Bamboo Crutch Design for Developing Communities in Zambia

Research, Ideation, and Design

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Abstract

The purpose of this project is to develop a crutch that can be built from local materials in Zambia and manufactured with basic hand tools. According to a joint paper by U.S. Aid and The World Health Organization, "providing adequate funding and improving affordability" should be among the primary strategies for improving accessibility to mobility aids in lesser resourced areas. By working with Non-Governmental Organizations (NGOs) that currently distribute aluminum crutches in Zambia, I have researched and identified the unique needs of mobility aid users in the region. The proposed design, consisting of primarily bamboo, directly addresses these needs, and costs less to manufacture and distribute than a traditional aluminum crutch. This report presents the user research performed for the Solwezi District of Zambia and the design objectives for the project. It presents the justification of the material selection used in the crutch and design heuristics based on these unique properties. Lastly, I present the ideation phases, which is split up into modular components and culminates with the final crutch design. The intent is that the implementation of the proposed design will allow NGOs that work in mobility aid distribution to better satisfy the demand for crutches in Zambia.

Introduction

This report identifies the status of mobility aid distribution in Zambia as a design opportunity. There exist a staggering proportion of disabled Zambians that lack access to a mobility aid: barriers to access being both economic and geographic. Current efforts by Non Governmental Organizations (NGOs) to collect and distribute aluminum crutches, though admirable, are not sufficient to satisfy the demand. I present the concept of a locally manufactured crutch which has the potential to improve mobility aid access in rural regions of Zambia. This concept is further developed as a set of clear design requirements upon which the success of the crutch is based (table 1). Local manufacturing allows for the reduction of cost and elimination of the need for shipping, both of which will improve accessibility. I present my research of local materials and conclude that bamboo is most suitable for the crutch design based on cost and structural properties. The material properties of bamboo largely dictate the types of structures that can be built. These properties are thus developed into a set of building heuristics, used to guide the designer throughout ideation. Ideation and concept selection are broken down into modules (joint design, tip design, hole design) and end with presenting the final crutch design.

Design Research

Needs assessment

It is difficult to estimate the precise number of people in Zambia that require a mobility aid, mostly due to a lack of accurate census information. According to a 2006 survey on Zambians with activity limitations, 11.0% of the 28,189 Zambians surveyed reported having a physical disability [1]. Another survey conducted by the World Health Organization (WHO) in 69 countries found that 18.6% of adults over the age of 18 report most often having moderate, severe or extreme difficulty related to moving around [2]. As the current population of Zambia is estimated at 15.72 million, I estimate the total number of Zambians that require a mobility aid to be between 1.7 and 2.9 million [3]. Crutches4Africa and the Charity Center for Children of Zambia, two NGOs with which we've partnered, have been focusing primarily on the need for crutches in the Solwezi District. Based on an estimated population of 203,797, the number of physically disabled persons in the Solwezi District is likely around 20,000 [4]. Approximately 85.2% of surveyed Zambians that desired an assistive technology did not have access to one, equating to roughly 17,000 disabled persons in the Solwezi District [1].

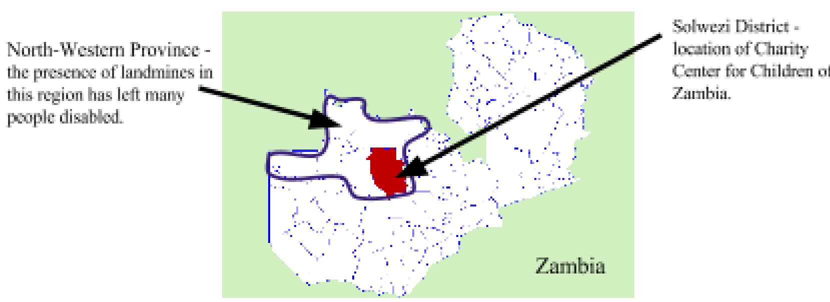


Figure 1: Crutches4Africa and The Charity Center for Children of Zambia have distributed over 3,000 mobility aids in the Solwezi District. The residual effects of Polio and landmines, in the North-Western Province especially, have left thousands of Zambians with permanent physical disabilities.

There are many causes of physical disability in Zambia. Diseases such as Polio and the prevalence of landmines in the North-Western province are two large causes of permanent disability [5]. Temporary injuries such as joint sprains and bone fractures are also common, and often warrant the use of crutches. Crutches4Africa has already distributed 3,000 mobility devices in the Solwezi District, with plans to distribute more in the near future.

Current designs

There are currently two main categories of crutch designs that exist in Zambia: traditional aluminum crutches, and locally crafted crutches built out of local materials. This section explores the various advantages and disadvantages associated with each design.

Aluminum underarm crutch: The aluminum crutches commonly used in the United States make up the bulk of the current distribution to Zambia. They consist of two, ¾" aluminum hollow extrusions that join at the bottom (Figure 2). These crutches are adjustable in the overall height, as well as the height of the handle, allowing them to be fit to any body size. Currently, the retail price of a pair of aluminum crutches is typically around $20 - $40 USD [6].

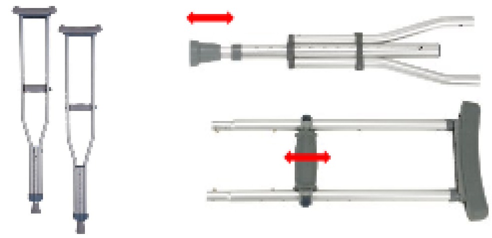


Figure 2: Traditional aluminum crutches are lightweight compared to crutches made from other materials. These crutches last a long time and are adjustable in handle height and overall height, allowing them to be used by more than one person.

The aluminum crutch is advantageous for a number of reasons. Aluminum has a high strength to weight ratio, making the crutches light and easy to use. While the tip and pads tend to wear down after a few years of use, lifespan of the aluminum frame typically extends well beyond its expected use. Lastly, an adjustable design means that the aluminum crutch can be transferred from person to person and resized.

Crutches built from local materials: In many developing nations, aluminum crutches are not accessible, due to economic reasons, geographic reasons, or both [7]. In these scenarios, disabled persons are forced to use the resources that are available to achieve mobility. Throughout their work in Sub-saharan Africa, Crutches4Africa has come across several locally built mobility aids.

Figure 3:When aluminum crutches are not accessible, local resources can be used to construct a mobility aid: (Left) a man using a long cane to "row" his disabled leg while walking, (Center) homemade crutches built from milled softwood, nails, and cloth, (Right) crutches constructed from tree branches and nails [7].

There are some advantages to building mobility aids from local materials. The cost to construct one of these devices is often very low, since many of the required materials occur naturally and can be acquired at little to no cost. They are often assembled using hand tools only, eliminating the need for electricity. There is no shipping cost because the crutches are made locally, and they are typically built from sustainable, renewable materials. Without any engineering analysis however, the structural integrity and lifespan of these devices is impossible to guarantee. Although homemade mobility devices are rarely adjustable, their low material costs may make a build-to-fit model economically feasible.

User personas

Two personas were created to help understand the NGOs' perspective and end user of the product. These personas reflect the needs and emotional response to the product.

Jacob Banji (NGO founder): Jacob is from an upper middle class family in Zambia and has earned his business degree in the United Kingdom. He has founded an NGO that focuses on a specific region to help those less fortunate than him. He has found partners in the U.S.A. and other countries that can distribute supplies to his organization. He has made a significant impact in his community but is always is looking to improve his organization. One area that could be improved is crutch distribution. He has partners in more developed countries that bring donated aluminum crutches but some parts of the crutch wear out too fast and there are too few crutches being distributed. In addition, there are local options that he observes people using but they do not last long and promote poor posture. His goal to be able to meet the demand for mobility aids in his community. In addition, he is wary of voluntourism and will only want to talk to people that are have a legitimate product and implementation plan, and are committed to completing the project.

Figure 4: Jacob Banji

Figure 5: Kenny Mutinta

Kenny Mutinta (end user): Kenny Mutinta is part of a lower middle class family in a small village in Zambia. He is a farmer and makes just enough money to sustain a modest lifestyle. Recently, he lost his left leg and had to quit farming. He has been able to get by with his wife working more. He would like to start working again but can't due to his disability. He currently has a crude pair of homemade crutches that are very uncomfortable to use and break often. Kenny uses there crutches because he can not afford a better crutch because of the low availability and high cost. He hopes to receive an aluminum crutch from the local NGO but those shipments do not come often and receiving them is a lottery system. In addition, he does not feel comfortable begging for a crutch and fears his neighbors would make fun of him if he did. Although aluminum crutches are considered the best option, Kenny does not have the time to wait for them. His wife is strained from working and money is getting tighter. He needs a mobility aid that can allow him to start working odd jobs without feeling uncomfortable and breaking.

Design requirements

After identifying a significant need for crutches in the Solwezi District, I compared and contrasted the current available crutch designs based on their accessibility and expected lifetime (Figure 6).

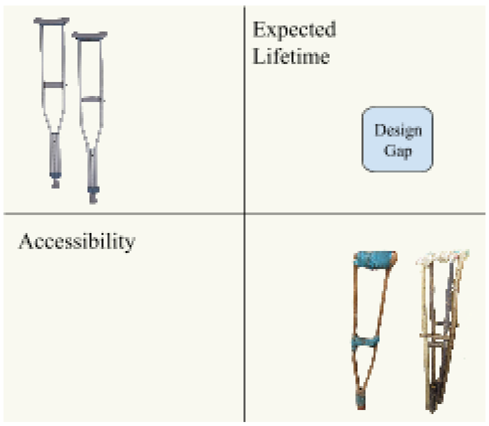


Figure 6: The product positioning chart showing existing crutches in the Solwezi District of Zambia. A design gap exists for a crutch that is as accessible as existing homemade crutches but with an expected lifetime closer to that of an aluminum crutch.

Traditional aluminum crutches are highly durable and often outlast the need of the user; however, their high retail and shipping costs make them inaccessible to many people in the Solwezi District. The homemade crutches built from local materials are the most accessible since material cost is low and shipping is not required. These crutches have a far lower expected lifetime due to their lack of standardized manufacturing plan or quality control. There exists a design opportunity to create a crutch that is as accessible as an existing homemade crutch with a longer life expectancy. Based on the above research, I have translated this design opportunity into the following requirements, which are critical to the success of the project (Table 1).

Table 1: Any design concept generated must fulfill these requirements.

Design Requirements:	Verification Method:
Support dynamic loading from a 160 lbs person [10]	Static load test
Last the user at least one year	Cyclic loading test*
Built from materials available in Solwezi District [5]	Material research, ethnography
Built using only hand tools	Prototype, manufacturing plan (Appendix. A)
Fabrication and distribution cost 10% of aluminum crutches	Price estimates from CCZ interviews [5]
Fabrication time less than 3 man hours	Follow manufacturing plan, time with stopwatch

*Cyclic loading tests has yet to be designed or performed

Material selection

Since the final crutch design should be able to be built with only hand tools, I immediately eliminated materials that required electricity to manipulate. This essentially left three main options for material choice: soft wood, hard wood and bamboo. Hard wood was excluded because of its high cost. This left softwood, such as pine, or bamboo. The cost of pine wood is approximated $2 per meter of plywood vs. $0.30 per meter for bamboo[5]. Another criteria for selection was the strength of the material. Bamboo has a tensile strength that's 3 times greater than pine and a similar compressive strength [8]. Finally, the last consideration that was made when selecting material was the ease of getting the material. Bamboo has the advantage that it can be grown very quickly in comparison to lumber. If the project were to grow large enough bamboo has the advantage of being able to be grown onsite.

Lashing bamboo together requires a form of rope or other fibrous material. In Zambia, some regions have access to basic hardware stores which carry twine. Alternatively, bamboo can be hammered into a thin, fibrous material (known as Fesho) and twisted together to form rope. It should be noted that many different kinds of lashing material can be used in the proposed design without a significant effect on the strength of the final product. Other materials of interest that were found to be in abundance in the Solwezi District include, bike tires, car tires, nails, wire, and plastic bags.

Bamboo material properties

Bamboo has a unique set of material properties which must be considered when designing structures. Bamboo is a natural composite consisting of cellulose fibers and a lignin matrix [9]. Like other composites, bamboo is highly orthotropic, meaning that its material properties vary in different directions. The concentration of fibers in bamboo is a function of radius, with the outer wall being far more fibrous than the inner wall. Materials whose properties vary spatially are known as functionally graded materials (FGMs) and are difficult to model computationally.

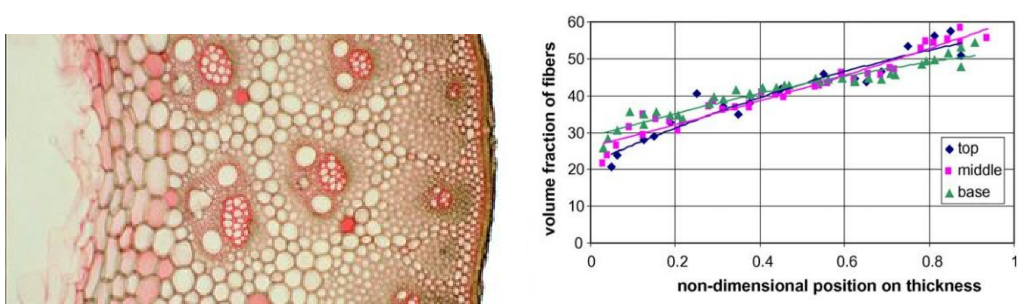


Figure 7: Bamboo is a functionally graded composite, featuring a higher concentration of fibers closer to the outer wall. (Left) a magnified cross section of bamboo demonstrating a higher concentration of lignin at the inner wall and a higher concentration of fiber at the outer wall. (Right) The volume fraction of fibers in a bamboo cross section as function of nondimensionalized thickness [9].

Another important bamboo property to consider when designing structures is the direction of the grain. Figure 8 shows that the direction of the fibers in the hollow culm (the region between two nodes) is homogeneous, whereas the direction of fibers in the solid nodes are highly variable.

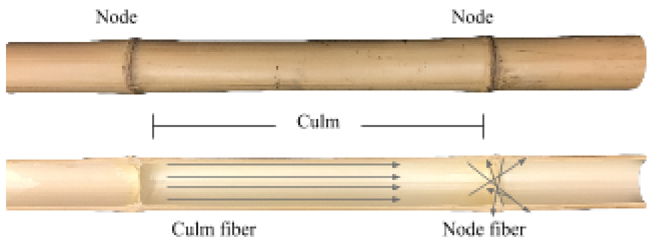


Figure 8: The direction of fibers is uniform in the culm and highly non-uniform in the node. This brings about important design considerations when working with bamboo.

Based on the above material properties, I have developed four design heuristics that should result in successful bamboo structure designs (Table 2). These heuristics are a useful design tool because they allow for the quick elimination of design concepts that put undesirable loads on the bamboo.

Table 2: These design heuristics are based on the unique material properties of bamboo, and were developed to aid in the ideation process.

Bamboo Design Heuristic	**Justification**
1. Load bamboo parallel to the grain	Compressive/tensile strength highest in the direction of grain
2. Position nodes to support radial loading	Varying grain direction makes nodes strong in radial direction
3. Avoid load-bearing lashings	Bamboo is stronger than lashing in tension and compression
4. Lash on either side of holes	Stress concentrations reduced, lashing acts as a boss

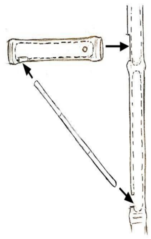
These heuristics are meant to be simple guidelines to help the designer during ideation. They are not meant as strict requirements and will sometimes be violated. For example, lashings will likely experience at least some loads during normal use, but those loads should be minimized.

Ideation and concept selection

Joint design

One of the most important design choices in this project is joint connection. Simple calculations with axial loads show that a segment of bamboo of 1 inch diameter is strong enough to hold 3 times the weight of a person before breaking. For this reason the joints are likely to dictate the structural integrity of the crutch. There is a long history in and ample documentation of methods of connecting bamboo sections. Most of these connecting methods pertain to the construction of static structures such as scaffolding and buildings. A crutch experiences cyclical loading subject to a number of possible loading cases. Due to all of this I investigated methods of connecting bamboo that would endure a person's static and cyclic loads during use.

Examples of proposed designs and their evaluation can be found in appendix A. The final joint design addresses all of the bamboo design heuristics (table 2) and requirements (table 1). The style of lashing is called a drilled lashing. The hole can be created using a knife and hand saw [12].



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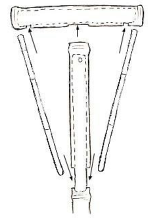

(10)

(11)

Figures 9, 10, 11: A few joint designs that were prototyped during the ideation phase. (9) This joint uses a thin bamboo reed as a truss for the handle. (10) This joint uses two bamboo reeds as trusses and is meant to support the underarm. (11) A simple whipping knot is used to lash joints at a right angle.

Modifications were made to the knot over time. In a traditional drilled lashing joint, the nodes of the two pieces of bamboo rest on each other to help prevent the joint from slipping down. Notches were added to both nodes to allow for greater contact area between the pieces. These flat surfaces allow the bamboo to support some of the load directly (table 2, heuristic 3). They also help eliminate play in the joint. One of the advantages of this connection is that the bamboo piece is not embedded in the other piece. Such an attachment greatly increased crack propagation because the bamboo would have to constrain a moment.

To strengthen the joint design, a bamboo reed is added as a truss for supporting and distributing the load. Since bamboo is strongest in tension, the truss structure is a good candidate for handle load support (table 2, heuristic 1) (figures 9).

Tip design

A new design for the tip was needed because current crutch tips wear out too fast in conditions in Zambia. In additionally, a crutch tip is necessary to prevent water damage inside the bamboo. The goal for the crutch tip is to design a tip that can provided floor grip, mechanical damping, and water protection for the crutch.

From the design ethnography it was discovered that crutch tips were being carved from used mining tires [7] (Figure 12). This tip design works well, but requires access to solid rubber tires, which are not common. This project focused on using rubber that is more accessible, such as the rubber from spent bike tires (figure 13).

(12) (13)

Figures 12 & 13: Alternative crutch tip designs. (12) a man carves a crutch tip from a solid rubber tire. These tires are only used on specialized vehicles, such as those used in mining. (13) A tip developed for this project, consisting of a spent bike tire and twine lashing.

To fasten the rubber onto the bamboo, the rubber is wrapped around the bamboo and lashed in place. The bike tire crutch tip was found to provide a similar damping sensation to the user as a traditional crutch tip. The new tip also provided a similar amount of traction. This design could likely be improved further by using plastic bags under the tire to protect the bamboo from moisture.

Hole design

Most forms of joints involve creating holes in the bamboo. An important consideration in this project is the tolerances associated with hand tool construction. In certain bamboo joints, tightly toleranced holes are needed to ensure a sturdy fit. In order to create these holes, the craftsmen would need to use hand drills which they will not necessarily have access to. Wherever holes were used in the crutch I made sure that the design could handle holes carved out of the bamboo using a knife. This meant taking into consideration the shape of carved holes as well as the tolerances available while using a knife. Another consideration was the effect of the holes on crack propagation through the bamboo. Crack propagation is affected by the stress intensity factor at the tip of a crack. The application of this principle means that internal corners in the square hole should be rounded off to hinder crack growth (table 2, heuristic 4).

Early design concepts

Based on early stage joint prototyping and experimentation with bamboo, several design concepts were generated (figure 14). Each design are analyzed based on design heuristics (table 2).

Design 1: Split Bamboo Crutch (Benchmark)

The Split Bamboo Crutch Design is considered the benchmark because an NGO partner reported that a local hospital in Kenya has been manufacturing this kind of crutch. A single shaft of bamboo can be partially split in half, where the end of the split is lashed tightly to prevent crack propagation. The under arm bamboo piece has two slots that can hold each side of the split bamboo. The handle bamboo can be lashed between the split bamboo shaft. This design loads bamboo parallel to the grain in the main shaft of the bamboo and utilized the strength of the node in the radial direction (table 2, heuristics 1, 2). However, the loading on the handle required loading on lashing (table 2, heuristic 3), which is unsafe to use. The tension of split bamboo gives the advantage of holding the handle in place, but also creates a safety hazard by introducing the possibility of snapping the user's hand if the handle falls apart.

Design 2: Bent Bamboo Crutch

The Bent Bamboo Crutch Design is inspired by current forearm crutches on the market. Fresh bamboo can be bent by heat treating it at about 110 degree Celsius, and the shaft will be dried for longer preservation. The handle bamboo is placed in the main shaft through drilled holes and lashed. This design satisfied the design heuristics (table 1). However, it's difficult to get fresh bamboo in the U.S. and so I was unable to prototype this design.

Design 3: T-Junction Single Shaft Crutch

The T-Junction Single Shaft Design consists mainly of T-junctions and is meant to simplify the manufacturing process. The main shaft is placed in the underarm bamboo rest through drilled holes and lashed. The handle bamboo is placed in the main shaft through drilled holes and lashed. This design utilized the strength of the node (table 2, heuristic 2). Loading on the handle creates a large moment on the connecting section with the main shaft which is structurally undesirable. This design could be improved with a truss, which transfers most of this load into pure compression (table 2, heuristic 1).

Design 4: Three-Shaft Crutch

The Three-Shaft Design is intended to relieve the bending moment applied by the handle on the supporting shaft. A bottom supporting shaft is directly supporting the handle on the ground to allow loading bamboo parallel to the grain of the bamboo (table 2, heuristic 1). The handle is carved to place on the top of the bottom supporting shaft, and lashed for constraint (table 2, heuristic 3). The sides of the handle are placed in the side shafts through drilled holes and lashed, which still may create a moment at connecting section of the main shafts (table 2, heuristic 1). The handle of this design raises questions as to whether it is ergonomically favorable, and the manufacturing steps need to be simplified.

Design 5: Four-Shaft Crutch

The Three-Shaft Design is intended to to avoid drilling in any supporting shaft that would experience a bending moment (table 1, heuristic 1). The handle bamboo is placed on two bottom supporting shafts and lashed tightly. The bottom supporting shafts are placed in a replaceable wood block. The two upper support shafts are placed in the underarm bamboo through drilled holes, where the upper support shaft experiences tensile loading (table 1, heuristic 1), and each of the upper supporting shaft's bottom part is lashed to the upper part of bottom supporting shaft (table 1, heuristic 3). The manufacturing steps of this design needs to be simplified for ease of manufacturing.

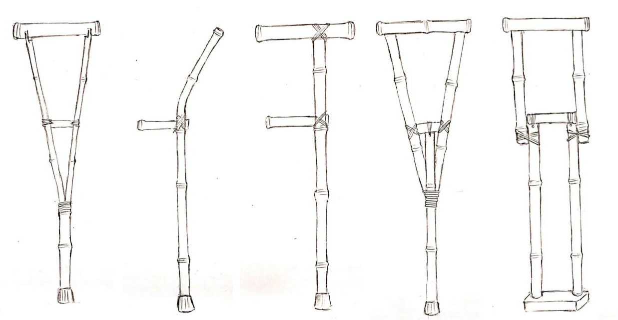

Figure 14: From left to right: Design 1 (Split Bamboo Crutch), Design 2 (Bent Bamb Crutch), Design 3 (T-Junction Single Shaft Crutch), Design 4 (Three-Shaft Crutch), and Design 5 (Four-Shaft Crutch).

Final crutch design

Through analyzing the earlier design concepts through design heuristics (table 1) and integrating different joint and tip designs, the final design is decided and shown in the following figure 15. The final design originated from one of the earlier concepts Design 3 (T-junction crutch) due to its simplicity to manufacture and the handle design part of Design 4 (Three-Shaft Crutch) for avoiding a bending moment in the supporting shaft . The final design implemented joint designs and truss support at the underarm and handle to support the necessary loading and bending moment. The tip design is integrated for protecting the bamboo shaft. Based on estimates from the materials research in the Solwezi District, the total material cost of the crutch is less than one U.S. dollar [5].

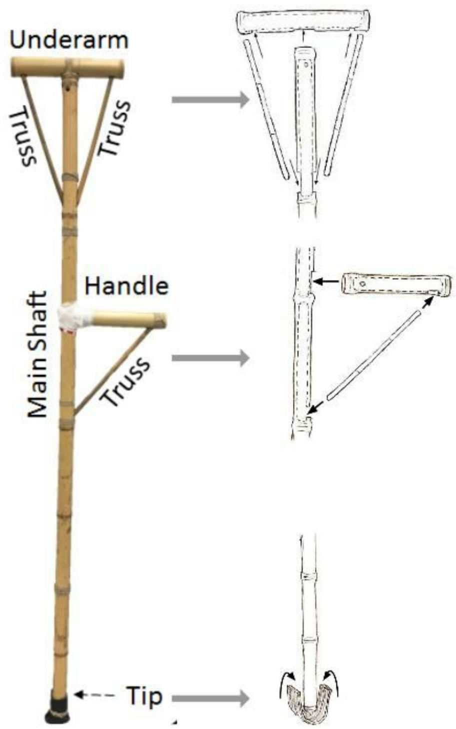

Figure 15: A prototype of the final design (left), with exploded views of the underarm support, handle, and tip (right). This design can be built out of local materials in the Solwezi district of Zambia, and does not require power tools. The total material cost of the crutch is estimated to be less than one U.S. dollar [5]. Hopefully, the modular design will be advantageous if mass manufacturing of the crutch is eventually realized.

Conclusion

The bamboo crutch design presented in this report has the potential to be an affordable and accessible mobility aid for rural areas in Zambia. Bamboo was selected as the primary building material for the crutch based on its availability, high growth rate, and advantageous structural properties. These properties largely dictated the strategy through ideation, which resulted in a successfully designed handle, underarm rest, and crutch tip. By using design heuristics (table 3), I was able to achieve the design requirements (table 1). The crutch can be fabricated entirely from local materials, without the need for power tools, and within two man hours. Based on my research, the proposed design is conservatively 95% less expensive than an aluminum crutch. Further testing is needed to evaluate the lifespan of the product. The distribution of the proposed design will likely involve Non-Governmental Organizations (NGOs) currently involved in mobility aid distribution. These organizations may choose to fabricate the crutches themselves, or distribute manufacturing plans so that local craftsmen and entrepreneurs can fabricate and sell the crutches themselves. I strongly encourage the further development of the proposed design and related manufacturing techniques in hopes that it will improve living conditions of the disabled community in rural areas of Zambia.

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Appendices

A. Joint designs

Various bamboo joints were built and evaluated based on their structural integrity. Below are examples of some of these joints.

Simple right angle joints

A.. Simple right angle joints lashed with twine and plastic bags

The two rods are fitted to each other and then lashed together. This joint was found to be insufficient because any moment producing load would put stress on the lashings (table 2, pg. 8, Heuristic 3). The load would weaken the design and would not satisfy the loading design requirement (table 1, pg 6)

Epoxy reinforced joints

A.2. Prototypes for Epoxy reinforced joints. It was later decided that epoxy was not locally obtainable. It was therefore ruled out as a building material.

These joints were basic prototypes made and then reinforced with various epoxies. Although the joint satisfy the design heuristics (table 2, pg 8), the joint will not satisfy the design requirements of using locally sourced materials (table 1 page 6). If Epoxy is available, it may be used to strengthen the joint but should never be an integral part.

Experimental joints

A.3. Experimental joint prototypes

The two joints is parallel (left) could be used to adjust the height of the crutch. This joint relies on friction and lashing tension to hold it togegher (table 2, pg. 8, violates heuristics 2 and 3) and would not provide a strong connection. The use of the two inch bamboo to hold a one inch bamboo rod (right) was secured by a simple pin and lashings. Although this joint provided a strong connection, I found that cutting a large hole in the 2 inch bamboo usually resulted in cracking. In addition, this joint design would increase the weight of the crutch and further analysis of the ergonomics would be needed.