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Novel Design for a Simple and Affordable End-Effector for an Upper-Limb Prosthesis

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***Abstract* - An affordable prosthetic arm was designed to be used in underprivileged areas to allow more upper-limb amputees to have access to prosthetics that can help them regain their independence. The primary user of the prosthesis will be the amputee(s) who receive the device; beneficiaries include the amputee's family and the community involved in the manufacturing of future prostheses. The customer requirements include cost-effectiveness, the ability to withstand humidity, cleanability, low maintenance, long life, lightweight, and the ability to perform simple tasks independently. A new end-effector was created that meets the range-of-motion required for the user to perform his/her required tasks. The end-effector is comprised of a PVC cap, PVC coupling, wooden ball holding the tool, and two wooden stop rings. The device screws onto the forearm PVC pipe and locks into place. Four end-effectors were created: toothbrush, fork, spoon, and pen. A change-out station was created to allow the user to independently attach and detach the different end-effectors. The total cost of the device was $20.66.**

Index Terms – upper-limb, prosthesis, end-effector, affordable, underprivileged.

INTRODUCTION

In areas with limited resources, prostheses and orthoses can be hard to obtain, along with the services necessary to teach amputees how to use and maintain them properly. The number of individuals unable to acquire needed prostheses and orthoses in developing areas is calculated to be more than 29 million.[1] If persons needing prostheses and orthoses had access to them, it could add value to their lives by increasing their independence and allow for the possibility of employment.[2]

Users in developing countries need upper-limb prostheses to be affordable, durable, comfortable, and usually body-powered.[3] With new developments, the cost of prosthetics in developing areas ranges from $125-$1,875.[4] Although this is significantly lower than the cost of a prosthetic in the United States, which can range from $5,000-$15,000, it is large in comparison to the average $300 annual income for a family living in such areas.[5] Prosthetic devices need to withstand environmental conditions including extreme heat and dust while still maintaining full functionality, avoid slipping of the prosthetic socket, and remain comfortable to the user. In order to maintain a properly-fit socket, a prosthesis in underdeveloped areas would ideally be adjustable by the user to account for the low supply of technicians and prosthetists in such areas, which currently falls short by approximately 40,000 individuals.[6] Manufacturing of prosthetic devices for resource-limited environments is best completed using local materials and simple techniques, in order to make the device more affordable,[7] allow for ease of maintenance, and provide an income to those doing the construction.

Body-powered devices are the preferred type of prostheses in developing countries.[8] The most general form of body-powered prostheses is cable-actuated and includes different end-effectors that range from a simple hook to a cosmetic, more natural-looking hand.[9] The total cost of traditionally used cable-controlled upper limb elbow prosthesis is $1,500 ($3,400 converted to today's value).[10] One lower-cost body-powered prosthetic device that is cable-actuated is the Gloveless Endoskeletal Prosthetic hand. Instead of using a glove to cover the finger frame, it uses a foam that is more lightweight and allows for less force to be required to grasp.[11] The prosthetic hand consists of four fingers that are capable of full flexion and a passive thumb.[12] For a production run of 1,000 units, each Gloveless Endoskeletal Prosthetic hand costs around $50.[13] The Victoria Hand is a similar cable-actuated prosthetic device that costs approximately $320 per hand, but includes ball-and-socket wrist motion, flexion of four fingers, and a rotatable thumb.[14] The hand is 3D printed, which makes it a lightweight option for amputees.[15] A group from Arizona State University improved upon tradition body-powered upper limb prostheses by modifying the end-effector hook and eliminating a cable actuation system.[16] To make the prosthetic lightweight, they constructed it out of PVC piping which also reduced the cost to a total of approximately $34.[17] With the modifications, a user is capable of performing activities of daily living, but with complaints of the socket being uncomfortable.[18]

Even with the advancement of prosthetic technology, there are still limitations with the previous devices in developing countries. Downfalls include the requirement that the amputee travel to a specialist, and the devices are not always made from materials that can be found locally. The body-powered upper-limb prosthetic designed by the group at Arizona State University meets the most requirements of a prosthesis for a developing country, but still needs improvement with the comfort of the device and the ability to manufacture it in resource-limited areas.[19] Our design works towards a device that incorporates all of the necessities in a prosthesis in a developing country including affordability, durability, lightweight, capable of performing activities of daily living, and locally manufactured using simple techniques with materials that are readily available.

Previous design groups at St. Ambrose University have worked to develop different phases of the device. The first phase included the design and testing of the socket.[20] The socket is woven from a material local to Brazil called Piacava, which is a renewable resource made from the bark of a tree, and regularly used by artisans to make products. Nearly all developing areas have similar woven products that could be used for this component of the device. An open-frame design allows breathability and Velcro allows the user to easily adjust the frame for a comfortable fit. The socket is held secure to the user with a harness from a body-powered prosthetic arm.

The second phase developed an elbow from PVC and an end effector utilizing interchangeable devices secured by a racquetball. The original sleeve design[21] was modified such that the woven components are glued to the inside of a 4" to 2" PVC reduction coupler (Figure 1A). The new sleeve connected to a 2" PVC pipe to simulate the upper arm. A slot was cut through the pipe as well as a 2.25" PVC pipe (forearm), and the two were connected with a nut

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and bolt to create a bendable elbow (Figure 1C and D). The curvature of the PVC created a lock where the two slotted pipes met that secured the elbow at either fully open (180 degrees-Figure 1D) or fully bent (approximately 60 degrees-Figure 1C). A second slot was cut into the end of the forearm pipe to allow the insertion of a racquetball (Figure 1E). Several tools were constructed (toothbrush, fork, pen) by inserting them into different racquetballs. A stand that allowed the user to change the end effector by themselves was also constructed (Figure 1G). The final prosthesis can be seen in Figure 1B.

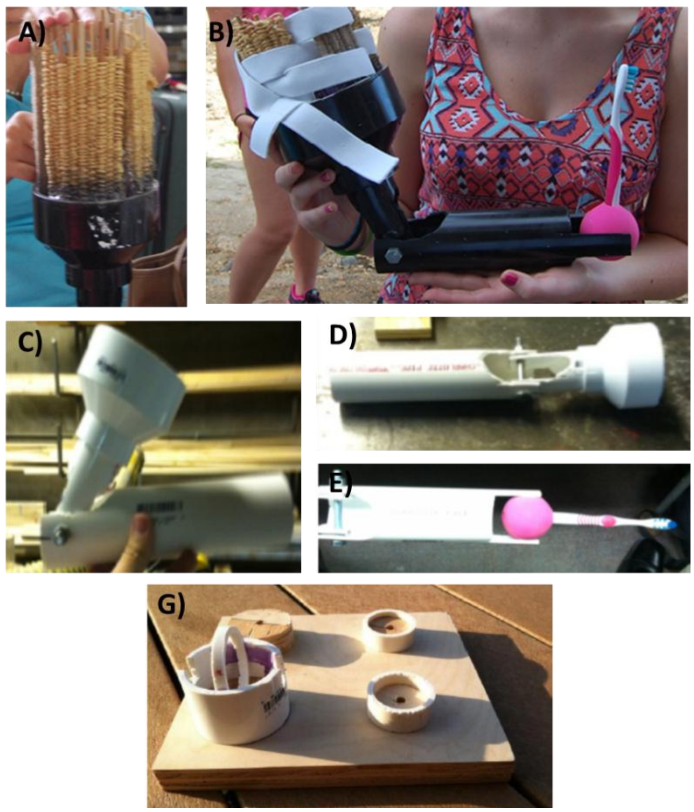

FIGURE 1
PREVIOUS DESIGN FOR AFFORDABLE UPPER LIMB PROSTHESIS

This design was tested with the user and feedback was obtained for the finalized improved design. The user was fitted with the prosthesis by adjusting the woven component with scissors and securing it to the user with straps from a body-powered prosthesis (Figure 2A and B). The end-effector functionality was tested as well as the change-out apparatus (Figure 2C and D). The user commended the fit, comfort, and weight of the device. While he could use the toothbrush to some extent, he had difficulty applying pressure to it without it moving out of place. The change-out apparatus was also not user-friendly and was too difficult to use. The focus of the next phase of the design was on improving the end-effector and change-out system.

FIGURE 2
USER TESTING OF PREVIOUS DESIGN FOR AFFORDABLE UPPER LIMB PROSTHESIS

PROBLEM DEFINITION

The primary user of the prosthesis was identified as the amputee; beneficiaries include the extended families as well as people and community involved with the manufacturing process. The goal of the device is to allow the user to regain independence, thus reducing the strain on caretakers. This will increase the overall quality of life for both the user and their family members. Those involved with the manufacturing of the device will gain financially and the entire community will benefit economically.

Specifications for the device (Table 1) were developed by communicating directly with a quadruple amputee in an impoverished area of Northeast Brazil who has been the recipient of both a modern body-powered device typical of that found in the US as well as preliminary prototypes of the current design.

TABLE I
DEVICE SPECIFICATIONS

Requirement	Specification
Cost effective	Less than $50.00
Withstand humidity	100% humidity
Cleanable	Can be cleaned easily using household products
Low maintenance	Every 8 to 12 months
Long life	Greater than 10 years
Lightweight	Less than 2 pounds
Elbow joint adjustable and moveable	140° range of motion minimum
Hold objects without slipping	Objects up to 5 pounds
Independently controlled	No outside help for changing end-effector or device once it is properly attached to the user.
Perform simple tasks	• Brush teeth • Eat • Pick up a cup and drink from it • Wipe face • Write name • Play video games

DETAILED DESIGN

The final design for the affordable upper-limb prosthesis utilizes the upper arm and elbow from previous designers (Figure 3, balloon 1) and an improved end-effector and change-out station. The end-effector is comprised of a PVC cap with the rounded end removed (Figure 3A, balloon 2), a PVC coupling (3), a wooden ball holding the tool (4), and two wooden circular stop pieces that hold the wooden ball in place (5). The end-effector screws onto the forearm PVC pipe using the wooden pegs extending from the pipe (6).

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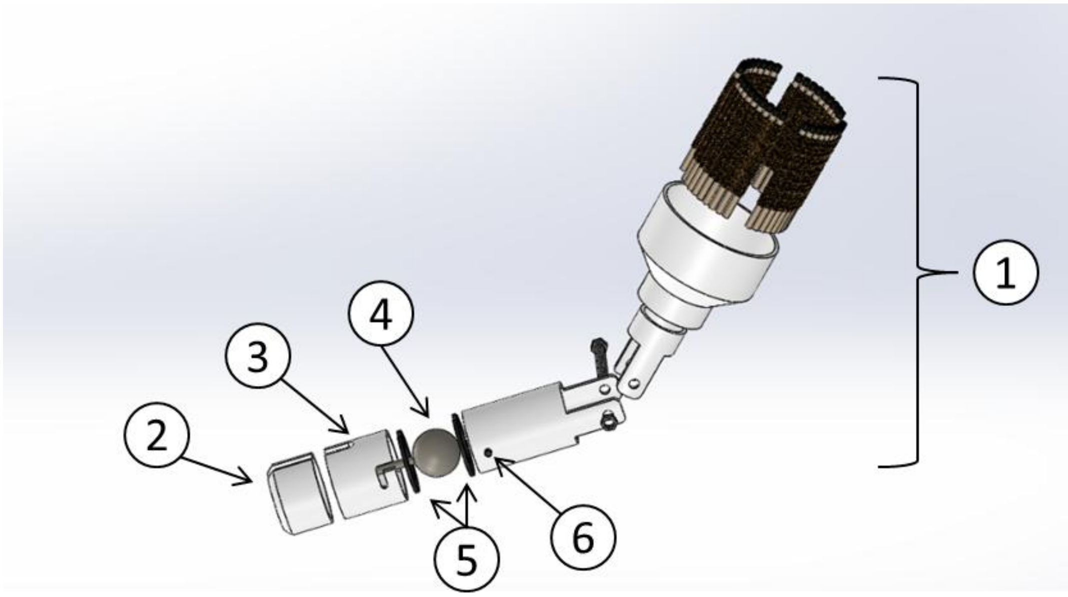

FIGURE 3
EXPLODED VIEW OF ENTIRE PROSTHESIS, INCLUDING NEW END-EFFECTOR DESIGN CONNECTED TO UPPER-ARM DESIGN

The end-effector (Figure 4) incorporates the rotational motion of the original racquetball design but improves upon the design by making it more secure. A wooden ball holding the tool is enclosed within the end-effector and has 30° rotational motion in all directions extending directly from the forearm. It can also be secured in a specific location for easier use via the slit along the side of the PVC cap and coupling (Figure 4A). The tools incorporated into the final device were a toothbrush, spoon, fork, and pen (Figure 4B-E). Each tool was analyzed independently to determine if a slit was needed and at what angle. It was decided to not use a slit in the end-effector for the toothbrush, but instead the toothbrush was modified to have two angled heads in order to make it easier for the user to brush more of his/her teeth (Figure 4B). The fork and spoon required slits in order to have the utensil point directly at the user to allow him/her to put food in his/her mouth (Figure 4C-D). The pen end-effector also has a slit since every person writes in a different way (Figure 4E).

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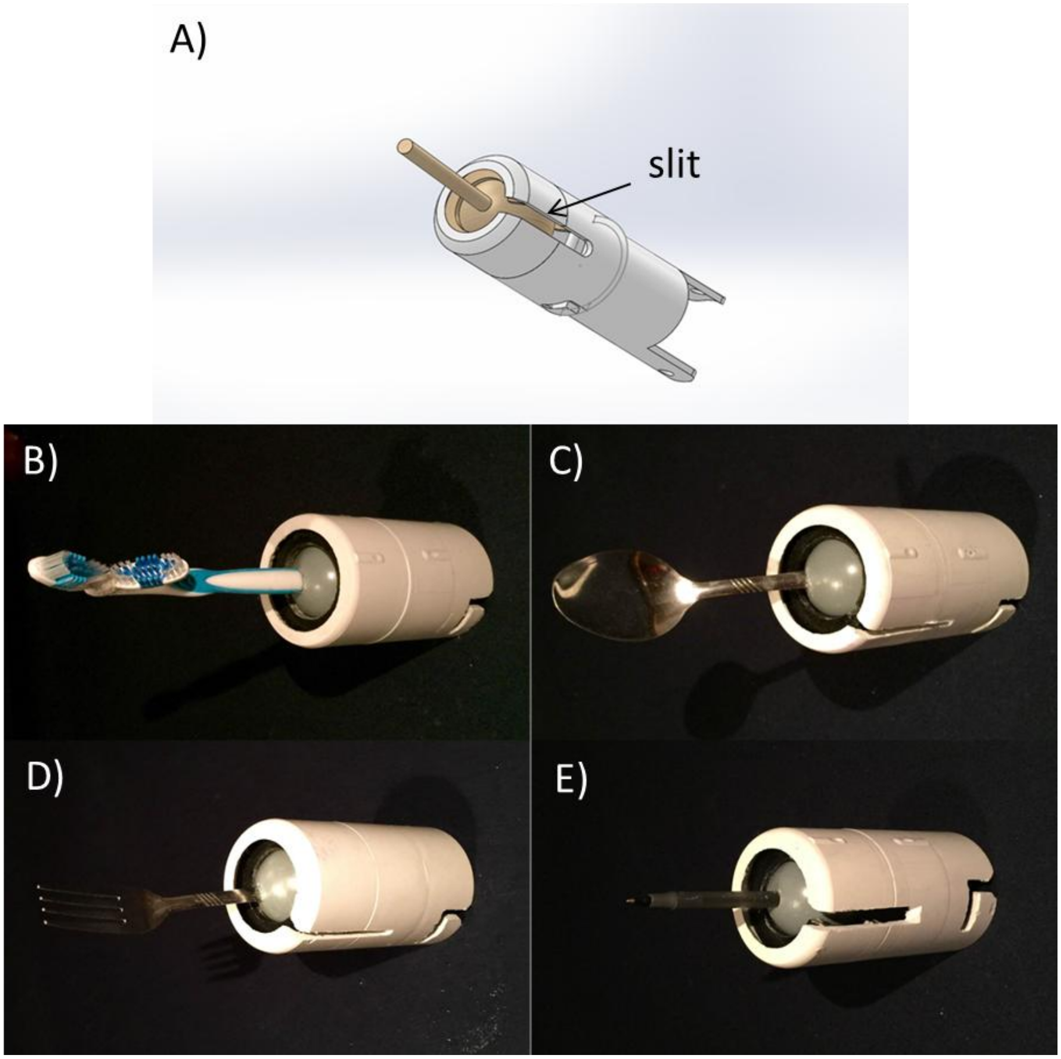

FIGURE 4
END-EFFECTORS FOR THE FINAL DEVICE

The new design also allows the user to easily change the end-effector independently. A device was needed that allowed the user to attach and detach the different end-effectors without assistance. A change-out station, shown in Figure 6, was created to solve this problem. The change-out station is secured along the edge of a table utilizing a slot at the bottom of the device (Figure 6B, balloon 1). Each of the four end-effectors is contained within their own compartment in the station (2). The tool is positioned directly out from the forearm when entering or exiting the station. A triangularly-shaped protrusion (3) on the change-out station serves to translate linear motion of the arm (upward) to rotational motion of the connector by contacting a tab on the end-effector (4).

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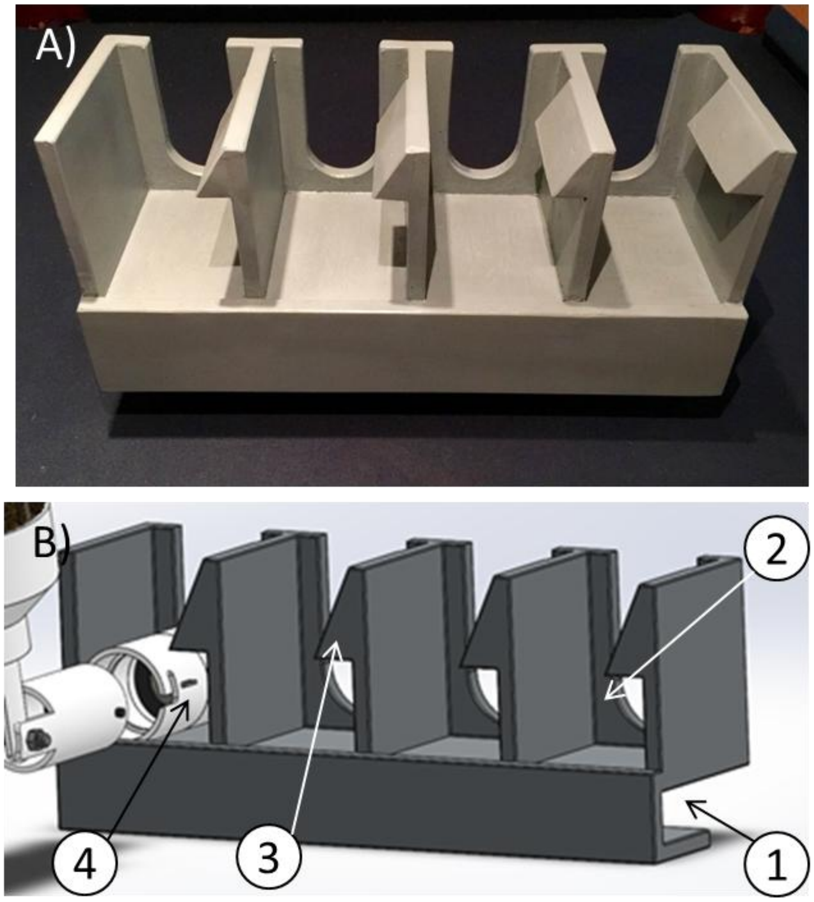

FIGURE 6
CHANGE-OUT STATION FOR END-EFFECTORS

The goal of the change-out station is to translate the twisting motion needed to screw on or off an end-effector into a linear motion that can be accomplished by the user. In order to secure a tool, the user inserts the PVC forearm into the selected end-effector (Figure 7A). To fully secure the end-effector onto the forearm, the user must move the arm upward, which allows the tab on the end-effector to hit the triangular-shaped protrusion (Figure 7B). By continuing to move the end-effector upward (Figure 7C), the wooden dowel moves into the locking mechanism, fully securing the end-effector for use (Figure 7D). To remove the current end-effector, the user must push the arm back down into the compartment, which will unscrew the connector from the forearm. To fully remove the end-effector, a lip restrains the end-effector when the user pulls the forearm from the station.

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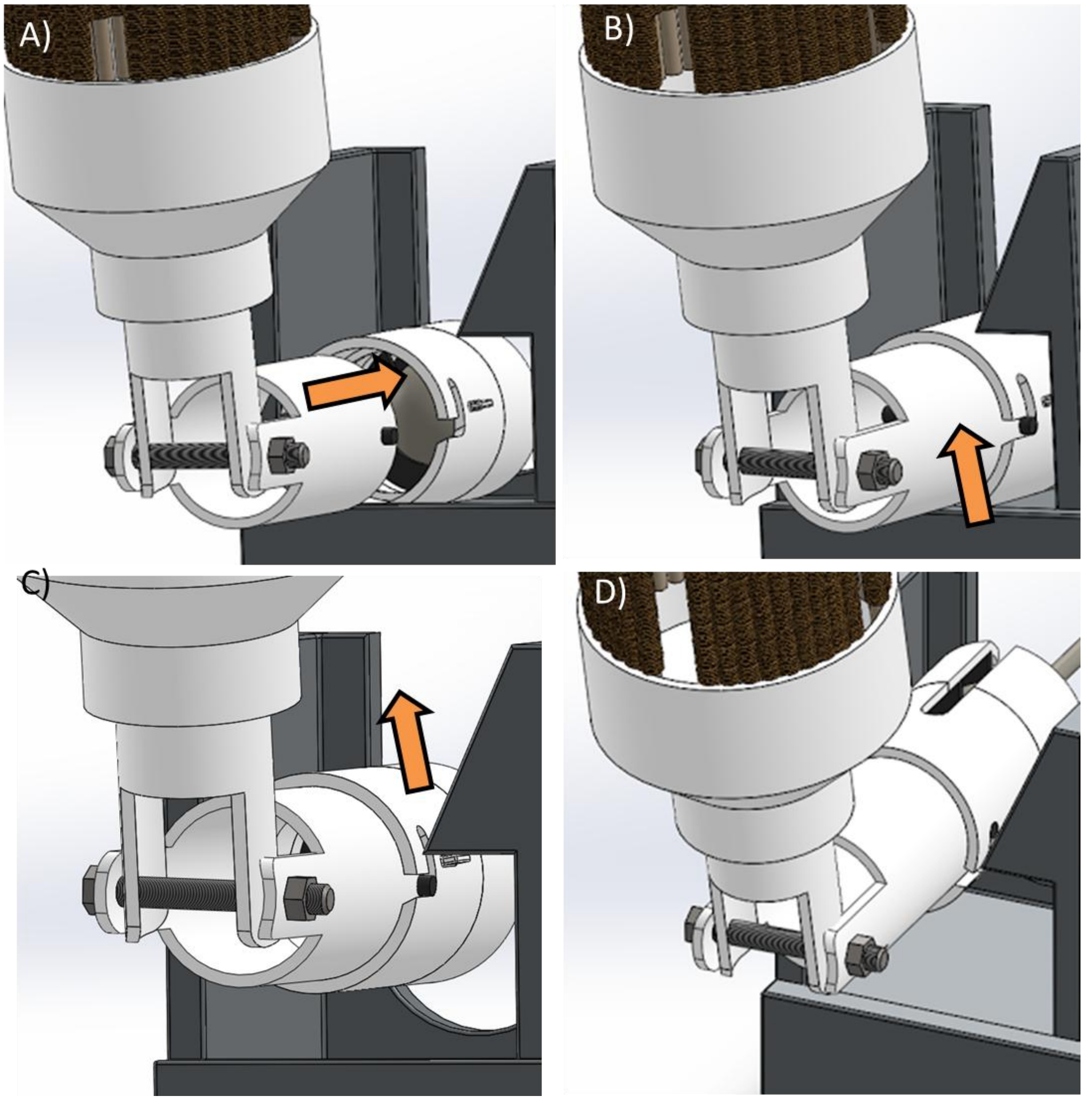

FIGURE 7
HOW TO UTILIZE CHANGE-OUT STATION TO ATTACH END-EFFECTOR

DESIGN ANALYSIS

Cost Analysis

A primary requirement for the prosthetic arm was to cost less than $50.00. The cost breakdown for the end-effectors and forearm are shown in Table 2. The total cost for one end-effector ranges based on the cost of the tool utilized. Many of the supplies—the wooden dowel, PVC pipe, plywood, PVC glue, and hot glue sticks—are used to make all four end-effectors. The cost breakdown does not include the remaining supplies needed to create the upper arm and connect it to the forearm. The price of creating all four end-effectors was $20.66.

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TABLE II
COST BREAKDOWN

Material/Supply	Cost ($)	Individual end-effector	Full set of end-effectors (4)
Wooden dowel rod (3' x 1/4")	0.89	0.08	$0.32
Wooden Ball 6 pack (1.75" diameter)	3.99	0.67	$2.68
2" PVC pipe coupling (slip to slip)	0.97	0.97	$3.88
2" PVC pipe cap (slip)	1.36	1.36	$5.44
Plywood (1/4" x 4' x 8')	19.99	0.08	$0.32
PVC glue (8 oz.)	6.48	0.07	$0.28
Hot glue sticks (25 pack)	2.85	0.12	$0.48
Toothbrush	2.00		
Spoon	2.50		
Fork	2.50		
Pen	0.26		
	Total:	**$3.61-$5.85**	**$20.66**

Failure Mode Analysis

Potential failures and their corresponding effects on the design are listed in Table 3. A risk priority number is listed for each potential failure based on severity, the frequency of it occurring, and the possibility of detecting the failure before it actually occurs.

The risk that has the highest priority for the current design is the possibility of the end-effector snapping off due to too much weight on the tool. However, the tool would likely break before the end-effector snapped off. To address this risk, users should be informed of weight restrictions prior to use. The tool should also be of a higher-quality material to handle weight to prevent failure.

Another risk that has a high priority is the locking mechanism loosening or breaking. This failure would cause the end-effector to detach from the forearm and prevent customer use. To minimize this risk, a usability test will be designed and implemented.

TABLE III

DESIGN FOR FAILURE MODE AND EFFECT ANALYSIS. SCALE FOR SEVERITY IS 10-EXTREMELY SEVERE *(1-NOT SEVERE; FOR OCCURRENCE IS 10-FREQUENT 1-INFREQUENT; AND FOR DETECTION 10-FREQUENT 1-INFREQUENT. RPN IS "RISK PRIORITY NUMBER.")*

Failure Mode	Effect of Failure	Severity	Occurrence	Detection	RPN
End-effector could snap off because of too much weight on the tool.	Due to increased weight, if the end-effector snaps off there will most likely be damage to the locking mechanism and the end-effector might not be able to stay on the forearm after that.	9	5	6	270
Locking mechanism could loosen or break.	The end-effector might not be able to go onto the forearm at all. If the locking mechanism loosens, the end-effector might go onto the forearm but slide off.	8	4	7	224
Stop ring inside could break from too much weight.	The ball would not have the restricted movement necessary to perform all operations.	6	5	5	150
PVC coupling and cap could separate.	Upon separation, there would be nothing holding the ball and tool to the forearm.	7	3	7	147
Ball joint could become too loose or too tight.	If the ball joint is too loose, the tool might not be able to be held in the proper place for use. If the ball joint becomes too tight, the tool might not be able to be rotated at all.	5	7	3	105
The tool could break.	The end-effector containing that tool could not be utilized for the appropriate actions.	6	5	3	90

CONCLUSION

The engineering design process was used to solve the problem of a user needing a more independently functioning and cost-effective end-effector on an upper limb prosthetic. In the end, four end-effectors were created that will allow the user to eat, brush his/her teeth, and write his/her name at a total cost of less than $21. To allow the user to change them out independently, a change-out station was also created. The development of additional end-effectors could increase the functionality for the customer, such as providing a device to allow the user to wipe his/her face, holding a cup for a drink, and playing video games. The next step is to have actual users test the device in real-life settings to determine its feasibility and accuracy involving the new change-out method.

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