DEVELOPMENT AND CHARACTERIZATION OF A MULTIARTICULATE PEDIATRIC HAND AS A RESEARCH PLATFORM FOR FUNCTIONAL IMPROVEMENTS

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ABSTRACT

Multiarticulate upper limb prostheses for children remain sparse despite the continued advancement of mechatronic technologies that have benefited the adult population. Research in the field of upper limb prostheses is predominately adult focused, although rates of pediatric upper limb prosthesis abandonment are inflated when compared to adults. The function a prosthesis offers is a driving factor influencing whether a child will continue to wear their prosthesis. The current standard-of-care pediatric devices typically offer a single degree of freedom open/close grasping function, a stark departure from the multiple grasp configurations provided in advanced adult devices. However, as mechatronic technologies continue to advance and multiarticulate devices emerge on the clinical horizon, understanding how this technology translates effectively to the pediatric population is essential. This includes exploring grasping movements that may provide the most beneficial outcomes as well as effective ways to control the newly available dexterity. Currently, no available pediatric research platforms exist that are dexterous and boast open access to hardware and programming that allows for the investigation and provision of multi-grasp function. Here we present the development of a pediatric research platform. This dexterous pediatric-sized hand offers six degrees of freedom and programmable grasping configurations. We present our design metrics, discuss the mechanical and electrical design, and provide device performance results through benchmark testing.

INTRODUCTION

Upper limb (UL) prosthesis abandonment is a pervasive issue in pediatric populations. In fact, 35%-45% of children will abandon their device in comparison to adults where abandonment rates are 23%-26% [1]. Adoption of a prosthesis requires the device to provide sufficient function and facilitate healthy social interactions to the extent that these benefits outweigh the drawbacks of discomfort, device weight, inadequate performance, and unwanted attention in social environments [1]. Standard-of-care devices often fall short of meeting these demands. One avenue to addressing the shortcomings of current pediatric prostheses entails increasing the functionality of these devices which may seem a daunting task given that hands move with 27 degrees of freedom [2] allowing for complex manipulations. However, nearly all tasks we perform with our hands rely on a limited repertoire of movements, and 6-9 hand grasp configurations can account for nearly 80% of activities in home and professional environments [3].

Numerous advanced adult UL prostheses are available and capable of achieving multiple grasp configurations including 4-5 of the top frequently used hand grasps [4]. However, there are limited pediatric devices with the same dexterity. Most children's devices provide a single degree of freedom open/close prehensile motion with the exception of a very few such as the Vincent Young 3, which provides up to 13 individual grasps. Recently, there have been experimental or non-clinical pediatric devices developed and reported in literature [5]–[9]. However, a common motivating theme among these designs has been to minimize the device cost, citing the expensive nature of commercially available pediatric prostheses. Many of these devices are therefore limited in functionality with 1-3 actuators [5]–[7] and thus a limited inventory of grasping motions is provided.

Despite current limitations, it is evident that advanced muti-grasp hands are on the clinical horizon for children. However, before effectively implementing these devices in the clinic or prescribing them to patients, further research and analysis are required to address current gaps in knowledge. For example, it is unknown which grasping motions may be most effective to support age-specific childhood play and daily activities. Further, it is unknown how conventional adult muscle-based prosthesis control may be translated to this population given that many were born with their limb difference and their affected muscles have never actuated an intact limb. However, few to no dexterous pediatric upper limb research platforms are available with open access to hardware and software programming that enable researchers to begin addressing these current knowledge gaps.

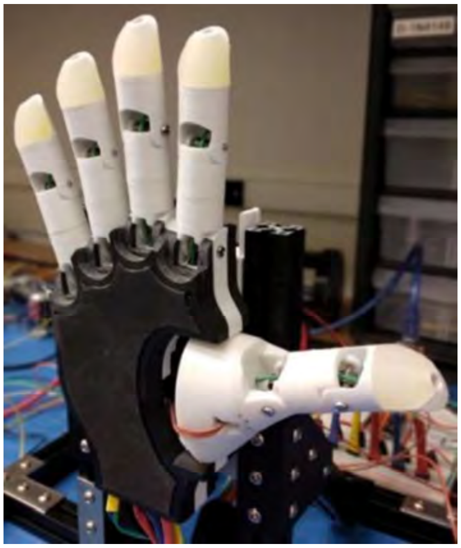

Figure 1. The BEAR PAW: a pediatric multiarticulate prosthetic hand with six degrees of freedom and programmable grasp configurations.

Our goal was to design an advanced child-size UL prosthesis with similar dexterity to those present in adult devices. We developed a UL pediatric prosthesis research platform that is openly programmable and capable of performing a multitude of grasp configurations. Here, we describe the design and fabrication of the Bionic Engineering and Assistive Robotics Laboratory's Pediatric Assistive Ware (BEAR PAW, Figure 1), as well as benchmark its mechanical and electrical performance.

DESIGN METRICS

Multiple design constraints were adopted to guide the development of the BEAR PAW. Firstly, the size of the prosthesis was important as a tradeoff exists between size and maximum digit actuation; as individual digit actuation increases, the size of the device also increases to effectively house the necessary components. To accommodate this metric, we referenced 50th percentile 8-year-old male and female anthropometric data to proportion our design [10], [11]. Our design can achieve 6 degrees of freedom which includes digit flexion/extension and thumb opposition. Weight is an important constraint, especially for children who do not yet have the strength of an adult [12]. The mass of an Ottobock Electrohand 2000 for children 8-13 years old was used as a baseline for comparison ($130\ g$). To achieve a lightweight dexterous design, we prioritized 3D-printing techniques for the advantages of the material's weight and produced a 177g device.

Electronics and the corresponding control were developed under two considerations: compact design and ease of use. An Arduino Pro Mini with a custom break out board mounted inside the wrist was developed to reduce the physical size of the electronics. Device communication was enabled via Bluetooth or USB to UART allowing for tethered or untethered control. A custom graphical user interface was developed in Processing 3 programming language to allow for ease of use through virtual buttons and potentiometers. Further, the device can accept serial inputs allowing it to communicate with common data acquisition systems. Together this allows for intuitive device control that can be agnostic to a variety of prosthetic control interfaces such as commercially available sEMG systems.

To define the physical capabilities of device actuation both closing time and force output were considered. Here, the time to close should be less than $1\ s$, reflecting values found among commercially available prosthetic systems [13]. The BEAR PAW was able to achieve an average of $0.67\ s$ for full hand articulation. Additionally, load considerations were selected to facilitate effective device performance across multiple grasping motions in a research setting. Target grasping force values of at least $500\ g$ $(4.9\ N)$ were selected as most grasps are applied to objects less than this value [14]. Here the force output was achieved for multiple grasp configurations with corresponding loads ranging from $305\ g$ to $736\ g$.

Finally, a device cost of less than \$1000 was selected to promote the accessibility of our system to other research laboratories. This was achieved by utilizing off-the-shelf componentry and open access software for a total raw materials cost of approximately \$500 USD. The above design requirements, their corresponding metric/value, and the values achieved by our design are presented in Table 1. These metrics are an aggregate of values reported in literature describing adult research platforms [15] paired with values derived from clinical and engineering discussions.

Table 1. Design Metrics.

Design Requirement	**Specification Metric:**	**Quantitative Value:**	**Achieved Value:**
Size	Anatomical proportions:	8-year-old child	Metric met
Mass	Low mass:	< 130 g	177 g
Inexpensive	Low cost:	< \$1000	\$500
Degrees of Freedom	Digit actuation:	Flexion/Extension Thumb opposition	Metric met
Actuators	Servo control:	6 servos	6 servos
Electronics	Compact design:	Enclosed in hand	Metric met
Operation Time	Substantial power:	Mains power	Metric met
Control	Communication:	Bluetooth or USB to UART	Metric met
Ease of Use	High usability:	Graphical interface	Metric met
Grasp Speed	Time to close:	< 1 s	0.67 s
Force	Minimum force:	> 4.9 N	7.22 N

MECHANICAL & ELECTRICAL DESIGN

Mechanical: The BEAR PAW was developed in the computer automated design software SolidWorks 2020 and fabricated using a SigmaX R19 3D Printer with PLA material. The hand utilizes six KST-X08 series servo motors to actuate digit flexion/extension and thumb opposition; therefore, it is capable of a multitude of common grasping movements. Servo motors are mounted on the palmar and dorsal sides of the hand for digit flexion and thumb opposition along with one housed inside the thumb for flexion. To actuate the hand, the servo motors and synthetic cables follow a common tendon-driven actuation mechanism (with the exception of the geared thumb opposition). Here a pulley adheres to the servo motor shaft on which the synthetic cable is attached. The cable transverses the finger and is attached to the fingertip. When the servo rotates in one direction the cable is wrapped around the pulley causing digit flexion. Digit extension is achieved via torsion springs built into each joint to return digits to their extended positions.

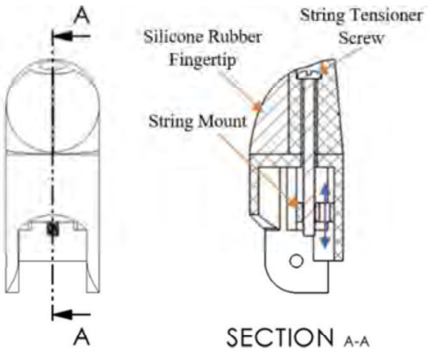

Figure 2. Cross-section of the distal and middle phalanx depicting the silicone rubber tip and the tendon tension mechanism. The string tensioner screw allows for the string mount to move up and down (motion given by the blue arrows) so that the string to be easily tensioned.

A novel cable tensioning mechanism is incorporated into each digit as depicted in Figure 2. The end of the synthetic cable is attached to a string mount that can be translated by tightening the string tensioner screw. Slack in the cable is inevitable and therefore the tensioning mechanism allows this to be mitigated. The BEAR PAW also includes silicone padded fingertips which aid in grabbing objects. These were made from Dragon Skin Silicone that were poured into 3D printed molds of the fingertips.

Electrical: The electronics enclosed in the hand consist of a 3.3V Arduino Pro Mini with an ATmega328 microcontroller, and a custom breakout board allowing for power connections and communication with external peripherals i.e., the six KST-X08 series servo motors and the HC-05 wireless Bluetooth module. The BEAR PAW can also be tethered to a computer by using a USB to UART breakout board and has six independently programmable degrees of freedom.

MECHANICAL & ELECTRICAL CHARACTERISTICS

The BEAR PAW was attached to a testing rig to obtain the mechanical and electrical characteristics of single-digit articulation along with 3 of the top 7 generalized hand grasps [14]. The force exerted by the hand, current under load, and power draw were captured. To obtain the mechanical force values, we developed a set of force-sensitive objects to be grasped by the BEAR PAW. Four custom manipulandum were fabricated to house calibrated SingleTact 8mm 10N miniature force sensors. An ACS723 current sensor was used to acquire the current load from the servo motors during actuation and the corresponding voltage was obtained to determine the power draw. These signals were passed into a National Instruments USB-6210 data acquisition system sampling at $4000\ Hz$ and were stored using a MATLAB script. An Arduino program was written to actuate each motion over a 5 second period which was repeated 10 times to collect sufficient data [16]. Manipulanda were strategically placed in front of the BEAR PAW to capture the mechanical and electrical values during motion postures. BEAR PAW actuation for each manipulandum is displayed in Figure 3 a-d.

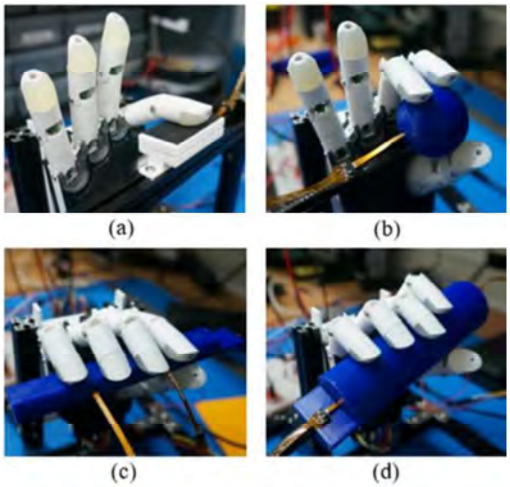

Figure 3. (a) Rectangular manipulandum used to test digit flexion and thumb opposition. (b) Sphere to test tripod (c) Flat edged small cylinder to test prismatic 4 finger grasp. (d) Large diameter cylinder to test power wrap.

A separate MATLAB script was written to read in the raw data for analysis. First, the force and current for each trial were converted from voltage via a linear transformation to newtons and amperes, respectively. Then each trial was cleaned to discard times when the hand was not active thereby collecting 2.5 seconds of force, current, and voltage data. The average force, current, and power values over the relevant time window were then calculated.

After obtaining the data for all ten trials across hand postures the averages and standard deviations for the force, current, and power were calculated. It was found that among the motion postures, the forces, currents, and power ranged from $0.76\ N - 7.22\ N$, $0.68\ A - 1.79\ A$, and $3.39\ W - 8.72\ W$, respectively. This is tabulated in Table 2. The force was obtained to determine the capacity in which the hand can effectively manipulate objects in a research setting. Additionally, the current and power define specifications for future non-tethered implementation.

Table 2. Average Mechanical and Electrical Characteristics

Motion Posture	**Mechanical and Electrical Characteristics**		
	Force (Newtons)	***Current (Amps)***	***Power (Watts)***
Digits 2-5 Flexion	1.709 (±0.076)	0.675 (±0.069)	3.388 (±0.343)
Thumb Flexion	0.761 (±0.042)	0.751 (±0.002)	3.763 (±0.010)
Thumb Opposition	2.454 (±0.069)	0.729 (±0.003)	3.656 (±0.014)
Wrap	7.216 (±0.578)	1.789 (±0.052)	8.718 (±0.242)
Tripod	2.989 (±0.253)	1.433 (±0.035)	7.030 (±0.166)
Prismatic 4 Finger	5.714 (±0.190)	1.644 (±0.068)	8.011 (±0.316)

FUTURE WORK & CONCLUSIONS

This paper presents the development of the BEAR PAW, an advanced multiarticulate pediatric prosthetic hand with similar dexterity to that of adult devices. As such, it has the capability to provide children with more dexterity through multiple grasping configurations. We present mechanical and electrical characteristics to evaluate the device's effectiveness as a research platform. The long-term goal of this work is to refine and release the BEAR PAW as an open-source research platform to study pediatric prosthetic use with dexterous devices. In preparation, we plan for expanded analyses to capture performance characteristics across a multitude of grasping configurations. Further, an in-depth analysis of the BEAR PAW's grasping and maintaining capabilities will be evaluated and compared to other prostheses using the AHAP test [17]. Preparations are currently underway for an open-source release which includes developing fabrication and assembly guides, building a comprehensive bill of materials, and refining software.

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