Redefining Mechanical Control for a Modular Upper Limb Prosthetic for Children

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ABSTRACT
In recent times, the global amputee population has proliferated and as such the demand and need for functional prosthetics on the market has risen as well. Nonetheless, amputees pursuing feasible aid are at most times left at a crossroads between choosing prosthetics offered at high prices with high functionality, but require frequent device replacement and those offered at a reasonable price, but with limited functionality. In an effort to resolve this issue, a modular, upper limb transradial prosthetic for children was fabricated to factor in the device complaints of cost, durability and device functionality. This study examines the control system aspect of the device’s functionality and its proposed role in keeping the prosthetic mechanically driven and affordable.

1. INTRODUCTION
According to the National Limb Loss Information Center, there are approximately 1.7 million people in the United States that have a residual limb [3]. Additionally, one in every 200 people in the United States has undergone amputation surgery [3]. Amputation surgery occurs 185,000 times per annum in the United States [6]. As a result of these conditions, amputees were recommended to use a prosthetic device to accommodate for their loss and also establish normalcy in their lives. However, amongst the amputee population, children rejecting prosthetic devices range from 10% to 49% in pediatric population [4]. Considering that children are physically active, one of the main concerns for the device is its ability to withstand adolescent activity.

The primary, underlying reasons for the discontinuation of a prosthetic’s usage have been mutual for both adults and children. Both age groups find that the majority of affordable prostheses do not greatly improve the ability to carry out daily tasks; instead it is more of a burden to wear. More specifically, users have demonstrated that their prosthetic device is uncomfortable due to its heaviness, skin irritability, and overproduced heat [1]. Research has also demonstrated that 74% of prosthetic users have experienced skin irritation due to the friction and pressure the device imposes on the residual limbs [1].

The architecture of a practical prosthetic is very complex, as each of its components have embedded engineering aspects that must be taken into account in the design process. The variations between the functions of different prosthetics is based on the socket type, extent to which the limb is amputated, function of the gripping component or hand, and how the prosthetic is powered. As such, an amputee has the option to choose between a nonfunctional cosmetic prosthetic and a more realistic, myoelectric or neuroprosthetic arm. The upper limb of an individual is subject to a myriad of tasks on a daily basis. Therefore, the prosthetic’s functionality must be able to facilitate a high percentage of these activities. The main objective of the project is to develop a functional prosthetic that is tractable for adjustment and can function cohesively as multiple modular components.

1.1 Upper limb control systems in review
Current upper limb prosthetics are divided into two spectrums, passive and functional. For those seeking a passive prosthesis, the desire for a device with resemblance to the human body is paramount. For those seeking a functional prosthesis, the control system incorporated in the operation of the device must enable them to carry out their everyday activities without disrupting their sense of normalcy.

These devices are offered in both mechanical and electrical form, with the electrically driven prosthetics granting the amputee a better opportunity to recreate human-like motion with their appendage. A prime example of this would be the DEKA arm system invented by Dean Kamen, shown in Figure 1. Labelled as one of the most advanced robotic prostheses ever built, the device utilizes a combination of control inputs. However, the main signals stem from electromyogram electrode control, which senses signals sent from the user’s brain to the contracted limb in order to enable completion of complex tasks by the user. The team behind the DEKA Arm system is still working on being commercialized to the general population at a reasonable price.
However, the costs associated with prosthesis such as electric-controlled devices offering high functionality prohibits the majority of amputees within low to middle class income levels from acquiring and maintaining a device for themselves. As such, these amputees must opt for lower priced prosthesis that are mechanically driven such as body-powered devices. These offer ample assistance in fulfilling basic day-to-day tasks. Of the body-powered devices available, the most commonly used are the hooks, prehensors and artificial hands.

The split-hook design in Figure 2 enables amputees to hold and squeeze objects between the split hooks. Its functionality and efficiency of use are best shown in its ability to grasp small objects and allow the amputee to witness its function in clear view.

Similar to hooks, prehensors are more functional than hands in some ways but possess flaws in other ways. Depending on the grip, they are capable of a wide range of prehension from delicate manipulations to magnum gripping power. These flaws primarily are the fact that it is not as good for picking up and working with small items. Additionally, they do not offer as much visual feedback because they are usually bulkier at the end.

Of the body-powered devices listed, artificial hands are the least functional of the group. What the hands lack in functionality, they offer in appearance and body image. The fact that artificial hands are the most visually similar to human hand contributes to its popularity among amputees.

The focus of the project was to fabricate a prosthetic with a terminal device that assumed grip and holding positions that provided advantages in use similar to those of the aforementioned devices.

2. PROJECT FORMULATION
Due to the intricacy of this project along with the allotted completion time, multiple phases were set to ensure our time effectiveness in fulfilling each of our goals. The two phases of this project are, first to design and optimize the physical components that will solve the targeted problem. The second phase is to expand on the functionality of the physical components, by implementing mechanical driving elements to establish and enhance user control of the device.

This paper will focus on Phase 2 of the project which is centralized on the design and crafting of a mechanically driven terminal device. As an additive stage to the overall objective, which is to produce a prosthetic that is modular and adjustable to accommodate to a child growth, the appendage is designed as a means to add value and function to this primary objective. At onset, the established design implements a hand consisting of a full rolling thumb and four fingers; collectively, the device is capable of producing a grasping motion.

3. TESTING AND ANALYSIS
3.1 Kinematic Analysis of Control Mechanism
Phase 2 of the design and analysis of this prosthetic involves the appendage. The study conducted primarily focuses on the reliability of the pin to gear mechanism. The function of this design is to allow each individual finger to move independently and to lock at different ranges of motion in one direction. Control of the fingers of the hands is first initiated by the wrist. By twisting the wrist lock, see Figure 5, a slider translates forward or backward allowing the pin to coincide with the ratchet gears. The design is similar to a ratchet and pawl.
shown in Figure 6. This is a reliable mechanism that is used in common ratchet tools.

Figure 5. Control mechanism in CAD model of prosthetic

Figure 6. Schematic of ratchet and pawl mechanism

In order to gauge the effectivene ss of this concept in the hand, a kinematic motion simulation was conducted using SolidWorks. The initial setup involved eliminating unnecessary parts to allow the simulation to run efficiently. Only the reactions between the pin and gears are the focus of the analysis. A torque is applied to the based finger which the ratchet gear is attached to, as shown in Figure 7. When a linearly increasing torque starting at 45 Newton meters is applied to the finger, the intention of the pin is to impede the motion in the direction of the ratchet gear teeth.

Figure 7. Depiction of coincidence between the pin and ratchet gear

To further evaluate the concept, a stress plot, deformation, and minimum factor of safety were determined. The evaluation displayed in Table 1 shows a minimum factor of safety of 3.3 and maximum deformation of 0.013 mm were achieved. These values lead to the conclusion that the aluminum pins are capable of withstanding a force applied by the gears.

<table>
<thead>
<tr>
<th>Test</th>
<th>Kinematic Motion Study</th>
</tr>
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<tbody>
<tr>
<td>Maximum Total Deformation (mm)</td>
<td>0.013</td>
</tr>
<tr>
<td>Minimum Factor of Safety</td>
<td>3.3</td>
</tr>
</tbody>
</table>

In actual testing, the gear attached to the base of each finger is likely to fail due to bending prior to the aluminum pin reaches complete failure. The reason for this is that the gears of the prototype are fabricated with a plastic. Figure 8 shows the results of the stress plot on the pin. The maximum stress occurs at the point of contact between the gear and the pin. Note that the stress on the gear, finger base, and other components are not evaluated in this study.

Figure 8. Stress applied on the pin due to the reaction of the gear

The results of the finite element analysis provide some validation on the aspects of the design, but to be able to produce a product that is marketable, actual physical testing should be conducted to verify analytical or simulation results. In this work, a prototype of the prosthetic was tested through various situations to determine how the product will actually perform. Along with physical stress test, the dexterity of the hand was evaluated. All this will be done to reason whether this design would sufficiently enable an amputee to carryout usual task, and the results were encouraging.

3.2 Experimental Testing

In both upper and lower extremity prosthetics, performance is the single-most important factor that influences the amputee’s acceptance of the device. For a normal child, they engage in multiple functions during their playtime activities such as twisting, pulling, pushing, lifting, catching, and throwing just to name a few. Nonetheless, for a child amputee, their playtime activities will be restricted to what their prosthetic can successfully achieve without failure.

The performance evaluation of the prosthetic’s control system was explored in two categories of experiments: range of motion tests and range of function tests.
In the range of motion tests, the prosthetic hand was made to mimic a variety of open and close hand positions in order to examine the permitted hand postures. The range of function test consists of exploring the different configurations possible with the hand. The basis of these tests was to assess the variability of positions that can be assumed by the hand while completing a function.

Figure 8. Open precision grip (L) Precision grip in-use to hold washer (R)

Figure 9. Hook grip (L) Hook grip in-use to hold bag (R)

3.3 Discussion

A number of grip positions were assessed by the hand, however, the positions shown in Figure 8 and 9 were two of the most critical for amputees who sought assistance in accomplishing daily tasks. Figure 8 shows the open precision grip which provides a way of picking up small objects more precisely. This is similar to the function provided by the prehensor.

Objects of different sizes that can be contained with the palm region can be held in a similar fashion so long as the wrist lock mechanism is activated, fixating the position of the fingers. Figure 9 displays the hook grip position.

This position is modeled after the function of a split hook prosthetic. Objects that need to be held can be suspended from the hand once the fingers are secured in a clenched stance. It provides a solution to objects that need to be carried while the arm is in the dead-position position such as grocery bags or briefcases.

4. CONCLUSION

This prototype was our first attempt to create a modular, below-elbow prosthetic limb for children that offers adjustment of the device’s length in order to extend longevity of usage and reduce cases of device abandonment. Even though the fabricated prototype was satisfactory for testing and evaluation of the prosthetic’s intended function, the team acknowledges that there are multiple opportunities through which our prototype can be optimized by others.

Firstly, advancements can be made to its function for future projects. The primary advancement that can be made is the integration of a myoelectric control system for the hand rather than the present mechanical system. The implementation of servo motors within the hand region can maximize the functionality of the prosthetic. Also, wrist mobility should be considered for inclusion in future work of this prosthetic in order to provide the amputee with an additional degree of flexion for mobility of the hand. This would reduce the effort required on the amputee’s part to operate the prosthetic in everyday tasks. As stated by Dr. Nielsen, the total number of persons with an amputation, and those using a prosthesis, is expected to increase by at least 47% by the year 2020 [2].

Our recommendation to any individuals pursuing this area is to prioritize the use of testing patients such that real world application of the prosthetic can be reenacted and any present limitations can be accounted for.

5. ACKNOWLEDGMENTS

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6. REFERENCES


