Bamboo Prehensor for the Developing Countries

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Table of contents

Introduction ........................................................................................................................................... 4
Design Criteria ......................................................................................................................................... 6
Conceptual Design ................................................................................................................................. 7
Dimensional Design .............................................................................................................................. 9
Final Prototype ....................................................................................................................................... 13
Evaluation of the Prototype ................................................................................................................. 14
Results ................................................................................................................................................ 15
Discussion........................................................................................................................................... 20
Conclusion and Future Recommendations ......................................................................................... 26
References ............................................................................................................................................. 27
Appenxinx A: User preferences and requirements
Appenxinx B: Forces needed and objects encountered during daily life
Appenxinx C: Bamboo
Appenxinx D: Technical drawings
Abstract

It is estimated that 25 million people around the world suffer from upper limb amputation. 82% of these amputees live in developing countries and usually find it difficult to provide for their families because they depend on physical labor. At first glance it would seem that the solution is simple, the use of a prosthesis. However currently available upper limb prostheses are beyond the capabilities of most of the people in the developing countries. Thus there is a need for a prosthesis that can be easily manufactured in the developing countries and which is affordable for the individuals.

Bamboo is a material that can be found in most developing countries, it has a good combination of properties such as specific strength and specific stiffness. Therefore, the goal of this research project is to make a body powered hand prosthesis out of bamboo. The prosthesis uses a combination of levers to move and to provide high gripping force with a low actuation force. However, the results show that there is a high energy loss occurring at the joints of the levers. Furthermore, the operating force is high (120 N) and the grasping force is low (14 N). However, by adjusting the position of the cable and spring the operating force can be reduced while the grasping force is increased. Thus, it can be stated that a prosthesis made out of bamboo is a feasible option; but the performance of the prosthesis is very sensitive to the accuracy of the manufacturing process.
Introduction

It is estimated that there are 25 million people around the world with upper limb amputation\(^1\). Approximately 82\% of these people live in the developing countries\(^2\). Many of them live in the rural areas and depend on physical labor to provide for their families. In addition to the psychological effect, losing a limb will have a negative impact on the economic status of the individuals as well. Owning an active upper limb prosthesis is thus important for these individuals in order to work as well as to perform their activities of daily life (ADL), such as holding a cup, tools, utensils, etc. However it is hard for them to obtain one. This is due to the lack of trained personnel who are able to manufacture the prosthesis in these countries, the high cost of the currently available prosthesis and the incompatibility between the amputees’ environment and the materials of currently available prosthesis\(^2\)\(^3\). A prosthesis for these individuals needs to provide good functionality in order to help with accomplishing most of the activities. In addition it needs to be reliable, durable and cheap. If the amputees would be able to assemble and maintain their own prosthesis, the costs for production and repairs would be lowered. Therefore, the prosthesis should be easy to manufacture. Finally other factors such as adaptability and cosmetic appeal are also important\(^3\)\(^4\).

Another method for reducing the price of a prosthesis is to eliminate the need for import of materials. This can be accomplished by the use of locally available materials. In a survey conducted on the availability of natural materials in the developing countries, it was concluded that bamboo is widely available in most of the countries\(^5\). In addition, bamboo has proven its efficiency in most of the Asian countries where it is used in households for making utensils, for building bridges and recently an electrical car\(^6\) was made out of bamboo. Furthermore, bamboo has a high tensile strength and low density, both properties that are important for a material that is used in a prosthesis. The combinations of these properties with the availability make bamboo a good candidate for making prostheses.

Currently available active upper limb prostheses are either body powered or externally powered. Externally powered prostheses have some advantages such as high gripping force and less energy expenditure is needed from the user\(^7\). Body powered prostheses are considered to be cheaper, lighter, and provide proprioceptive feedback to the wearer\(^8\). This improvement in feedback is due to the use of a shoulder harness which transmits the forces required to move the prosthesis through a cable (see Figure 1). Moreover, body powered prostheses are more suitable to the environment of the developing countries, because they are less sensitive to dirt and do not need a battery to function. The aforementioned advantages of body powered prostheses over externally powered prostheses make them more suitable.
Body powered prostheses can be divided into two types; voluntary opening and voluntary closing\(^9\)\(^,\)\(^10\). This classification defines how the prehensor, which is the terminal part of the prosthesis, moves when force is applied. In voluntary opening prosthesis the prehensor is held closed when the cable is relaxed by means of a spring or a rubber band. The strength of the spring or the rubber band determines the maximum grasping force. Pulling the cable will cause the hand to open. In the voluntary closing prosthesis the same concept is used, however when the cable is relaxed the prehensor is held open and pulling the cable will cause the prehensor to close. Voluntary closing prosthesis are considered to be physiologically more correct due to the fact that increasing the operating force, causes an increase in the pinching force\(^12\). However continuous application of force is required in order to maintain this grip, causing fatigue of the muscles and thereby the need for a locking mechanism which complicates the mechanisms design. In voluntary opening this is not a problem, unless the grasping force needs to be smaller than the maximum force. In this case the user has to counteract the spring.

The prehensors of the body powered prostheses can further be divided according to the appearance; as either hand or hook. Hook prehensors are considered to be more functional, lighter, less expensive and more durable than hand prehensors\(^13\) but hand prehensors are more socially accepted due to its more natural appearance. In a survey conducted by LeBlanc in the developed countries, it was found that, although the prosthesis should have more natural movement and should not attract unwanted attention, wearers emphasized on need for good functionality first\(^14\).

**Goal**
The goal of this project is to prove the feasibility of the use of bamboo as the material for designing a body powered prosthetic prehensor for the developing countries. The prehensor should help the amputee in accomplishing most of the ADL, should be cheap, easy to manufacture, comfortable to use and can be adapted to each amputees’ abilities.
Design Criteria

A good design of a prosthesis must fulfill the three main requirements comfort, control and cosmetic appeal\textsuperscript{15}. Based on these requirements a list of criteria can be made. The importance of these criteria depends on what the prosthesis is used for. As previously mentioned, for the proposed prosthesis functionality is more important than cosmetic appeal. By looking at the environment in the developing countries as well as the reasons for not owning prosthesis, it is possible to quantify these criteria.

Size
The prosthesis will be designed for an adult human. Therefore the dimensions of the prehensor should be close that of an average adult human hand. The average length of an adult human hand with an age between is 20 to 30 years is 180 mm, the width is 97 mm and the depth is 24 mm\textsuperscript{16}.

Weight
A human hand has a mass of around 500 gr. However, the prosthesis is considered as an external body attached to the arm, therefore in general upper limb prostheses are desired to be less than 500 gr. Furthermore, it is desired that the amputee feels comfortable wearing this prosthesis for long periods of time; therefore it is preferred to further reduce the mass to less than 250 gr.

Prehensor appearance
Some amputees prefer the use of hand prehensors due to cosmetic reasons while other amputees prefer the use of the hook prehensors due to its better functionality\textsuperscript{17} and reduced price. In this case, the costs and functionality are considered to be of high importance. Therefore, the focus of the design will be on those aspects of the prosthesis. With these aspects in mind, the prosthesis will be made as cosmetically appealing as possible. However, due to the physical appearance of bamboo it remains to be seen if this is possible.

Cosmetic glove
In general most hand prehensors are covered with a cosmetic glove, which improves the appearance and protects the inside from corrosion and abrasions\textsuperscript{18}. However a cosmetic glove also increases the preliminary as well as maintenance cost of the prosthesis, especially due to the fact that it wears after three to six months depending on the environment and the method of use. Furthermore, due to the stiffness of the cosmetic glove, the force required to operate the prosthesis is increased. In this case, the benefit of the cosmetic appeal does not outweigh the aforementioned problems. Therefore it is decided not to use a cosmetic glove for the proposed prosthesis.

Ease of manufacture
As previously mentioned body powered prostheses are divided as voluntary opening and voluntary closing. Due to the fact that a voluntary opening prosthesis requires no locking mechanism, it is easier for the amputees to manufacture and contains fewer parts that will require maintenance.
Operating force
In accordance with the findings of an experiment conducted in 2010, the highest force that needs to be generated by the user should be kept around 20-30 N in order to get good feedback\textsuperscript{19}. When higher operating forces are required, of around 40 N, some users complain of pain due to muscle fatigue. Therefore, the maximum operating force should be kept around 30 N.

Tip grasping force
There was no data found that shows what are the grasping forces to satisfactorily operate a prosthesis. However one study conducted in 1947, showed that a maximum force of 53 N is required to achieve most of ADL\textsuperscript{20}. However, many tasks can be done with a lower force. For more details on these activities see appendix B. The aim will be to obtain a tip grasping force of around 53 N.

Grip opening width
From the list of current commercially available prostheses that was found in a study \textsuperscript{21} it can be concluded that the average opening width is around 70 mm (see Table 3). Nieuwendijk\textsuperscript{22} also listed objects that a person is likely to encounter in daily life and concluded that the maximum opening width of between 70 to 80 mm is sufficient for adults to accomplish most of the ADL.

Cable excursion
According to Taylor\textsuperscript{23}, in general an amputee can produce a maximum of 50 mm of cable excursion. Therefore, the movement of the prosthesis from closing to maximum opening should be accomplished with a cable excursion of 50 mm or less.

Adjustability
Because the prosthesis will be manufactured by hand it is possible the behavior will not be as expected. In order to compensate for this, the prototype should be made such that the behavior can be altered. This can be done by making it easy to make changes to the dimensions of the parts that influence the opening and closing of the prosthesis.

Conceptual design
For a prosthesis it is important to achieve high grasping force while maintaining a low operating force. This can be achieved by using a force magnifier, for example a lever or pulley system. Because a lever system is easier to manufacture and implement, this method is chosen. By applying the operating force at the longer end of the lever, the force will be amplified. By changing the distances to the center of rotation (CoR) the amplification can be controlled.

For a voluntary closing prosthesis, two opposing forces are needed in order to obtain the grasping force. As can be seen in figure 2, by attaching the spring closer the CoR of the lever while attaching the cable further away, the operating force is reduced (eq. 1). However, the grasping force is also reduced (eq. 2).
When the lever starts moving by using the cable, there is no moment produced by the grasping force (grasping force \(F_g\) times the moment arm \(l_3\)). Therefore the operating force \(F_o\) can be determined by dividing the moment produced by the spring (spring force \(F_s\) times the moment arm \(l_2\)), by the arm of the operating force \(l_1\):

\[
\sum M = F_o \cdot l_2 - F_s \cdot l_1 = 0
\]

\[
F_o = \frac{F_s \cdot l_1}{l_2} \quad \text{eq}(1)
\]

When the lever is held closed, the spring force can be calculated:

\[
\sum M = F_g \cdot l_3 - F_s \cdot l_1 = 0
\]

\[
F_s = \frac{F_g \cdot l_3}{l_1} \quad \text{eq}(2)
\]

In order to see if a lever would be sufficient, a simple calculation was done. Equations 1 and 2 were combined into:

\[
l_2 = \frac{F_g \cdot l_3}{F_o} \quad \text{eq}(3)
\]

The values for the grasping (53 N) and operating force (30 N) were substituted in to equation 3, and the moment arm of the grasping force was estimated to be 70 mm (length of a thumb). The moment arm of the operating force would then be:
\[
l_2 = \frac{53 \times 70}{30}
\]

\[
l_2 = 123 \text{ mm}
\]

Since the size of the prosthesis should be similar to that of an adult human hand, 123 mm is clearly too long. Even if the moment arm of the grasping force would be smaller, the lever required to amplify the operating force would not fit inside the prosthesis. Thus, although this concept is relatively easy to implement, it will not be sufficient. This problem can be solved by adding a second lever to the configuration.

When a second lever is added a configuration as shown in figure 3 can be made. The output of the first lever is connected to the input of the second lever, by a rod. The operating cable is connected to the lever 1, while the spring used to keep the prosthesis closed is connected to lever 2.

\[\text{Figure 3 Schematic showing the final concept}\]

In the next section, the dimensions of this concept will be given and the prototype will be presented.

**Dimensional design**

In order to determine the required dimensions for the levers and rods, a free body diagram of each lever has been made. In addition, relationships for the grip opening and cable excursion are determined, as shown below:

*Lever 1*

Assuming that there is no friction occurring at the CoR of the lever, there are two forces acting on the first lever which cause a moment (\(M_1\)). The first is the cable operating force (\(F_c\)) and the second is the output force between the lever and the rod (\(F_{\text{out}}\)) (see Figure 4).
Figure 4 Schematic showing the forces acting on lever 1

\[ M_1 = -F_c \cdot l_1 \cdot \cos(a_1) + F_{out1} \cdot l_2 \cdot \sin(a_2) = 0 \]

\[ F_c = \frac{F_{out1} \cdot l_2 \cdot \sin(a_2)}{l_1 \cdot \cos(a_1)} \quad \text{eq(4)} \]

**Lever 2**

There are three forces acting on the second lever which cause a moment \((M_2)\). The first is the input force for the second lever \((F_{in2})\), which is equal to the output force of the first lever. The second force is the spring force \((F_s)\) and the third is the grasping force \((F_g)\) (see Figure 5)

\[ \sum M_2 = F_g \cdot L_5 \cdot \sin(c_4) + F_{in2} \cdot (L_3 + L_4) \cdot \cos(c_1) - F_s \cdot L_4 \cdot \sin(c_2) = 0 \]

Figure 5 Schematic of the forces acting on lever 2
When the prosthesis is held open, the grasping force can be considered to be zero. Thus the force between the rod and the second lever can be determined by the spring.

\[
F_g = \frac{F_s \cdot L_4 \cdot \sin(c_2) - F_{in2} \cdot (L_3 + L_4) \cdot \cos(c_1)}{L_5 \cdot \sin(c_4)} \quad \text{eq}(5)
\]

\[
F_{in2} = \frac{F_s \cdot L_4 \cdot \sin(c_2)}{(L_3 + L_4) \cdot \cos(c_1)} \quad \text{eq}(6)
\]

**Cable Excursion**

The amount of cable excursion (CE) required to produce a specific grip opening (G_o); can be determined from the change in the angle (a) of the first lever between opening and closing; as well as the length of the first lever.

![Figure 6 Schematic showing the movement of the first lever](image)

From the law of sines:

\[
CE = \frac{L_1}{\sin(a)} \sin\left(\frac{180-a}{2}\right)
\]

\[
CE = \frac{L_1 \cdot \sin(a)}{\sin\left(\frac{180-a}{2}\right)} \quad \text{eq}(7)
\]

**Grip opening**

The amount of the grip opening is dependent on the length of the second lever, the length of the moving finger and the change of the angle (c) of the second lever between opening and closing.

\[
G_o = \frac{(L_6 + L_5 \cdot \cos(c_4)) \cdot \sin(c)}{\sin\left(\frac{180-c}{2}\right)} \quad \text{eq}(8)
\]

The change in the angle of the second lever is dependent on the change in the angle of the first lever.
Figure 7 Schematic showing the angles in the system

\[ d_i = \sin^{-1}\left(\frac{L_r}{L_7}\right) \]

\[ b = 180 - a_{1i} - d_i \]

\[ e = 90 - d_i \]

\[ f = 180 - c_{3f} - e - 90 \]

The angles b and f do not change with the change in the position of the levers. Thus;

\[ d_f = 180 - a_{1f} - b \quad eq(9) \]

\[ e = 90 - d_f \quad eq(10) \]

\[ c_{3f} = 90 - f - e \quad eq(11) \]

Where; \( L_r \) is the distance between the attachment of the rod to the first lever and the second lever and \( L_7 \) is the length of the rod

As can be noted from the shown analysis, there are too many unknowns, which makes it impossible to give a simple example. Therefore, an optimization was performed using Matlab (v.2010b Mathworks). The result of which was that it is possible to have an operating force of less than 40 N, however the grasping force will only be 20 N with a cable excursion of 30 mm and grip opening of 70 mm.
**Final Prototype**

Figure 8 shows the final prototype of the prosthesis. As can be seen in the figure the visible part of the prosthesis consists of two fingers; the moving finger and the stationary finger which is attached to the base. The base is made out of bamboo with a diameter of 60 mm. Therefore there was enough space for inside the hollow bamboo stem in which the levers mechanism could operate. In addition the length of the base allowed for making two holes on which the spring can be attached. The difference between the positions is around 4 mm. Thus it was possible to have two different spring forces in case the user is unable to provide the required operating force to counteract the stiffer spring.

As can be seen in the figure, the moving finger consists out of multiple bamboo pieces that were glued together. This was done to give the moving finger a more curved like appearance, similar to a human finger. The same method was used to manufacture the stationary finger.

![Moving finger](image)

**Figure 8 First manufactured prototype**

Figure 9 shows a solidwork picture of the internal mechanism. Here the levers and rod can be seen. Calculations given in the previous section showed spring with a stiffness of 10 N/mm however a spring with stiffness of 14 N/mm was used because it was easier to obtain. During the manufacturing of the prosthesis it was noted that the spring force caused the steel rod around which the first lever rotates, to bend. Therefore a rod of a bigger diameter (4mm) was used. The new rod collided with the spring; therefore the position of the spring was moved closer to the CoR of the second lever. In addition the cable attachment became closer to the CoR of the first lever.
In order to see if the prototype is working as expected, and how sensitive the functionality of the prosthesis is to the changes done, an evaluation was performed. This is explained in the next section.

**Evaluation of the prototype**

All papers found during this project, tested the efficiency of the prosthesis, by two tests; excursion test and the prehension gripping test\(^2\). Therefore, these tests were used to evaluate the prototype.

Both tests were made using a manually operated custom built test bench (see Figure 10). For the excursion test a load cell in combination with a linear variable differential transducer (LVDT) were used to measure the cable excursion and the operating force during maximum opening and closing of the prosthesis. A maximum opening of 50 mm was chosen due to the limited allowable extension of the spring used. For the prehension gripping test, a pinch force sensor (thickness 10 mm) was attached to the stationary finger, at the point where the moving finger comes in contact with the stationary finger (see Figure 11). The cable was pulled until the pinch force was equal to 0 N and then released again, to ensure that the same force can be obtained.
Each test was repeated ten times while the prosthesis was dry and two times while the prosthesis was wet; in order to test whether there would be an increase in friction due to expansion of the bamboo. In addition the tests were conducted with the spring attached to the two different positions (see Figure 8). The data was then processed using Matlab 2010b; which allowed for the making of the plots.

In addition it was also possible to calculate the friction and the work required to open and close the prosthesis, and therefore the dissipated energy. The calculation of energy dissipation is important because the more energy dissipated, the more the work is required by the prosthesis user. In case of high energy dissipation, this might indicate high friction levels that need to be dealt with.

**Results**

The measured cable excursion, the operating force, and the pinch force with the spring in both situations, are plotted in figure 12, figure 13, figure 14 and figure 15. Each figure shows only three measurements. This is due to the fact that when all the measurements
were shown, the figures were unreadable. Thus only the highest, lowest and middle measurements were plotted.

Figure 12 Cable excursion versus operating force with the spring at position 1

Figure 13 Cable excursion versus operating force with the spring at position 2
Figure 14 Grasping force versus operating force with the spring at position 1

Figure 15 Grasping force versus operating force with the spring at position 2
From the measured data the forces acting on each joint in the system were calculated. These forces are friction forces at the center of levers 1 and 2, and the forces acting on the two joints of the rod. A static friction coefficient between steel and bamboo was measured to be around 0.4. The obtained results are plotted in figure 16 and figure 17.
In table 1 the measured mass and the dimensions of the prototype are listed. In addition, the calculated hysteresis and work from the measurements as well as the maximum operating force and grasping force are listed in table 2.

Table 1 Weight and size of prosthesis

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>Mass [gr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Width</td>
</tr>
<tr>
<td>Base Part</td>
<td>84</td>
</tr>
<tr>
<td>Stationary fingers</td>
<td>40</td>
</tr>
<tr>
<td>Moving fingers</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 2 Forces and hysteresis of the prosthesis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring at position 1</td>
<td>85±18</td>
<td>7.5±0.8</td>
<td>241</td>
<td>973±37</td>
<td>732±37</td>
</tr>
<tr>
<td>Spring at position 2</td>
<td>125±31</td>
<td>14±0.5</td>
<td>622</td>
<td>2090±7</td>
<td>1468±49</td>
</tr>
</tbody>
</table>

Discussion

From the obtained results it can be noted, that although some parameters are good when compared to the design criteria, others need to be addressed. Each criteria is discussed below.

Size
The size of the proposed prosthesis is around \( \pi \times 37.5^2 \times 84 \). The shape of the prosthesis is cylindrical which doesn’t make it easy to compare with other prosthesis nor an adult hand. However the size of the prosthesis is around \( 3.7 \times 10^5 \) mm\(^3\) and the adult hand has a hand of around \( 4.1 \times 10^5 \) mm\(^3\). Therefore, it can be stated that the prosthesis is slightly smaller than an average adult hand.

Weight
From table 3, it can be concluded that the Otto bock 8K24 without the inner frame is the lightest (220 gr) commercially available prosthesis.

The prototype has a mass of 170 gr, which makes it 22% lighter than the Otto bock 8K24.Furthermore, the proposed prosthesis is used without a cosmetic glove. From table 3, by adding the inner and cosmetic glove to the Otto bock 8K24 prosthesis the mass is increased by 203 gr. Therefore, the proposed prosthesis is almost 59% lighter.

Ease of Manufacture
During the manufacturing of the prosthesis only hand tools and construction glue were used. Moreover, the manufacturing process took 3 days. However, as can be noted from figure 18, there is a big difference between the behaviors of the operating forces for the two spring positions. Therefore, accuracy is important during the manufacturing process in order to ensure good functionality.

Operating force
Results show that a high operating force is required in order to operate the proposed prosthesis (see figures 12 and 13). This force is around 125 N when the spring is at
position 2 and around 85 N when the spring is in position 1 (table 2). Both forces are higher than the 30 N operating force that was desired.

Theoretical calculations show that if the change in the rod diameter was taken in consideration when calculating the correct position of the attachment points, the operating force would be 50 N at 20 mm of cable excursion (see Figure 18). In this theoretical model the spring was attached further away from the CoR of lever 2, the cable was also attached further away from the CoR of lever 1. However, it still needs to be tested whether the expected improvement from the theoretical model can be obtained.

![Image of graph showing operating forces versus cable displacement with theoretical behavior and spring at both positions](image)

**Figure 18 Operating forces versus cable displacement of the prosthesis with the spring at both positions and the theoretical model**

**Tip Grasping force**

As can be seen from Figures 14 and 15, the pinching force for both spring positions is also low when compared to the 53 N that is required to achieve all of the ADL. However this force is sufficient to do activities such as holding books, tools or a cup\(^1\). Moreover, the grasping force with spring at position 2 is similar to the one obtained from the Otto bock’s prostheses (14 N). Furthermore, with the spring attached to either of the two positions, the grasping force is higher than the force obtained from the Hosmer soft hand (5 N) (tables 2 and 3). Figure shows that with the theoretical model the grasping force can be up to 18.5 N.
Hysteresis

By comparing the hysteresis of the proposed prosthesis (table 2) with some of the commercially available prosthesis (table 3), it can be seen that there is a lot of energy loss due to hysteresis. This hysteresis is due to the friction between the steel rod and bamboo levers (calculated friction coefficient= 0.4).

As can be noted from figure 16 and figure 17 the friction force at the CoR of the first lever increases from around 20 N to around 95 N for spring position 1 and from around 58 N to around 135 N for spring position 2. While the friction force at the CoR of the second lever increase from 0 N to around 10 for spring position 1 and from around 0 to 20 N for spring position 2. This agrees with the bending that occurred with the smaller rod first used for the rotation of lever 1. The high forces around the joints of lever 1 also lead to higher energy losses when compared with lever 2.

The friction occurred at the points of contact between the steel rod and the bamboo. The measured static friction coefficient was 0.4, for bamboo on bamboo the friction coefficient was 0.2. Therefore, a reduction in the amount of friction and thereby the energy expenditure can be obtained by making a rod around which the levers can rotate out of bamboo as well.

Figure 19 Grasping forces versus operating forces of the prosthesis with the spring at both positions and the theoretical model
Table 3 Some characteristics of currently available prosthesis

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>Mass (gr)</th>
<th>Opening width (mm)</th>
<th>Maximum cable excursion (mm), n=4</th>
<th>Work closing (Nmm), n=4</th>
<th>Cycle hysteresis (Nmm), n=4</th>
<th>Work closing and pinching force for a 15 N pinch (N), n=4</th>
<th>Required cable force at a 15 N pinch (N), n=4</th>
<th>Pinch force at a 100 N pinch (N)</th>
<th>Pinch force drop at a 15 N pinch (N), n=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hosmer APRL hand, 52541 (L) size 8</td>
<td>347</td>
<td>44 (70*)</td>
<td>37 ± 0.1</td>
<td>1058 ± 4</td>
<td>298 ± 8</td>
<td>831 ± 1</td>
<td>61 ± 0.6</td>
<td>41</td>
<td>7.3 ± 0.4</td>
</tr>
<tr>
<td>Hosmer APRL hook, 52601 (R)</td>
<td>248</td>
<td>73 (33**)</td>
<td>38 ± 0.1</td>
<td>720 ± 6</td>
<td>138 ± 3</td>
<td>687 ± 2</td>
<td>62 ± 0.0</td>
<td>30</td>
<td>10 ± 1.5</td>
</tr>
<tr>
<td>Hosmer soft hand, 61794 (R) size 7f1</td>
<td>366</td>
<td>71</td>
<td>38 ± 0.3</td>
<td>2292 ± 12</td>
<td>1409 ± 37</td>
<td>2176 ± 16</td>
<td>131 ± 0.7</td>
<td>5</td>
<td>14 ± 1.7</td>
</tr>
<tr>
<td>Otto Bock, 8K24 (L) size 7f1, frame</td>
<td>220</td>
<td>100</td>
<td>60 ± 0.5</td>
<td>1624 ± 8</td>
<td>389 ± 19</td>
<td>1545 ± 1</td>
<td>78 ± 0.3</td>
<td>28</td>
<td>6.7 ± 0.5</td>
</tr>
<tr>
<td>Otto Bock, 8K24 (L) size 7f1, frame + inner glove</td>
<td>350</td>
<td>69</td>
<td>41 ± 0.2</td>
<td>1639 ± 24</td>
<td>672 ± 8</td>
<td>1694 ± 16</td>
<td>90 ± 0.9</td>
<td>19</td>
<td>5.9 ± 0.4</td>
</tr>
<tr>
<td>Otto Bock, 8K24 (L) size 7f1, frame + inner glove and cosmetic glove</td>
<td>423</td>
<td>57</td>
<td>38 ± 0.5</td>
<td>1710 ± 20</td>
<td>681 ± 23</td>
<td>1636 ± 29</td>
<td>98 ± 0.5</td>
<td>14</td>
<td>6.5 ± 0.3</td>
</tr>
<tr>
<td>TRS hook, Grip 2S</td>
<td>318</td>
<td>72</td>
<td>49 ± 0.1</td>
<td>284 ± 3</td>
<td>52 ± 1</td>
<td>243 ± 3</td>
<td>33 ± 0.2</td>
<td>58</td>
<td>–</td>
</tr>
</tbody>
</table>

**Thumb positioned in 'wide' position. **Hook adjusted to small range.
**Grip opening**
From figure 12 and figure 13, it can be noted that only 20 mm of cable excursion is required to have an opening width of 50 mm. This cable excursion is lower than the one needed by other prosthesis (table 3).

The cable excursion and operating force are depending on each other. When one increases, the other decreases. However since, the cable excursion is less than 50 mm, and the operating force is too high it is possible to move the cable attachment further away from the CoR of the first lever. As a result it will be possible to achieve the required reduction in the operating force.

**Wet test**
One of the proposed tests was testing the forces when the prosthesis is wet. Unfortunately making the prosthesis wet, led to swelling of the bamboo fibers. The swelling of the bamboo prevented the rotation of the lever around the steel rods even though a force of 100 N was applied, the prosthesis did not open. Therefore, it is important to cover the prosthesis under wet conditions. Another solution is to add a second material between the bamboo and the rotation rods, such as a small metal cylinder which will not expand when it becomes wet. This will allow for the continuous working of the prosthesis.

Table 4 shows a summary of the characteristics of the proposed prosthesis. The table show also how it relates to the commercially available prostheses.
Table 4 Summary of the characteristics of the prosthesis in comparison with commercially available prostheses

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Required</td>
<td>70-80</td>
<td>50</td>
<td>53</td>
<td>30</td>
<td>250</td>
<td>180<em>97</em>24</td>
</tr>
<tr>
<td>Proposed prosthesis with spring at position 1</td>
<td>50</td>
<td>16</td>
<td>7.5</td>
<td>85</td>
<td>170</td>
<td>3.7 * 10^5</td>
</tr>
<tr>
<td>Proposed prosthesis with spring at position 2</td>
<td>50</td>
<td>16</td>
<td>14</td>
<td>120</td>
<td>170</td>
<td>3.7 * 10^5</td>
</tr>
<tr>
<td>Theroitical Model</td>
<td>50</td>
<td>20</td>
<td>18.5</td>
<td>50</td>
<td>170</td>
<td>3.7 * 10^5</td>
</tr>
<tr>
<td>Comparision with commercially available prosthesis</td>
<td>Same range as all prosthesis</td>
<td>Lower than all prosthesis</td>
<td>Same range as the Ottobock but higher than the Hosmer soft hand</td>
<td>Same range as most but higher than the Hosmer APRL and TRS hook</td>
<td>Lower</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion and future recommendation

When comparing the proposed prosthesis with commercially available prosthesis, it can be concluded that, when looking at the operating forces, the prototype is not performing as well as the other prostheses. However the mass is lower and the opening grip is in the same range. Unfortunately, the prototype does not work as well as predicted by the theoretical model. The model predicted that the performance of the bamboo prosthesis should have lower operating force and higher grip force. This is most likely due to errors in the positioning of the spring and CoR as well as friction. Furthermore, when the prosthesis comes into contact with water, the operating force highly increases. Further research needs to be done to find out how this can be solved. In addition it would be interesting to compare the proposed prosthesis with some of the prostheses designed for the developing countries, such as the LN-4 and the ICRC transhumeral prosthesis. Unfortunately, there was no published data found with regards to the forces.

The prosthesis was manufactured using hand tools and locally available materials. Therefore, it can be concluded that it is easy to manufacture. In addition, only bamboo and steel were used which made it cheap (the material for the prototype was donated, therefore the price of the prototype is unknown). It is recommended to test the durability of the prosthesis and to investigate the possibility of having a child version. Furthermore, it might be interesting to test the possibility of making the rotation rods of the two levers out of bamboo in order to reduce the friction.

For some users the appearance of the prosthesis might seem bulky mainly due to the cylindrical shape of the prosthesis. This cylindrical shape adds width to the fixed part of the prosthesis, which is not found in other prosthesis. However, the use of bamboo offers the possibility to easily make shapes and coloring on the surface, therefore it is possible to personalize the prosthesis.

In conclusion, it can be stated that despite the room for improvement, the designed prosthesis is a feasible option for individuals that need a cheap, functional prosthesis, with acceptable appearance.
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APPENDIX A: User Preferences and Requirements

Currently there is no clear indication of what the ideal prostheses should be like. This might be due to the different personal preferences of each amputee, level of amputation, manual dexterity, amputation level, motivation of amputee, health and employment status. Currently there are some surveys that were conducted in the developed and the developing countries on the complaints and the preferences of the amputees. After comparing the surveys it could be said that there are similar preferences between the different countries, the only difference is in their order. However one important preference for the developing countries is the need for low cost prosthesis especially among the poor in those countries.

User Preferences and Complaints

In 1994 a study was conducted in Slovenia among 414 upper limb amputees, 266 were only analyzed. The results of the study showed that there is a higher use for the hand prehensor compared with the hook prehensor. Some of the main findings of this study was that 43.9% of the amputees did not use their prosthesis due to complains of heat and sweating, this is followed by loss of sensation (17.8%), weight (16.2%) and damage possibility (14.6%). Furthermore it was concluded that there is more emphasis on the cosmetic appearance of the prosthesis and comfort rather than functionality.

Another more comprehensive study was conducted in 1996 at the Institute for Rehabilitation and Research in USA among 2477 individuals, 1020 of which used body powered prostheses. In this study, it was stated that cable breakage and glove replacement are the main problems related to maintenance. Ability of holding objects of different sized, need for less weight and appearance were some of the listed preferences of the amputees.

Another study that was conducted in India in 2003 among 71 amputees showed that 16% used the prosthesis for cosmetic reasons, 68% used their prosthesis for mechanical reasons while 16% were non users. The reasons for inadequate usage varied from cosmetic reasons to functional reasons. Among complains of the amputees, unreliability of the prosthesis ranked on the top (28%), followed by financial constrains (21%), pain and poor fitting (14%) and finally heavy weight (2.8%).

A final study was conducted, in 2007 at the university of Toronto, among 242 amputees, of which 35% used body powered prostheses as their primary prosthesis. Similar to the finding of the study in Slovenia, users complained of heat and perspiration, and heavy weight that caused discomfort as well as lack of sensory feedback. In addition there were complains about the grip force provided, ability to grasp objects of different sizes and the mechanical reliability.

Comparing the above studies shows that even though there is a different order in the preferences, prostheses users in general have the same preferences. Unfortunately, all of the mentioned surveys only gave a general overview of the requirements. However, with regards to a prehensor design these preferences can be summarized into:

- Better more life-like appearance especially during maneuverability was required.
- Better functionality especially in regards to the gripping forces.
- Better reliability especially with the cables and the cosmetic gloves. Cable breakage and need for regular glove replacement due to wear add to the costs which for some users is considered as a problem.
- Most of these prosthesis are worn for a lot of hours, therefore comfort is a big factor for reasons for rejection. Less weight and reduced heat are very important.

**Conclusion in respect with the project**

This project is only focused on the poor population in the developing countries. Therefore, although the study in Slovenia states that cosmetic appeal is the most important, functionality should also be improved.

High priority needs to be given to improving the gripping force and ability to grasp large as well as small objects this is due to the different hand tools that are used by this population. This should be accomplished while keeping the forces need to operate the prosthesis as low as possible in order to provide comfort to the user.

With respect to comfort, sweating and heat are not a concern at this stage of the project. This is due to the fact that this design only deals with the prehensors and not with the socket. Reduction of the weight is a primary concern. This is one of the reason bamboo was chosen for this design, because it has low density with high strength.

In addition in order to reduce the costs of this prosthesis the use of cosmetic glove will be eliminated, especially since when used during farming for example, the glove will wear faster. Although cable breakage is also a complain of the users, it could be dealt with in a later stage.
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APPENDIX B: Forces needed and objects encountered during daily life

Following are two tables with a list of objects that are encountered during daily life. The reported data is compared to the parameters of the prosthesis in order to determine whether it will be possibility to accomplish the activity.

Table 4 Forces and sizes of some objects encountered in daily life according to LeBlanc

<table>
<thead>
<tr>
<th>Object</th>
<th>Description</th>
<th>Force or Weight to operate [N]</th>
<th>Possibility to operate with the proposed prosthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telephone receiver</td>
<td>Standard French type</td>
<td>5.5</td>
<td>Yes</td>
</tr>
<tr>
<td>Light switch</td>
<td>Toggle Wall type</td>
<td>7</td>
<td>Yes</td>
</tr>
<tr>
<td>Suit case</td>
<td>Empty</td>
<td>53</td>
<td>No</td>
</tr>
<tr>
<td>Aircraft type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Packed Lightly</td>
<td>97</td>
<td>No</td>
</tr>
<tr>
<td>Double hung windows</td>
<td>609 mm* 762 mm</td>
<td>38</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------</td>
<td>-----</td>
<td>---</td>
</tr>
<tr>
<td>Light Switch</td>
<td>Pull cord</td>
<td>8</td>
<td>Yes</td>
</tr>
<tr>
<td>Teacup</td>
<td>76 mm* 86mm -diameter</td>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>Drinaing glass</td>
<td>101 mm*59 mm -diameter</td>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>Book</td>
<td>50 mm* 152 mm* 203 mm</td>
<td>11</td>
<td>No</td>
</tr>
<tr>
<td>Lifting jar or bottle</td>
<td>76 mm -diameter</td>
<td>2-4</td>
<td>Yes</td>
</tr>
<tr>
<td>Pulling on sock</td>
<td>Per wool</td>
<td>34</td>
<td>No</td>
</tr>
<tr>
<td>Pulling on shoe</td>
<td>Oxford</td>
<td>53</td>
<td>No</td>
</tr>
<tr>
<td>Pulling on Pants</td>
<td>Standard</td>
<td>25</td>
<td>No</td>
</tr>
</tbody>
</table>
Table 2 Sizes of objects encountered in daily life according to Niewendijk\textsuperscript{2}

<table>
<thead>
<tr>
<th>Object</th>
<th>Size [mm]</th>
<th>Description</th>
<th>Possibility to grasp with the proposed prosthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utensils</td>
<td>5<em>15 to 10</em>30</td>
<td>Square/Oval</td>
<td>Yes</td>
</tr>
<tr>
<td>Kitchen Knife</td>
<td>20*30</td>
<td>Oval</td>
<td>Yes</td>
</tr>
<tr>
<td>Glass</td>
<td>60 to 70</td>
<td>Round</td>
<td>No</td>
</tr>
<tr>
<td>Mug</td>
<td>70 to 80</td>
<td>Round</td>
<td>No</td>
</tr>
<tr>
<td>Mug held by ear</td>
<td>11*8</td>
<td>Square/Oval</td>
<td>Yes</td>
</tr>
<tr>
<td>Pepper mill</td>
<td>50</td>
<td>Round</td>
<td>Yes</td>
</tr>
<tr>
<td>Bottle of oil/wine</td>
<td>80</td>
<td>Round/Square</td>
<td>No</td>
</tr>
<tr>
<td>Plate</td>
<td>3 thick</td>
<td>Flat</td>
<td>Yes</td>
</tr>
<tr>
<td>Apple/Orange/pear</td>
<td>70</td>
<td>Round</td>
<td>No</td>
</tr>
<tr>
<td>Item</td>
<td>Dimensions</td>
<td>Shape</td>
<td>Safe for Pan?</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------</td>
<td>------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Orange Juice Cartoon</td>
<td>65*95</td>
<td>Rectangular</td>
<td>No</td>
</tr>
<tr>
<td>Pan</td>
<td>35*25</td>
<td>Square/Oval</td>
<td>Yes</td>
</tr>
<tr>
<td>Soap/Shampoo bottle</td>
<td>60*90</td>
<td>Rectangular</td>
<td>No</td>
</tr>
<tr>
<td>Toothpaste</td>
<td>35</td>
<td>Round/Oval</td>
<td>Yes</td>
</tr>
<tr>
<td>Toothbrush</td>
<td>7*15</td>
<td>Round/Rectangular</td>
<td>Yes</td>
</tr>
<tr>
<td>Hairbrush</td>
<td>11*30</td>
<td>Rectangular</td>
<td>Yes</td>
</tr>
<tr>
<td>Hairdryer</td>
<td>40</td>
<td>Round</td>
<td>Yes</td>
</tr>
<tr>
<td>Door handle</td>
<td>12*25</td>
<td>Rectangular</td>
<td>Yes</td>
</tr>
<tr>
<td>Round door knob</td>
<td>70</td>
<td>Round</td>
<td>Yes</td>
</tr>
<tr>
<td>Back of chair</td>
<td>30 thick</td>
<td>Flat</td>
<td>Yes</td>
</tr>
<tr>
<td>Banisters</td>
<td>40</td>
<td>Round</td>
<td>Yes</td>
</tr>
</tbody>
</table>
References

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Appendix C: Bamboo

What is Bamboo?

Bamboo is a woody giant herbage that belongs to the family Gramineae and subfamily Bambusoideae. There are around 1600 different species of bamboo and they differ in size, color, node distribution and configuration, mechanical properties and climatic preferences. The sizes of the different species range from a few centimeters up to 40 cm in height and from 1 up to 30 cm in diameter. It grows in many countries especially in Asia, Africa and Latin America.

A bamboo branch is divided into an aerial part and a subterranean part. The aerial part is formed of the culm and the branches while the subterranean part is formed from the rizome stream with the roots. The rizome system is where the food and nutrition is stored. Furthermore, the bamboo plant can be divided into two different parts according to the subterranean: the leptomorph or monopodial type and the pachymorph or sympodial type.

The environment conditions for the growth of bamboo differ according to the species and depend on factors such as temperature, soil, topography, etc. In general, moderate temperature (9-36°C) and moisture (80%) are important for the growth of bamboo. Bamboo species that belong to the pachymorph group grow only in tropical zones and therefore have less resistance to high temperatures than the leptomorph group which grows in temperate zones.

Bamboo Anatomy

The bamboo stem has a cylindrical wall and is usually hollow. It is divided into segments called internodes by diaphragms (nodes). These internodes together with the cylindrical wall give the stem its mechanical strength. Although there are some variations, in the percentages according to the species, the stem is mainly composed of parenchyma (50%), fibers (40%) and conduction vessels (10%).

In general the bamboo stem matures after about 4 years. This increase in age affects the mechanical properties as well as the anatomical structure. As the stem matures, all the mechanical properties increase; except for the modulus of rupture. Increase in density, vascular wall and fiber wall thickness also results in increase in compression strength. The bamboo node cells are transversely inter-connected, whilst the cell at the internodes are axially oriented. Unlike wood bamboo stem lacks the radial cells.

Mechanical properties

Although there has been some attempts to study the mechanical properties of natural fibers, there are still not enough data on bamboo. However, table 1 shows the ranges for most of the bamboo species as well as the found properties for Amabiless, Phyllostachys.
and Babmooza which are the species used during this report. All of these species share similar properties to the Guadua angustifolia which is the species mostly used in industry.

Table 1 Mechanical properties of bamboo in general and Guada Angustifolia

<table>
<thead>
<tr>
<th>Property</th>
<th>General</th>
<th>Species used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>15-20 GPA</td>
<td>18.4-20.7 GPA</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>1.21-1.36 GPA</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.32-0.46</td>
<td></td>
</tr>
<tr>
<td>Tensile strength</td>
<td>160-320 MPA</td>
<td></td>
</tr>
<tr>
<td>Yield strength</td>
<td>35.9-43.9 MPA</td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>60-100 MPA</td>
<td>28-41 MPA</td>
</tr>
<tr>
<td>Shear strength</td>
<td>10-20 MPA</td>
<td>7.3-7.9</td>
</tr>
</tbody>
</table>

One of the main concerns with wood is the effect of the increase or decrease of the moisture content. The change in the moisture content causes changes in the dimension, as well as the mechanical properties. Unlike wood, the dimension of bamboo start to change as soon as the moisture content is changed. The rate of change is:

\[
\text{Shrinkage} \% = \frac{\text{decrease in dimension}(V,L,R,T)}{\text{original dimension}} \times 100
\]

\[
\text{Swelling} \% = \frac{\text{increase in dimension}(V,L,R,T)}{\text{original dimension}} \times 100
\]

**Bamboo Joint**

For the purpose of this project, it was important to investigate different ways in which joints between bamboo can be made. This is due to the fact that a curved shape needed to be made to simulate the look of a hand.

Bamboo has similar properties as wood, thus wood adhesive was used. However, in order to provide additional support the following were added:

1- Pins made from bamboo were inserted in the longitudinal direction, penetrating the two bamboo pieces.
2- Similar to the first connection, pins made of steel were inserted in the longitudinal direction, penetrating the two bamboo pieces.
3- Bamboo Lamello is a piece of bamboo that has an oval shape. This piece is pushed inside a groove made in the bamboo pieces.
**Bamboo joint testing**

In order to test how the joints will react under load, tensional test was done. Both devices applied tensional force however one was able to apply 10 KN and the other 100 KN. The measurements allowed for observing the displacement as well as the force.

Due to time constraints as well as lack of material only 2 specimens for each method were tested. Each specimen had a cross sectional area of around 28mm$^2$. Force was applied until the bamboo joint was completely broken.

**Test Results**

As can be seen in figure 1 for all the three different methods the force required to break the glue is higher than that required to break the bamboo pins and lamella (more than 200 N).

![Figure 1 Comparison of the strength of the different connection methods](image)

However, in one of the specimens using the bamboo lamella it was noted that the force required to break the glue is less around 150 N, this is due to the decrease in the cross sectional area on which the glue was applied. While in the second specimen the position and size of the lamella were changed, which provided additional support as it was placed in the highest cross sectional area (near the point of application of force).
In the case of the steel pins, after the break of the glue connection and around an applied force of 250 N, the pins started to bend in the direction of the force applied.

Conclusion

Adding support to the construction wood adhesive did not increase the connection strength of the bamboo joint. Therefore it might be feasible to use the adhesive separately. Especially since the maximum force required for this project is around 40 N, which is the average gripping force needed to accomplish most of the daily life activities.

However, any of the methods with the exception to the bamboo pins can be used instead of the construction glue, in case glue cannot be found.

Furthermore bamboo is a material that has a good combination of properties, however when the moisture content is changed, there is instability in the properties that need to be addressed.
References

3 Joinery bamboo
Appendix D: Technical drawings
UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 SURFACE FINISH:
 TOLERANCES:
 LINEAR:
 ANGULAR:

FINISH:

DEBUR AND BITER SHARP EDGES

TITLE:

NAME SIGNATURE DATE

DRAWN
CHECKED
APPROVED
MFG
QA

MATERIAL:

DWG NO.

WEIGHT:

SCALE 2:1

SHEET 1 OF 1

rod

A4