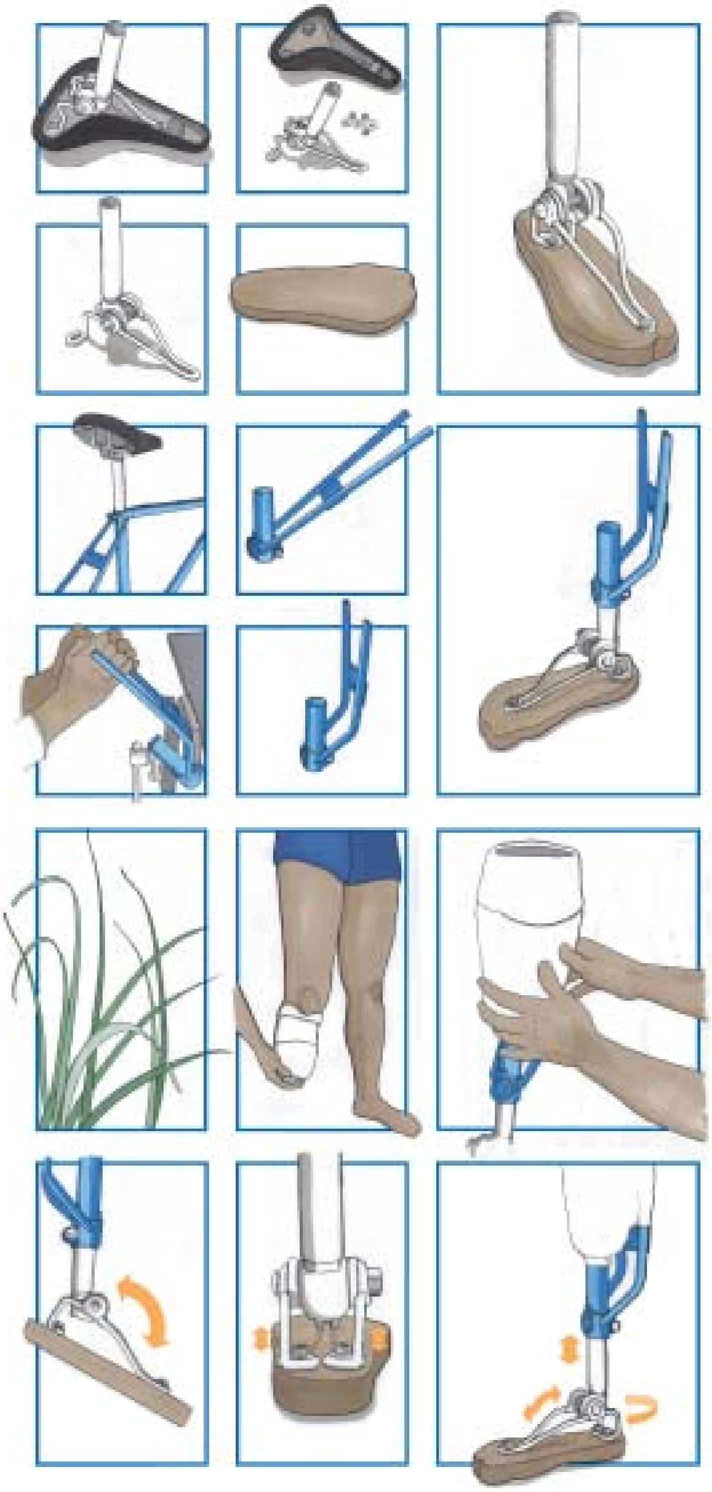

A Victim Assistance Solution:

Adapting bicycle technology for the manufacture of adjustable prosthetic legs for children

By Vivian Cheng
Carleton University
School of Industrial Design

A VICTIM ASSISTANCE SOLUTION:

ADAPTING BICYCLE TECHNOLOGY FOR THE MANUFACTURE OF ADJUSTABLE PROSTHETIC LEGS FOR CHILDREN

By Vivian Cheng
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ABSTRACT

This document details the development of an adjustable trans-tibial prosthetic leg for child landmine victims. The cost and availability is a concern to lower-leg amputees who, without the aid of a prosthetic device may not be able to function, thrive and/or be accepted in society. The proposed prosthetic device adapts bicycle technology that is readily available in the majority of developing countries. This design offers a number of improvements over prosthetics currently available to landmine victims, including: adjustability points for growth and gait, adjustability at all points with a single tool, inexpensive replaceable components (socket and foot), and the use of locally available materials.

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Introduction

"Anti-personnel mines have been laid haphazardly in large numbers in many developing countries, and this has generated a worldwide epidemic of injuries".

— The Arms Project of Human Rights Watch and Physicians for Human Rights, 1993[1]

Landmine victims are not limited to those involved in war since the local people surrounding a minefield are those most often injured after a conflict. Since most local villagers are aware of minefields, it is most often children who are the civilian victims. Although there are significant efforts in de-mining and education regarding the dangers and prevalence of landmines, the victims of such atrocities will continue to require aid for the rest of their lives. Of the types of injuries sustained by landmine victims, amputation of a lower limb is one of the most common.[2,3] Lower limb amputations are either trans-femoral (above the knee), or trans-tibial (below the knee). This project will specifically discuss trans-tibial prosthetics.

The needs of those with landmine-induced disabilities are fraught with a number of problems, including:

1) The lack of services in rural area
2) The availability of materials for prosthetic devices
3) The cost of prosthetic devices
4) The need to replace prosthetics when worn. While adults require replacement approximately every 1 to 2 years, children require more frequent replacements of approximately every six months[4]

[1] The Arms Project of Human Rights Watch and Physicians for Human Rights. *"Landmines: a deadly legacy."* New York: Human Rights Watch, 1993.

[2] Coupland, Robin M. and Russbach, Remi. *"Victims of Antipersonnel Mines: What is being Done?."* Medicine and Global Survival, 1:18-22 (1994)

[3] Rountree, Mark S., Harris, Robert M. *"Countering the Global landmine Epidemic Through Basic Science Research."* Journal of Mine Action, Version 4.2 (June 2000)

[4] Kraft, Peter Paul, Prosthetist of Ampos Orthopaedics in Ottawa Ontario, Personal communication, 22 March 2004.

Background research

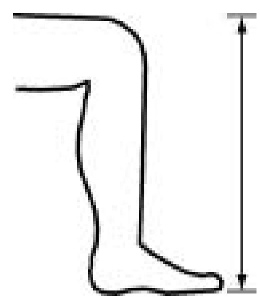
A Child's Growth

With children, prosthetic aids need to be replaced frequently to adjust for the growth. If a child continues to wear an ill-fitting prosthetic leg, spinal misalignments can occur due to uneven leg lengths, or an unnatural and uncomfortable gait can develop.[5] However, prosthetic limbs are expensive, especially in developing countries where the cost of a prosthetic can equal a family's annual income. To reduce the overall cost of prosthetic aids, an ideal prosthetic would either be less expensive or easier to manufacture, or have an increased usable lifespan so that it is replaced less frequently.

Children's knee to foot lengths typically grow an average of 0.75" every year between the ages of four to sixteen years (see Table 1).

Table 1. Ergonomic data for knee to foot length for 50th percentile children between the ages of four to sixteen[6]

Age	Length of knee top to bottom of foot (inches)	Difference in length from previous year (inches)
4	11.7	1.1
5	12.7	1.0
6	13.7	1.0
7	14.6	0.9
8	15.5	0.9
9	16.3	0.8
10	17.1	0.8
11	17.9	0.8
12	18.6	0.7
13	19.3	0.7
14	19.9	0.6
15	20.3	0.4
16	20.7	0.4



The benefit of having a prosthetic aid that could adjust for the growing length of a child's leg could have implications in its usable lifespan. That is, a trans-tibial prosthetic that could extend in length by 3" could last a child for up to three years.

[5] Werner, David. *"Chapter 56: Making Sure Aids and Procedures Do More Good than Harm."* Disabled Village Children: A guide for community health workers, rehabilitation workers, and families. Berkeley, CA: 1999

[6] de Alba, Roberto, ed. *The Measure of Man and Woman: Human Factors in Design*. New York: Whitney Library of Design, 1993.

The Adaptation of Technologies Used for Manufacturing Bicycles

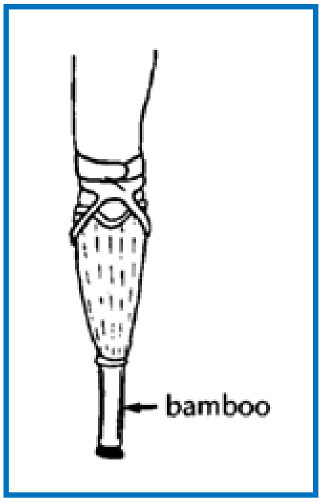
There is already a push for locally made wheelchairs from bicycle components.[7] The advantages of using bicycle components are many. By building locally, jobs are created, local expertise is used and the community benefits. Using bicycle components is cost-effective since they are readily available, and in addition, the bicycle components are made to withstand local conditions. Finally, if there are facilities for manufacturing wheelchairs out of bicycle components, there is already an infrastructure established that may aid in the rehabilitation of those that require prosthetic aids.

Existing Transtibial Prosthetics Used in the Developing World

Many innovations in prosthetics have been made within the villages of developing countries. These prosthetics are able to perform a basic function, utilize locally found materials and act as a starting point of what can be manufactured in limited conditions.

BAMBOO PROSTHETIC[8]

FIGURE 1. BAMBOO AND PLASTER PROSTHETIC

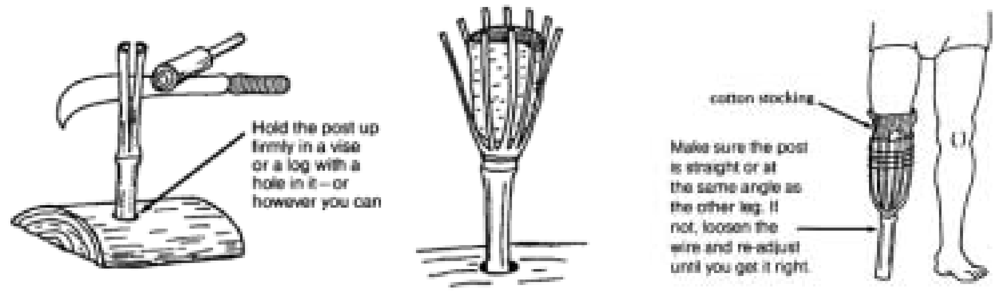


The basic bamboo limb consists of a plaster cast that fits over the stump sock. To make the cast stronger and water-resistant, the plaster is mixed with glue. The joint of the bamboo offers great strength and thus, a piece of bamboo is cut so that the joint of the bamboo is about 2 cm below the end of the stump. One end of the bamboo is split into centimetre wide strips, and these strips are spread around the plaster socket.

[7] Hof, Henry, Hotchkiss, Ralf and Pfaelzer, Peter. *"Building Wheelchairs, Creating Opportunities: Collaborating to Build Wheelchairs in Developing Countries."* Technology and Disability – International Perspectives, Volume 2 Number 2 (Spring 1993) <http://whirlwind.sfsu.edu/general_info/news_articles/building_wheelchairs/building_wheelchairs1.html> (26 March 2004)

[8] Werner, David. *"Chapter 67: Artificial Legs."* Disabled Village Children: A guide for community health works, rehabilitation workers, and families. Berkeley, CA: 1999.

Figure 2. Steps in making a bamboo leg



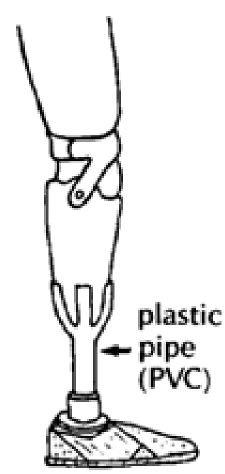
Once the socket is correctly positioned, wire is used to wrap the bamboo strips tightly. The bamboo strips are then trimmed and covered with a layer of glue, sawdust and gauze bandage.

The main advantage of this type of prosthetic is that it is very inexpensive and easy to make. The disadvantage is that a child fitted with such a prosthetic will require a replacement rather quickly. In addition, the simple peg foot would not be well suited to very sandy or muddy terrain, since the 'foot' offers very little surface area over which to distribute the child's weight, and may result in sinking or getting stuck.

Polyvinylchloride (PVC) Prosthetic With Wooden Foot[9]

For areas where bamboo may not be readily available, it is sometimes substituted for a PVC pipe. The PVC pipe must be heated in an oven in order to allow the manipulation of it around the stump socket and offers the same advantages as the bamboo limb. Note that adding a wooden cylinder that fits within the bamboo or pipe with an additional ring of bamboo or pipe can lengthen both the bamboo limb and PVC limb. The ease of the lengthening procedure may depend on the availability of materials, or it may be easier to replace the pipe or bamboo with an entirely new piece.

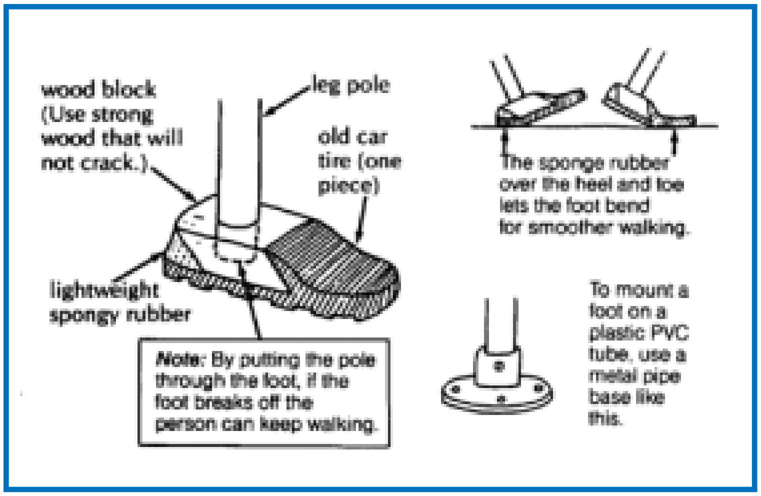
Figure 3. PVC pipe leg with wooden foot



In this example of the PVC leg, a wooden foot is shown. The basic wooden foot is simply a carved piece of wood. Some feet are lined with tire rubber and additional cushioning can be added to the heel for greater shock absorption (figure 4). The addition of even the simplest foot offers the child a more natural gait and improved means of travelling over soft terrain.

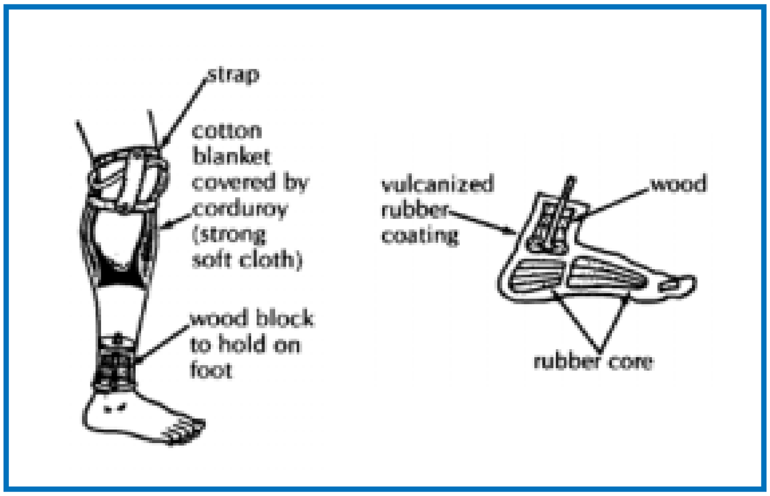
[9] Werner, David. *"Chapter 67: Artificial Legs."* Disabled Village Children: A guide for community health works, rehabilitation workers, and families. Berkeley, CA: 1999.

Figure 4. Wooden foot lined with rubber



Jaipur Limb and Foot[10]

Figure 5. The Jaipur limb and foot



Jaipur limbs are named for the city in India from which they were first developed (figure 5). They were first developed because 'Western' prosthetics were not suitable for being barefoot or squatting, as is common in India. The benefits of the Jaipur limb are that they are cheap to manufacture (approximately $20US) using feet made from tire rubber and polyethylene pipe as the limb support. The materials are both waterproof and sturdy. However, the drawback of the Jaipur limb is that making them requires skill and training, along with specialized equipment.

[10] Werner, David. *"Chapter 67: Artificial Legs."* Disabled Village Children: A guide for community health works, rehabilitation workers, and families. Berkeley, CA: 1999.

Related Prosthetics Used in the Developed World

Typical prosthetics in developed countries are vacuum-moulded plastic, which may not be suitable for the high temperatures experienced in some developing countries as the plastic would require lamination to prevent warping.

Pre-preparatory/temporary prosthetic[11]

This form of prosthetic is very economical and closest to what could be easily made and used in developing countries. The socket is made from resin-impregnated bandage, which is wrapped around the amputees stump shortly after the operation. The prosthetic is made quickly and inexpensively in comparison to other more permanent aids. In addition, the temporary prosthetic is easily adjusted to the user because there are points of adjustment that allow for a specific fit for the user (figure 6).

Figure 6. A Pre-preparatory prosthetic with a Solid Angle Cushioned Heel (SACH) foot.

Note the steel wedges that allow for adjustment in the angle of the foot with relation to the stump.

[11] Kraft, Peter Paul. Prosthetist of Ampos Orthopaedics in Ottawa Ontario, Personal communication, 22 March 2004

Proposed Design Objectives

Considering the problems involved with prosthetics in developing countries, the objectives for a new prosthetic limb are:

1. Components of the prosthetic leg should be adjustable to account for the growth of the child, or inexpensively replaceable to accommodate for the wearing down of parts. These two factors should reduce to overall cost of prostheses during childhood.
2. The prosthetic leg should maintain its functionality and stability even in very hot temperatures and consist of materials that offer some weather-resistance.
3. The prosthetic leg should be inexpensive and simple to manufacture in developing countries with existing technologies. Ideally, the manufacturing procedure would require only minimal training.
4. Materials for the prosthetic leg should be locally available.

Manufacturing Methods — From the Foot Up

The proposed design adapts available technology used for bicycles for the use in prosthetic legs. The parts would either come from reclaimed bicycles that are no longer useful, or from raw components from bicycle manufacturing facilities. The design merges the advantages of prosthetics already made in developing world (made of existing materials from available processes), with the technical advantages of a pre-preparatory prosthetic found in developed countries. In the following prototyping example, a reclaimed ten-speed bicycle was used for parts, however a specific type of bicycle would not be necessary although some adaptations to the following method may be required.

Manufacturing the Foot and Lower Shin from the Bicycle Seat Components

Figure 7. Manufacturing procedure for the foot and lower shin

1 A typical bicycle seat, removed from the frame

2 The bolts and washers that hold the seat post to the seat are removed

3 The seat post is reversed and repositioned to form the lower shin and foot

4 A simple wooden foot is fashioned from a 1" thick piece of wood and lined with rubber. The rubber can be easily replaced when worn out.

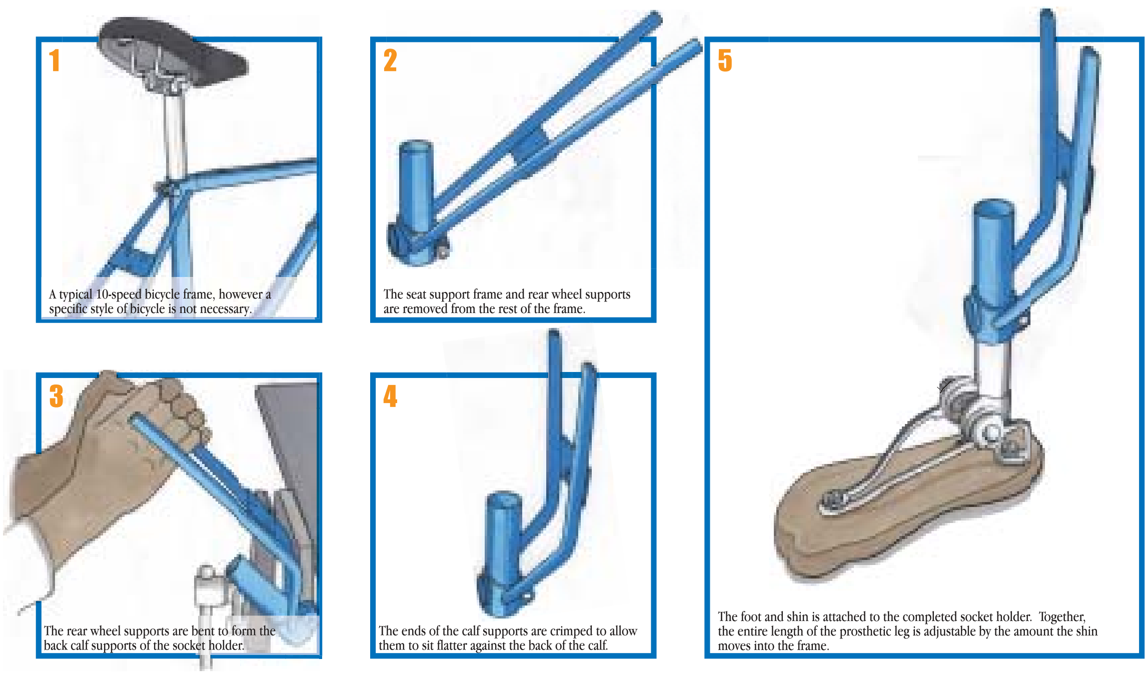
5 The back attachment points of the seat are bent inwards and bolted to the wooden foot

Manufacturing the foot and lower shin requires the seat post components from the bicycle (see figure 7). After removing the seat from the bicycle, the seat is disassembled and only the supports and hardware is kept for the foot. The seat post attachment is reversed on the seat support to form the 'ankle' joint and lower shin. A simple foot is fashioned from a 1" thick piece of wood that is shaped to the appropriate size and shape. The hardware from the seat is used to bolt the seat support to the wooden foot. Finally, the bottom of the foot is lined with a piece of tire rubber.

The benefit of using a wooden board foot is that it requires less skill to manufacture than a more three-dimensional carved foot and offers many points of adjustment (which are discussed in a later section). Because the foot is simplified, it is also easier and less expensive to replace as compared to a carved three-dimensional foot. Also, the rubber tread can be removed when worn, or the entire foot can be replaced without excessive cost when worn or outgrown. Lining the foot with rubber is important since many children in developing countries often do not wear any footwear. In the case where a child may where footwear, the foot can be covered with a stocking or sock and have a more natural appearance.

Manufacturing the Stump Socket Holder From the Bicycle Frame

FIGURE 8. MANUFACTURING PROCEDURE FOR MAKING THE STUMP SOCKET HOLDER



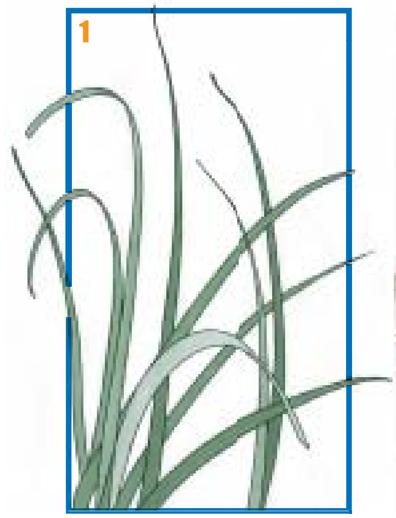
The steel alloy frame provides a supporting strength and stability for the user. Like the shin/foot assembly, the stump socket holder also offers an adjustment point for the leg.

To make the socket holder, a hacksaw is used to remove the required part of the bicycle frame. (Alternatively, the required parts of the frame could be obtained new from a bicycle manufacturing facility). With a handheld saw, the cutting process takes approximately thirty minutes. The main horizontal support is removed as much as possible with the saw, and the remainder is ground away with a hand file or grinder. A length of approximately four inches is left from the seat support of the frame, and twelve inches of each support that held the rear axle are cut (figure 8).

The rear supports are then bent by hand while held in a vice. The ends are crimped and flattened for a more comfortable fit, as these rear supports will act to support the calf of the stump. The piece of frame is then ready to be attached to the already made foot and lower shin assembly.

Reducing the Cost of the Stump Socket by Using Local Vegetation

FIGURE 9. MAKING THE STUMP SOCKET



A mixture of locally available tree resin or glue and long strands of cellulose rich vegetation (elephant grass) provide the casting materials.

The stump socket is cast directly onto the patient's stump to ensure a perfect fit. The stump is covered with a liner sock, soft capper, foam pads to reduce contact at bony areas a wooden support disk that will rest on the top of the stump support.

The rest of the prosthetic is attached to the stump socket by plastering over the arms of the socket holder. The prosthetic is held in securely to the patient with a belt system and the entire assembly can be removed when desired.

An exact fit of the stump is required to best reduce the occurrence of sores, increase comfort to the user and improve gait in the use of the prosthetic. Even in the modern world, prosthetics are made by making a plaster replica of the amputee's stump, and forming the socket from the plaster copy. The most cost-effective means of manufacturing a socket is by making a direct cast of the stump. Typically in developed countries, the cast is made with plaster and orthotic bandages, however cost savings and environmental benefits could be found in using more locally available alternatives.

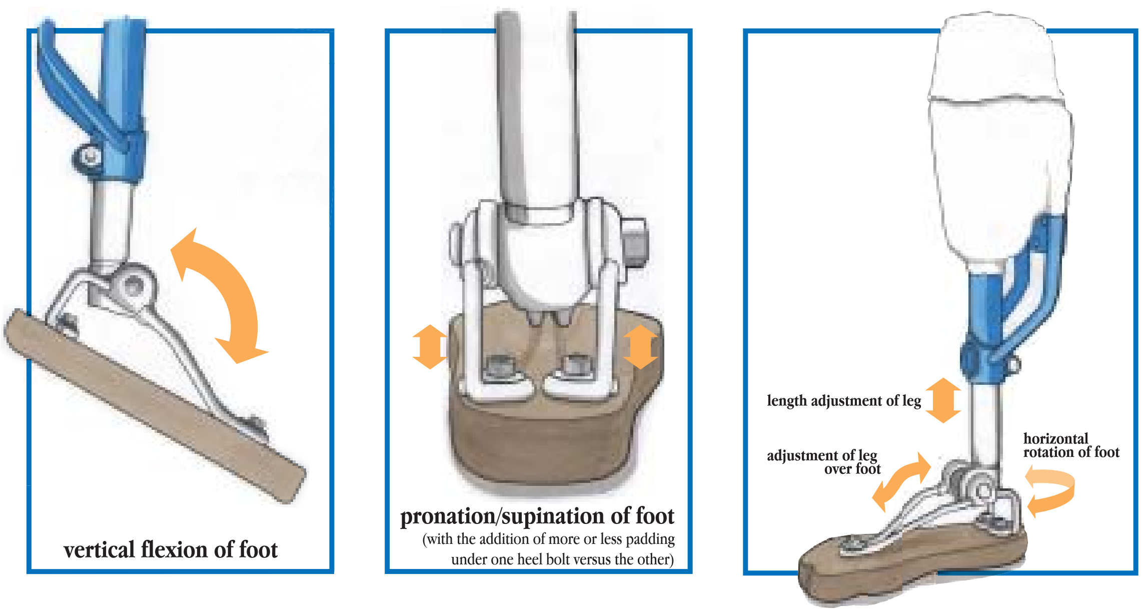
If plaster bandages are unavailable, an alternative could be made by using tree resin or glue and locally available cellulose-rich vegetation such as long grasses, or cornhusks that have been chopped. Some experimentation would be required to perfect the optimal ratio of glue or resin to cellulose. Long, fibrous strands would likely work best and would be similar to the strand/resin mixture of modern fibreglass technologies. Because this portion of the prosthetic is not adjustable and must be replaced, this part should be replaceable and made as inexpensively as possible, while allowing use of at least six months.

In order to make the stump socket, a plastic liner is placed around the stump to assist the removal of the socket afterwards. Next, a stump sock is placed on the stump and the plaster bandages or alternative casting material is wrapped around the stump. After the initial layer, additional layers of plaster bandages are wrapped around the stump and the stump socket holder and this holds the two parts together. Prior to the last layer of plaster, attachment points for a knee-belt or waist-belt attachment are pressed against the cast, and additional plaster is added to secure the belt.

The Points of Adjustment for the Bicycle-Based Prosthetic

The bicycle-based prosthetic has five points of adjustment. The adjustment points could be used for one user, for the life of the product. Alternatively, the same product could be made in batches and used for a wide variety of different users. The adjustment points allow the prosthetic to be specifically altered to suit the individual at whatever stage of growth he/she may be experiencing.

Figure 10. Points of adjustment of the bicycle-based prosthetic



The five points of adjustment are:

1) Vertical flexion of the foot: Specifically, this adjustment aligns the angle of the leg to the foot to what is most natural for the user.

2) Pronation/supination of the foot: This refers to the side-to-side angle of the foot relative to the ground. Adding rubber washers under one or both heel bolts for the foot makes this adjustment possible. Again, the purpose of this adjustment would be to give the user the most natural gait.

3) Adjustment of leg over foot:This adjustment allows for the positioning of the shin over the foot, which differs between individuals, or could change as a child grows

4) Horizontal rotation of the foot: This refers to how much the foot is turned inwards or outwards when standing. The amount of rotation can be adjusted to what is most comfortable for the user.

5) Length adjustment of leg: For a child, the adjustment could easily be made with a wrench, as he/she grows taller. It is important that the natural leg and the prosthetic leg are the same length to prevent curvature of the spine.

Advantages of the bicycle-based prosthetic

Adjustability

The bicycle-based prosthetic could be adjusted by the user as they grow without having to plan a special visit to the nearest rehabilitation centre which could be many days' journey away. Instead the child could have the length of the leg adjusted nearby or at home, since only one tool (a wrench) would be required.

Little Technical Skill Required for Manufacturing

While other inexpensive means of manufacturing prosthetics for developing countries have been produced (such as the Jaipur limb) they often require extensive training, advanced skills and specific tooling before they can be cost-effectively produced. The proposed prosthetic not only relies on bicycle parts, but on the existing skilled labour that supports the bicycle industry as well. The tools required to make the bicycle-based prosthetic are a vice, hacksaw and carving implements for the foot.

Weight

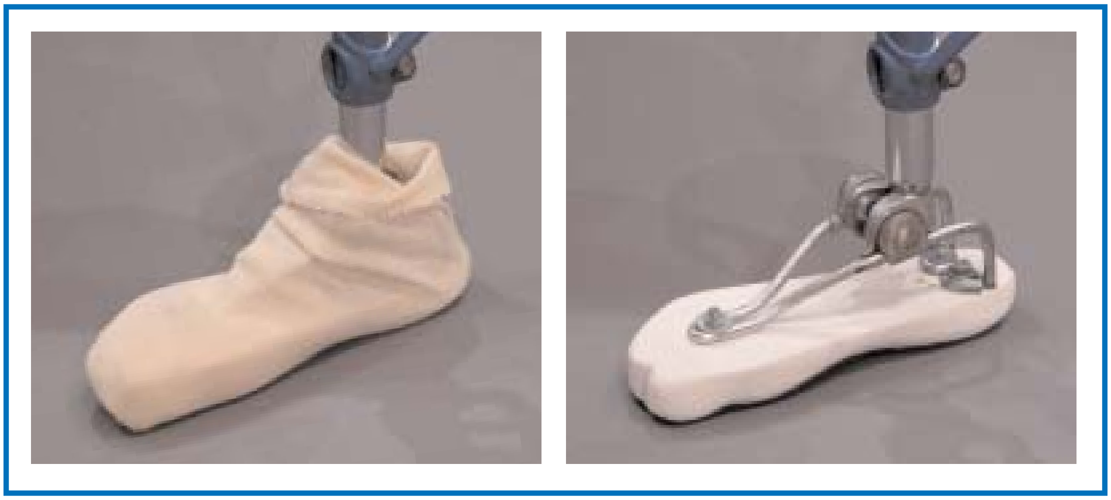
There were some initial concerns that a bicycle-based prosthetic may be too heavy for a person to use. However, the weight of the prototype is comparable to the pre-preparatory prosthetic. In addition, consultation with a prosthetist determined that more weight as opposed to less weight is desired for prosthetic legs, since the greater weight gives an improved sense of stability to the user.

Replaceable Parts

A typical prosthetic in developing countries may need to be replaced every two years for adults and every six months for a growing child. However, not all parts of a prosthetic limb wear at the same rate. The bicycle-based prosthetic design addresses this by having the most frequently worn parts be easily replaceable – specifically, the foot and stump socket.

Because these parts of most frequently replaced, they are made of inexpensive materials. The wooden foot has a rubber tread that can be replaced before replacing an entire foot. The replacement of parts would be especially important for children. To address cosmesis issues, the board foot can be covered with a sock and footwear such as sandals (as would be common in many countries) (figure 11).

FIGURE 11. THE BOARD FOOT OF THE BICYCLE-BASED PROSTHETIC, WITH AND WITHOUT A SOCK COVER



Once the child reaches adulthood, a more permanent foot such as the Jaipur or Niagara foot (figure 12) could be attached to the end of the limb.

FIGURE 12. THE NIAGARA FOOT IS AN ALTERNATIVE DYNAMIC FOOT THAT COULD BE ATTACHED TO THE LIMB WHEN THE CHILD REACHES ADULTHOOD[12]

Weather-Resistance

The bicycle-based prosthetic is expected to have a product life similar to what a bicycle would have in developing countries. While it is possible that being exposed to harsh or wet climates may cause parts to rust, the components would still be structurally viable and usable.

[12] *"Niagara foot: Boon to Landmine Survivors"* Orthotics and Prosthetics: O&P.com March 2003 <http://www.oandp.com/edge/issues/articles/2003-03_08.asp> 31 March 2004

Prototyping and costs

Reclaimed Bike Frame and Seat Post

The cost would be negligible if a reclaimed bicycle is otherwise unusable. Buying new parts is an alternative and would vary in price depending on the local manufacturer and surplus availability in the developing country. A used frame and seat could range in cost between $5 – $20CDN (based on Canadian used bicycle frame costs). No additional hardware is needed aside from what can be reclaimed from the bicycle.

Simple Wooden Board Foot

Depending on the size of the foot, the cost of the piece of wood would be greatly reduced if large quantities were purchased, but the expected cost per foot is less than $1CDN (based on Canadian costs). The rubber lining for the foot could be obtained from automobile tires or even bicycle tires.

Stump Socket (Cast)

The cost of orthotic bandages is approximately $7CDN per roll (based on Canadian costs), and a cast would require one to two rolls depending on the size of the stump. To significantly reduce this cost an exploration of locally available resins and cellulose-rich plants would be advisable.

Conclusions

The proposed bicycle-based prosthetic leg addresses several needs. It is inexpensive and uses materials and technologies that are readily available in most developing countries. Little skill or training would be required to manufacture the prosthetic in local villages, where introducing such a manufacturing facility could boost the economy.

Moreover, it addresses the needs of children who will require prosthetic legs for the rest of their lives. This proposed design provides a cost-effective alternative to constantly replacing prosthetics during their childhood and will hopefully help to alleviate this specific financial burden that must be endured by the family.

Figure 13. An initial prototype of the bicycle-based prosthetic for children in developing countries

Acknowledgements

Special thanks to Mr. Peter Paul Kraft and the staff of Ampos Orthopaedics in Ottawa, Ontario, for their time in imparting a vast knowledge of prosthetics.

Appendix: Presentation boards for the Carleton University School of Industrial Design

CATIMAC 2004: A Victim Assistance Solution

Prosthetic devices can be very expensive for those in developing countries.

While technology may be limited in these countries, there is a often a significant number of bicycles and a support system for the manufacture and repair of bicycles. For this reason, an adjustable prosthetic made locally from new or reclaimed bicycle parts could offer both a cost savings in terms of manufacturing costs, as well as extend the useful life of a single prosthetic aid.

Vivian Cheng

Adapting bicycle technology for the manufacture of an adjustable transtibial prosthetic

CATIMAC 2004: A Victim Assistance Solution

Vivian Cheng

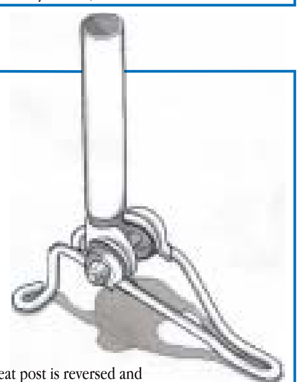
1

A typical bicycle seat, removed from the frame

2

The bolts and washers that hold the seat post to the seat are removed

3

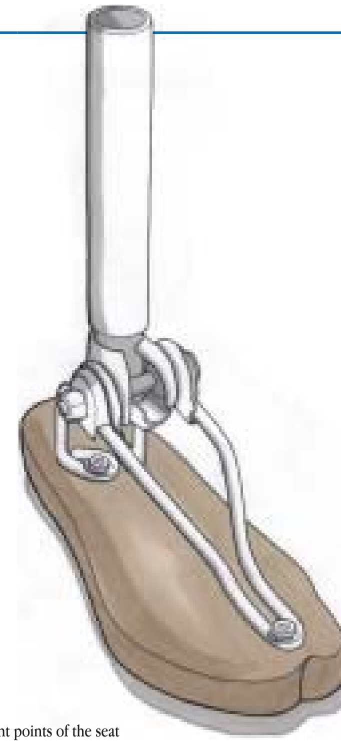


The seat post is reversed and repositioned to form the lower shin and foot

4

A simple wooden foot is fashioned from a 1" thick piece of wood and lined with rubber. The rubber can be easily replaced when worn out.

5



The back attachment points of the seat are bent inwards and bolted to the wooden foot

Manufacturing the foot and shin from the bicycle seat components

CATIMAC 2004: A Victim Assistance Solution

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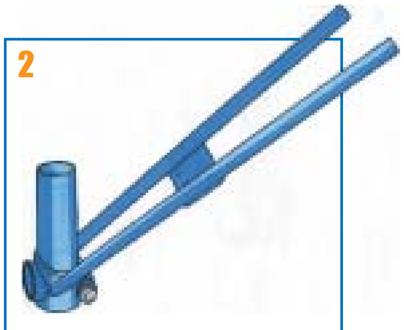
1

A typical 10-speed bicycle frame, however a specific style of bicycle is not necessary.

2



The seat support frame and rear wheel supports are removed from the rest of the frame.

3

The rear wheel supports are bent to form the back calf supports of the socket holder.

4

The ends of the calf supports are crimped to allow them to sit flatter against the back of the calf.

5

The foot and shin is attached to the completed socket holder. Together, the entire length of the prosthetic leg is adjustable by the amount the shin moves into the frame.

Manufacturing the stump socket holder from the bicycle frame

CATIMAC 2004: A Victim Assistance Solution

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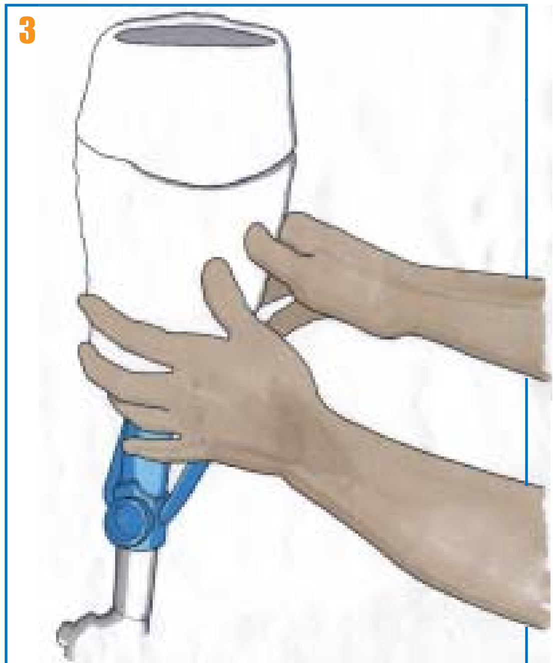
1

A mixture of locally available tree resin or glue and long strands of cellulose rich vegetation (elephant grass) provide the casting materials.

2

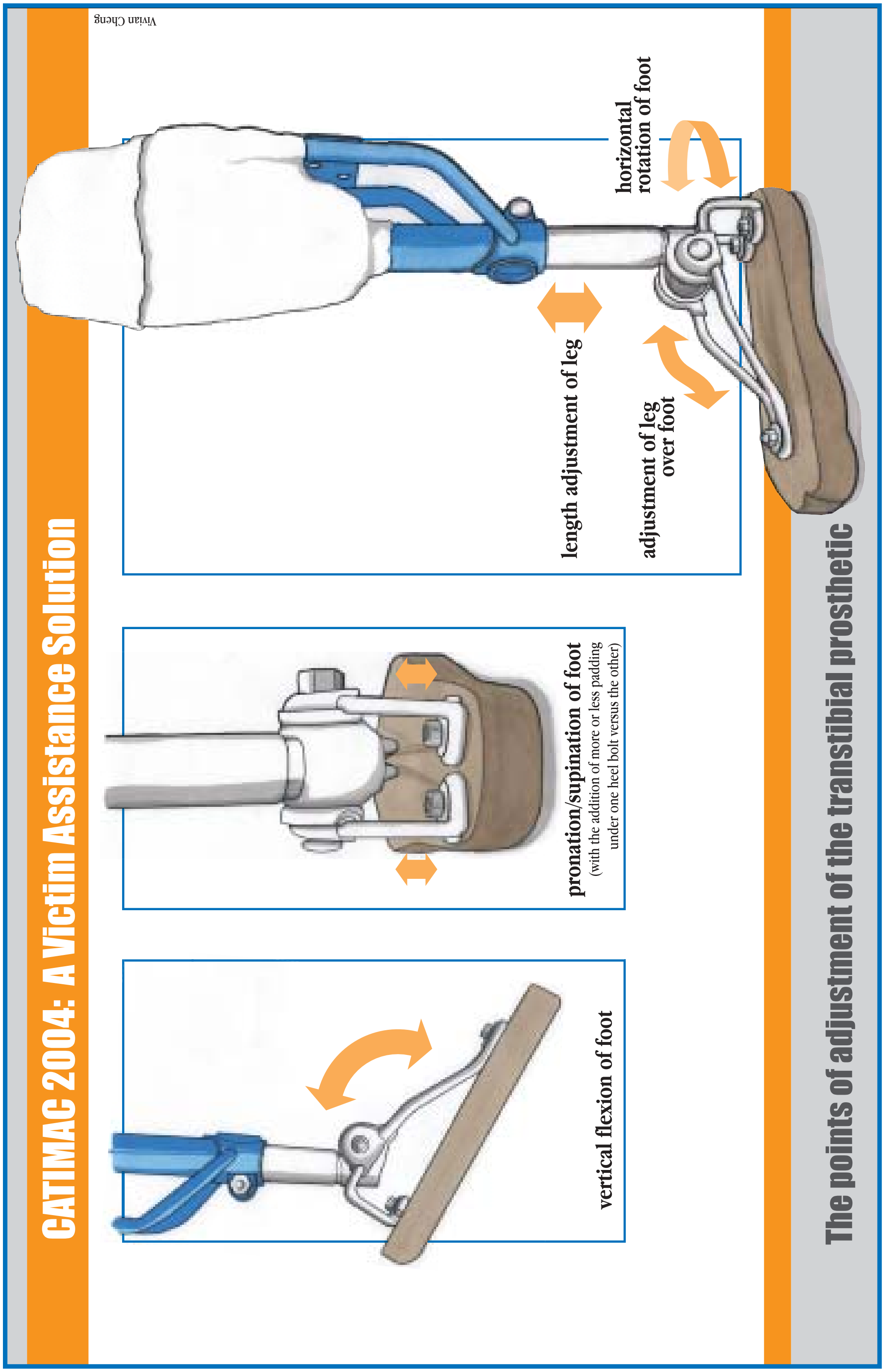
The stump socket is cast directly onto the patient's stump to ensure a perfect fit. The stump is covered with a liner sock, soft capper, foam pads to reduce contact at bony areas
a wooden support disk that will rest on the top of the stump support.

3



The rest of the prosthetic is attached to the stump socket by plastering over the arms of the socket holder. The prosthetic is held in securely to the patient with a belt system and the entire assembly can be removed when desired.

Reducing the cost of the stump socket by using local vegetation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vertical flexion of foot
pronation/supination of foot
(with the addition of more or less padding
under one heel bolt versus the other)
length adjustment of leg
adjustment of leg
over foot
horizontal
rotation of foot
The points of adjustment of the transtibial prosthetic

CATIMAC 2004: A Victim Assistance Solution

- The proposed prosthetic requires little skill to manufacture and can be made locally with reclaimed bicycle components
- The same mass-produced, bicycle-component parts can be made ahead of time and used for a wide range of patients because the parts can be specifically adjusted for each patient
- The proposed prosthetic offers cost savings because the most frequently worn-out parts can be fitted with low-cost replacements made out of locally-available materials
- The usable lifespan of the parts adapted from bicycle components have a potential lifespan of several years instead of a a few months and can be replaced less frequently

Vivian Cheng

Advantages of an adjustable transtibial prosthetic