure 29: Selecting “Erase and Fill” under Modify in Direct Editing mode.

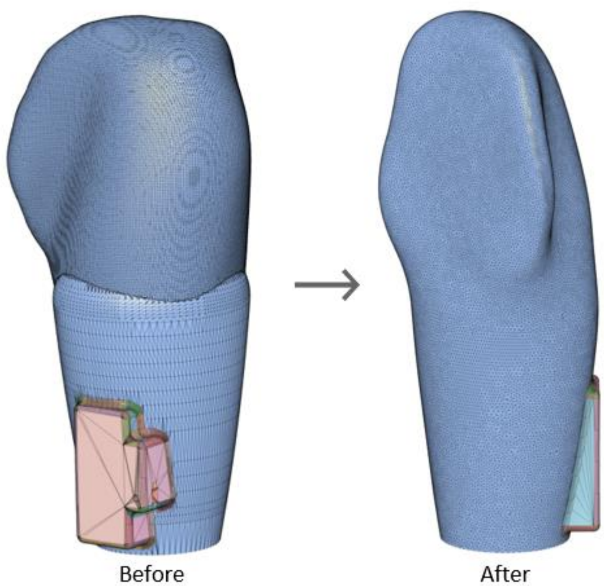


Figure 30: Cleaning up the transition between the lower and upper portion of the socket in Fusion 360.

Step 7. Boolean Difference the limb impression and combined socket

Now that the exterior appearance of the socket is smooth and cosmetically appealing, a Boolean Difference operation can be performed to cut the patient's limb impression from the combined socket. This is the last step in the workflow, and because the inside of the socket is not further edited after cutting the limb impression out of the socket, the accuracy of the patient's scan data is not affected and the fit of the socket on the patient is optimized. Additionally, the limb impression could be offset outwards prior to performing the Boolean Difference operation, which would allow space for an amputee to wear a prosthetic liner or "sock" with their prosthetic device for comfort. Now that the socket is complete it can be exported from Fusion 360 as a .stl file and is ready for 3D printing.

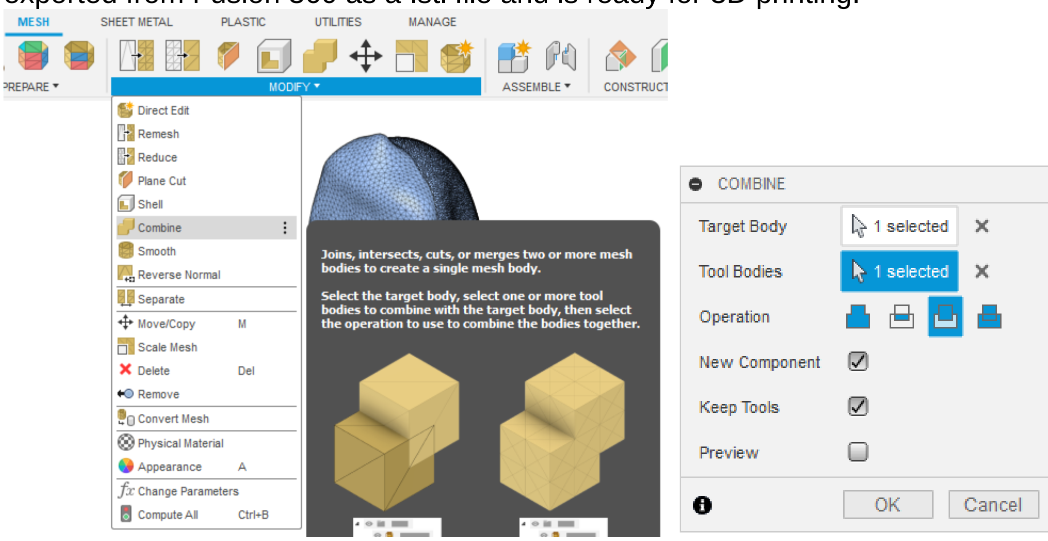


Figure 31: Selecting "Combine" under Modify in the Mesh Workspace and selecting the "Cut" operation.

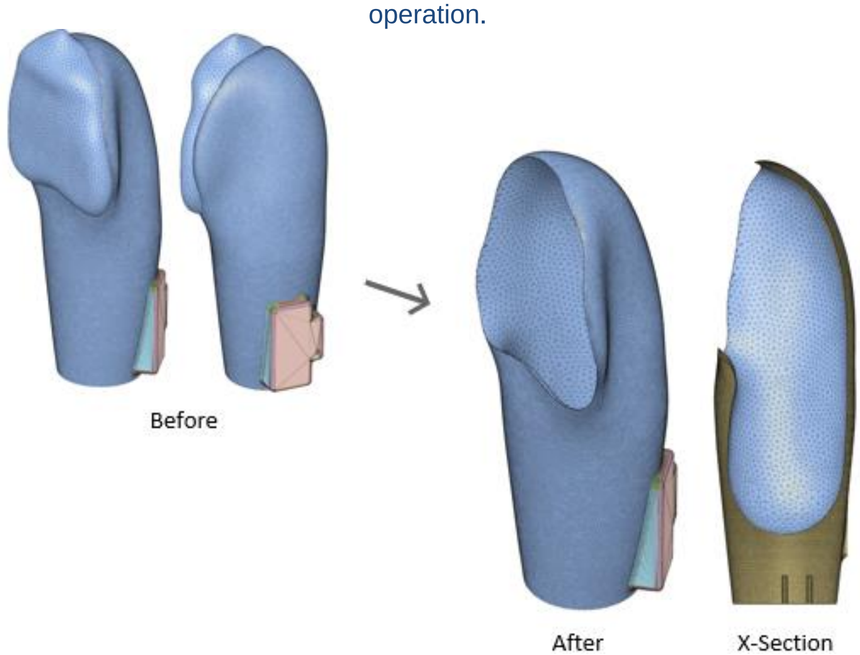


Figure 32: Performing a Boolean Difference operation in Fusion 360 to cut the limb impression shape from the socket.

Advantages of the Optimized Workflow for Creating Trans-Humeral Sockets

In comparison to the original workflow, there are many advantages to using the optimized workflow for creating the custom trans-humeral sockets. By keeping the patient's scan as a mesh in Fusion 360, working in the mesh workspace, and not editing the inside of the socket after the limb impression has been cut out of the socket, the final outcome of the socket is very precise. This results in a better socket fit for the user and increases the functionality of the device from a prosthetics point of view. It also decreases the chances of the user rejecting the prosthetic device. The high accuracy of the mesh and mesh offset also create a socket with a uniform thickness, which is a desirable feature when 3D printing a thin component.

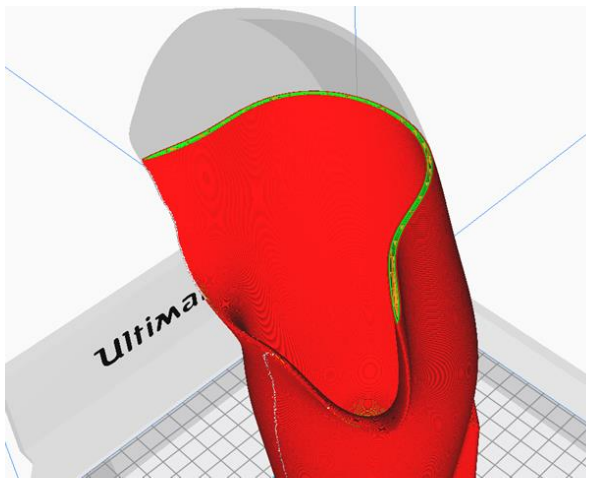


Figure 33: Trans-humeral socket in Cura being prepared for 3D printing.

Using the Fusion 360 Mesh Workspace features such as erase and fill, remesh, and smoothing, creates a socket with a seamless transition between the two separate components of the socket.

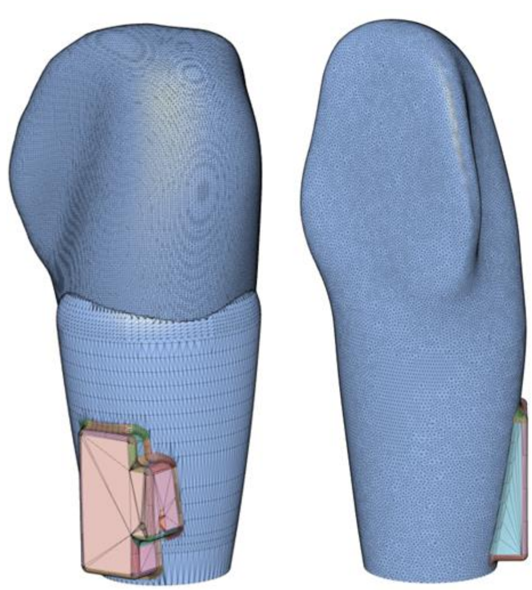


Figure 34: Trans-humeral socket in Fusion 360 before and after smoothing the transition between the lower and upper portions of the socket.

Figure 35: Trans-humeral socket comparison between optimized and original workflow.

A portion of this workflow can also be integrated with the Fusion 360 API and VHP-developed software to ease the workflow for VHP’s in-country clinical partners. As the Fusion 360 API capabilities expand to include Mesh Workspace features, VHP will be further developing the software to automate even more portions of the new workflow.

Being able to semi-automate the alignment process of the limb impression and lower portion of the socket using the optimized workflow is another major advantage of this method. This removes some of the human error that can occur when aligning the two components manually, as was previously done in the original workflow using Meshmixer. It also makes the alignment process considerably faster for the clinician to perform and makes it so that the lower socket has more consistent wall thicknesses since the limb is centrally positioned automatically within the lower socket. However, the clinician can still apply their knowledge and expertise to create a trans-humeral socket with an appropriate fit for the user.

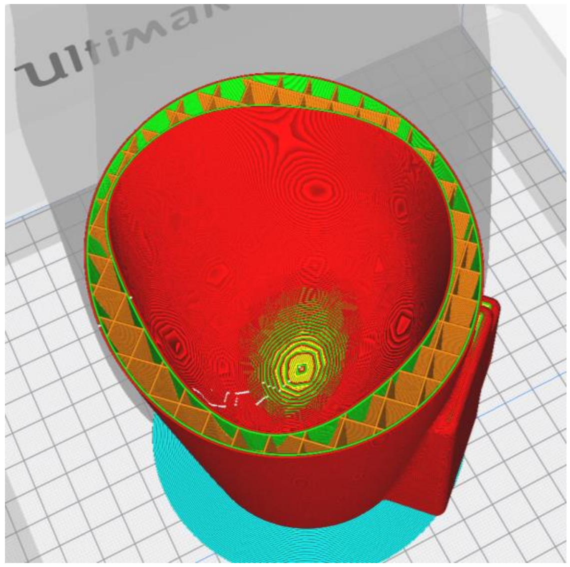


Figure 36: Lower socket wall thickness shown in Cura.

Since the workflow is performed in only Fusion 360, the lower socket can be more easily re-sized throughout the workflow until the Boolean operations have been performed, and the step of aligning the limb impression with the lower socket does not need to be repeated, such as in the original workflow in Meshmixer if the lower socket was the incorrect size. Even after the Boolean operations have been performed (which are non-parametric operations), minimal steps need to be repeated to complete the socket, and those steps that are repeated are quick and simple to complete.

If required, the limb impression is also easy to be realigned by editing the rigid joint between the central line in the limb impression and the lower socket and easily changing the depth of the limb impression in the lower socket, or the rotation of it relative to the lower socket. Overall, the entire workflow has been significantly improved and simplified from the original workflow and produces a trans-humeral socket that is much more cosmetically appealing.

Case Study Demonstration

A patient recently sought out VHP's partner clinic in Haiti to receive prosthetic care. John (name was changed and identifying features are hidden for anonymity) was injured when his house collapsed on top of him in the 7.0 magnitude earthquake that struck near Port-au-Prince on January 12, 2010. Hundreds of thousands of people were killed or injured in this disaster, and the effects of it are still felt in the country today[2]. Due to the massive number of people injured in the disaster he did not receive care for 8 days and lost his arm above his elbow due to an infection that could have been prevented. Since losing his arm, John was unable to receive a prosthetic device until he heard about VHP's devices.

Figure 37: “John” meeting with VHP’s Haiti partner clinician.

John met with VHP’s partner clinic in Haiti where the clinician took a plaster limb impression and anatomical measurements using VHP’s trans-humeral fitting sheet. The plaster limb impression was then digitized using methods of photogrammetry and Autodesk Recap Pro, as described earlier. The clinician then uses the optimized workflow for creating the trans-humeral sockets using Fusion 360 by inputting the patient’s anatomical measurements into the lower socket solid body design and importing the patient’s limb impression as a mesh. Here the clinician is able to apply their knowledge and expertise to create a socket with proper suspension required for the patient’s anatomy and functionality.

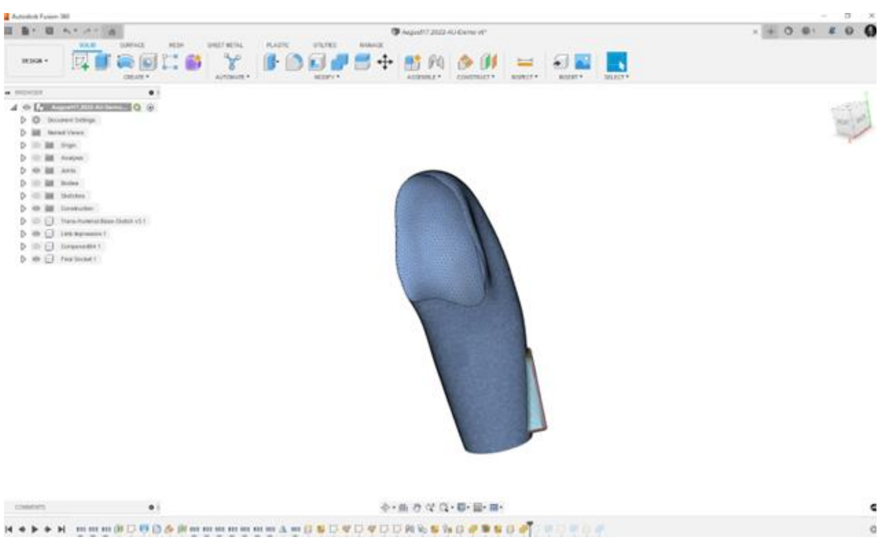


Figure 38: Completed trans-humeral socket in Fusion 360.

Once the socket is complete in Fusion 360, it is exported as a .stl file and imported into Cura slicing software and prepared to be 3D printed on an Ultimaker 3D printer.

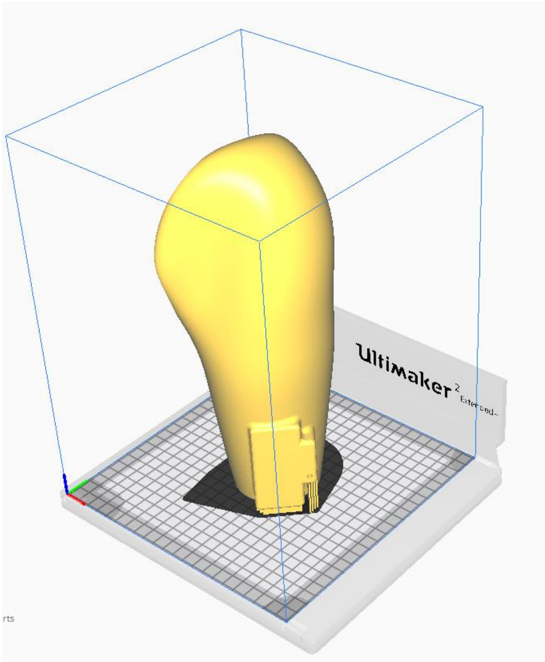


Figure 39: Trans-humeral socket being prepared for 3D printing in Cura.

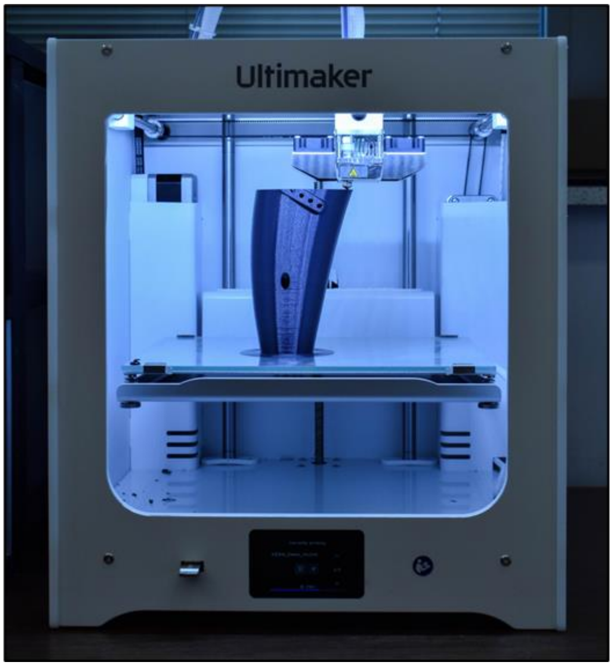


Figure 40: VHP socket printing on an Ultimaker 3D printer.

While this is going on, the remaining components of the trans-humeral system are 3D printed by the local 3D print technician. This includes the Victoria Hand, wrist socket, forearm socket (also parametrically sized), functional elbow, pawl handle, Backlock Mechanism components, and harnessing components.

Figure 41: Trans-humeral prosthetic system.

Figure 42: VHP harnessing components.

Once all components of the trans-humeral prosthetic system have been 3D printed, the device is assembled by the local 3D print technician. From there the clinician will take the device and fit it to the patient.

Workflow Implementation

The workflow covered in the previous sections will be conducted by VHP's partners to make the custom prosthetic arms. VHP's team has developed this trans-humeral workflow, and similar workflows for making other prosthetic devices (i.e. the trans-radial devices), to make it easier for the in-country partners to create the prosthetic devices themselves. This is important because many of VHP's partners have a clinical background and extensive expertise in prosthetics, but they do not always have strong computer aided design (CAD) knowledge, such as Fusion 360.

Victoria Hand Project Software Solutions

This led VHP to create a deployment model and workflow which can easily be performed by the clinical partners, without them needing to learn all of the necessary design skills. VHP's team has developed these software solutions and pre-made 3D print files to make it easier for the in-country partners to make the custom devices. A clinician uses the VHP software to select the model of hand that they want, and various features to better customize the prosthetic hand to their desire. This includes selecting whether the hand is left or right, the model of Victoria Hand (different models described on the VHP website), and specific features to allow for easier use for mobility-impaired patients (such as patients missing both hands). This is briefly highlighted in a VHP video. After going through the process, the clinician can choose to create a custom-sized socket for the user. The Victoria Hand prosthetic sockets are designed in Fusion 360 and are parametrically dimensioned so they can be scaled to the user's size. When a clinician enters the patient's anatomical dimensions into the VHP software, the Fusion 360 API will push these measurements to the Fusion 360 model to change the size of the socket. This allows the clinicians to quickly and easily generate the size of socket they want, rather than needing to choose from a library of standard socket sizes (as described above).

By using the VHP software and the Fusion 360 API the clinician does not need to create the custom-sized socket in Fusion 360 themselves. While accessing the Fusion 360 equation-manager and adjusting features can be straight-forward for many experienced designers and engineers, the clinicians that VHP works with do not always have much experience designing with CAD tools. Entering the design space and adjusting certain features may not be as straight-forward for them and may be a learning curve. For those clinicians who have experience with CAD, the use of the software and API allows for a much quicker workflow for making these adjustments. VHP has developed and implemented software solutions for making the custom trans-radial sockets, but at this time VHP is also working to implement a trans-humeral workflow into the software. This would be similar to the trans-radial workflow, where a clinician can select the model of hand and features, and also create a custom limb socket.

Future Work

VHP's design and engineering team is always searching for new ways to improve the workflows and allow clinicians to make these prosthetic devices in their clinics with less effort. The workflow demonstrated in this handout, and the accompanying presentation, is constantly changing as VHP's design team finds new ways to better perform various steps.

In the near future, VHP's team will begin to utilize the Fusion 360 API tools to automate various steps in the workflow. The Fusion 360 API will perform steps at the push of a button, such as performing extrusions (or cut extrudes), or thickening features. These steps can also be completed in series so when the user clicks a button titled 'Create Socket' in the VHP software, the Fusion 360 API can offset the shell of the upper component to make it 5mm thick, combine the upper and lower socket components, then export the combined body as a .stl file. These steps can be performed in a matter of seconds and require minimal user input. There are some steps that are more difficult to implement, such as selecting a specific face to offset, as this would need to be done manually by the clinician. However, by automating other steps the overall workflow becomes much easier for the clinician. Also, it also means that the clinician does not need to remember what steps to perform, since they can be automated by the software program.

Additionally, VHP would like to find a way to use true color information in Fusion 360 to allow for better customization of the sockets. When prosthetists are making a plaster impression of a patient's limb, they will sketch out the desired shape of the socket directly on the impression. They can then use that information to create the custom socket to the desired size. The shape of the socket can depend on the patient's limb shape, amount of shoulder suspension required, and the presence of soft tissue or bony prominences. The prosthetist will use their expertise and training to determine this, and it is very important information for utilize.

Figure 43: Plaster impression with the desired shape sketched on.

The output from Recap Pro will contain true color information from the photos. At this time, VHP's team has not found a way to utilize this color information in Fusion 360. Currently, a clinician must look at the plaster impression or at photos of the impression when selecting the surface on the 3D scan to offset and create the shell. However, it would be valuable to be able to overlay this onto the imported mesh part in Fusion 360 so the clinician can create the exact shape of the socket that they want with no guessing required. This creates a better-fitting socket and will reduce the chances of adjustments being required after making the socket.

Keep up to date on Victoria Hand Project's work by following the social media pages listed below and VHP's website.

Victoria Hand Project

Prosthetics Within Reach

Victoria Hand Project	Victoria Hand Project
@VicHandProject	Victoria Hand Project
@VicHandProject	www.victoriahandproject.com

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[1] M. Marino, S. Pattni, M. Greenberg and A. Miller, "Access to prosthetic devices in developing countries: Pathways and challenges", 2015. Available: https://www.researchgate.net/publication/285591611_Access_to_prosthetic_devices_in_developing_countries_Pathways_and_challenges. [Accessed: June 28, 2019].

[2] “2010 Haiti earthquake,” History.com, 18-Jul-2011. [Online]. Available: https://www.history.com/this-day-in-history/massive-earthquake-strikes-haiti. [Accessed: August 19, 2022].