An Open Source 3D-Printed Transitional Hand Prosthesis for Children

Jorge M. Zuniga, PhD, Jean Peck, OTL, CHT, Rakesh Srivastava, MS, CPO, Dimitrios Katsavelis, PhD, Adam Carson, BS

ABSTRACT

Introduction: Advancements in computer-aided design programs, additive manufacturing, and open-source image editing software offer the possibility of designing, printing, and fitting transitional prosthetic hands and other prosthetic devices at very low cost. The development and use of 3D-printed transitional prosthetic devices to increase range of motion (ROM), strength, and other relevant variables would have a significant clinical impact for children with upper-limb deficiencies. Thus, the purpose of this study was to identify anthropometric, active ROM, and strength changes after 6 months of using a wrist-driven 3D-printed transitional prosthetic hand for children with upper-limb deficiencies.

Materials and Methods: Anthropometric, active ROM, and strength measurements were assessed before and after 6 months of using a 3D-printed transitional hand prosthesis. Five children (two girls and three boys, 3–10 years of age) with absent digits (one traumatic and four congenital) participated in this study and were fitted with a 3D-printed transitional hand prosthesis.

Results: There were significant hand × time interactions for the forearm circumference (p = 0.02), active ROM for flexion (p = 0.02), and extension values (p = 0.04). There were no significant hand × time interactions, however, for wrist flexion strength (p = 0.29), wrist extension strength (p = 0.84), active ROM for ulnar deviation (p = 0.5), active ROM for radial deviation (p = 0.25), and forearm skinfold values (p = 0.11).

Conclusion: Although durability, environment, and lack of printing standards for the manufacturing of 3D-printed prostheses are factors to consider when using these types of devices, the practicality and cost-effectiveness represent a promising new option for clinicians and those patients with upper-limb deficiencies living in developing countries. Thus, the Cyborg Beast transitional prosthetic hand represents a low-cost prosthetic solution for those in need of a transitional device to increase ROM and forearm circumference. (J Prosthet Orthot. 2016;28:103–108.)

KEY INDEXING TERMS: 3D printing, computer-aided design, low-cost prostheses, custom-made prostheses, prosthesis for children, range of motion

Children's prosthetic needs are complex because of their small size, constant growth, and psychosocial development. For most traumatic amputees, muscle atrophy, decreased mobility, and asymmetry are typical characteristics of the affected limb. Most upper-limb prostheses for children include a terminal device, with the objective to replace the missing hand or fingers. Electric-powered units (i.e., myoelectric) and mechanical devices (i.e., body powered) have been improved to accommodate children's needs, but the cost of maintenance and replacement makes their access difficult to many families.

The term transitional prosthesis has been widely used in the field of orthodontics, specifically with hemimandibulectomy patients. For upper- and lower-limb prostheses, however, these types of devices are referred as a “temporary prosthesis,” “initial prosthesis,” or “immediate postoperative prosthesis.” Previous investigations have used transitional prosthetic devices, such as opposition posts and thermoplastic devices, with the objective of restoring and preserving strength and range of motion (ROM) in children with upper-limb reduction deficiencies. Although functional, these devices may not be visually appealing to children, which may increase their rejection rates. Despite great efforts by nonprofit organizations, such as LN-4 and others, a number of children with upper-limb deficiencies from developing countries are still not being fitted with any type of prosthesis because of lack of trained technicians able to provide these services and a local shortage of the necessary componentry for the production of upper-limb prostheses. There is a critical need for practical, easily fitted and maintained, customized, aesthetically appealing, low-cost transitional prosthetic devices for children.
Advancements in computer-aided design programs, additive manufacturing, and open-source image editing software offer the possibility of designing, printing, and fitting transitional prosthetic hands and other prosthetic or assistive devices at very low cost.¹³,¹⁴ The development and use of 3D-printed transitional prosthetic devices to increase ROM, strength, and other relevant variables would have a significant clinical impact for children with upper-limb deficiencies. Thus, the purpose of this study was to identify anthropometric, active ROM, and strength changes after 6 months of using a wrist-driven 3D-printed transitional prosthetic hand for children with upper-limb deficiencies.

METHODS

EXPERIMENTAL DESIGN

Anthropometric, active ROM, and strength measurements were assessed before and after 6 months of using a low-cost 3D-printed prosthetic hand.

PARTICIPANTS

Five children (two girls and three boys, 3–10 years of age) with absent digits (one traumatic and four congenital) participated in this study and were fitted with a low-cost 3D-printed prosthetic hand (Table 1). Inclusion criteria included boys and girls from 3 to 17 years of age with unilateral carpus upper-limb reductions, missing one or all fingers, and wrist active ROM of the affected wrist greater than 20°. Exclusion criteria included upper-limb injury within the past month and any medical conditions that would contraindicate the use of the transitional prosthesis, such as skin abrasions and musculoskeletal injuries. All subjects completed a medical history questionnaire. All parents and children were informed about the study and parents signed a parental permission form. For children aged 6 to 10 years, an assent was explained by the principal investigator and signed by the children and their parents. In addition, detailed safety guidelines were given to the parents regarding the use and care of the prosthetic hand. Participants were asked to visit the laboratory on two occasions. During the first visit, fitting procedures and anthropometric measurements were performed. After 6 months of using the prosthesis, participants visited the laboratory for a second time and repeated all measurements performed during the first visit. The study was approved by the Creighton University Institutional Review Board.

ANTHROPOMETRIC AND ACTIVE ROM MEASUREMENTS

Six variables from the affected and nonaffected hands, including circumferences, skin folds, and active ROM for flexion, extension, radial deviation (RD), and ulnar deviation (UD), were measured on each research participant by a trained occupational therapist. Circumferences were measured three times over the maximal girth of the forearm proximal to the elbow joint. A standard Gulick anthropometric tape measure was used; the therapist ensured the tape was lying flat on the skin for accuracy purposes. Skin folds were taken three times at the maximal girth of the forearm (at the middle third of the forearm, superficial, and directly medial) over the flexor carpi ulnaris using a Lange skinfold caliper (Creative Health Process Products Inc, Ann Arbor, MI, USA). Wrist ROM measurements were performed by a certified hand therapist using the clinical assessment recommendations established by the American Society of Hand Therapists. With the forearm in neutral, wrist flexion was measured with one arm of the goniometer on the dorsum of the midforearm and the other arm along the dorsum of the middle metacarpal. Wrist extension was measured with the proximal arm of the goniometer on the midvolar forearm and the distal arm along the middle metacarpal on the palmar surface. For wrist UD and RD measurements, the subject’s elbow was flexed at 90°, with the forearm and hand supported on a table with the forearm in pronation. The goniometer axis was placed over the dorsal capitale with the proximal arm at the dorsal midline of the forearm. The distal arm was parallel to the longitudinal axis of the third metacarpal. The subject was asked to perform movement on the frontal plane in medial and lateral directions. For all ROM measurements, the forearm was stabilized to prevent pronation, supination, or shoulder rotation.

STRENGTH MEASUREMENTS

Wrist flexion and extension strength was measured for both hands using a muscle testing dynamometer (microFET3; Hoggan Health Industries, West Jordan, UT, USA). The investigator stabilized the applicator pad of the muscle testing dynamometer at the palm of the nonaffected hand and at the distal end of the affected hand with wrist and forearm in neutral position. The subject was asked to push the pad of the muscle testing dynamometer down toward flexion and extension of the wrist as hard as possible. Each measure was repeated three times for each motion and the average of the three measures was used for the analysis.

LOW-COST 3D-PRINTED TRANSITIONAL PROSTHETIC HAND CHARACTERISTICS

The low-cost 3D-printed transitional prosthetic hand prototype named “Cyborg Beast”¹⁵ (Figure 1) was designed using a modeling software program (Blender 7.2; Blender Foundation, Amsterdam, the Netherlands) and manufactured in the 3D Research & Innovation Laboratory at Creighton University using desktop 3D printers (Makerbot Replicator 2X, Makerbot Industries, Brooklyn, NY, USA; and Ultimaker 2, Ultimaker BV, Geldermalsen, the Netherlands). The Cyborg Beast hand was designed to allow easy fitting with minimal anthropometric measurement requirements.¹³ As previously reported,¹³ this fitting procedure can also be performed at a distance by obtaining three simple photographs. Briefly, after saving the image files with calibrated measurements, they were imported as plane files in Blender. Calibration of the metric scale on Blender was performed by changing the default unit (meter) to centimeters by adjusting

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD (range)</th>
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<tr>
<td>Age, y</td>
<td>6.60 ± 3.1 (3–10)</td>
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<tr>
<td>Body mass, kg</td>
<td>26.4 ± 11.4 (16.8–43.5)</td>
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<tr>
<td>Height, cm</td>
<td>122.9 ± 23.4 (98–137.2)</td>
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the scale to 0.001. The image plane was resized to match the size of the 1-cm background grid on Blender using the ruler on the imported image plane. The accuracy of the calibrations was confirmed using the interactive ruler tool in Blender by performing several measurements over the ruler included in the image plane. After the image plane was calibrated, customized adjustments to the hand prosthesis file were made on Blender to ensure proper fit. All custom adjustments were made by a trained 3D anatomical designer under the supervision of a certified prosthetist and a licensed hand therapist. It is strongly recommended to consult with clinical experts in the process of fitting the prosthetic device to avoid skin abrasions or breakdown due to improper fit.

Elastic cords placed inside the dorsal aspect of the fingers provide passive finger extension. Finger flexion is driven by nonelastic cords along the palmar surface of each finger and is activated through 20° to 30° of wrist flexion. The result is a composite fist (flexing the fingers towards the palm) for gross grasp.

The materials used for printing the prosthetic hand are polylactide (PLA) plastic and acrylonitrile butadiene styrene. Other components of the prosthetic hand include Chicago screws of various sizes, a 1-mm lift nylon cord, a 1.5-mm elastic cord, Velcro, medical-grade firm padded foam, a protective skin sock, and a dial tensioner system (Mid power reel M3; BOA Technology Inc, Denver, CO, USA). The average time to 3D print and fully assemble the prosthetic hand design is approximately 4 to 7 hours. The weight of a fully assembled hand for a 15-year-old boy is 184.2 g. The Cyborg Beast prosthetic hand is well suited for activities that involve the manipulation of light objects using lateral, power (composite), and spherical prehensile patterns. The fitting procedure for the prosthetic hand requires a few simple anthropometric measures of both limbs to properly scale the prosthetic device.13 The files for the design are available online on the National Institutes of Health 3D print exchange Web site (http://3dprint.nih.gov/discover/3dp-000524) and Thingiverse (http://www.thingiverse.com/thing:261462). The Cyborg Beast prosthetic hand has been labeled as an investigational device.

STATISTICAL ANALYSIS

ANTHROPOMETRIC, ACTIVE RANGE OF MOTION, AND STRENGTH MEASUREMENTS

Several separate two-way repeated-measures analysis of variance (2 × 2; hand [affected vs nonaffected] × time [before and after]) were performed to analyze the data. A p value of ≤0.05 was considered statistically significant for all comparisons.

RESULTS

The physical characteristics of the research participants are described in Table 1. Table 2 shows the mean ± SD for anthropometric, active ROM, and strength measurements.

There were significant hand × time interactions for the forearm circumference (F1, 4 = 16.90; p = 0.02), active ROM flexion (F1, 4 = 12.70; p = 0.02), and active ROM extension values (F1, 4 = 8.80; p = 0.04). There were also significant main effects for time (values collapsed across affected and nonaffected hands) for forearm circumference (p = 0.02), active ROM flexion (p = 0.02), and active ROM extension (p = 0.03). Furthermore, there were significant main effects for hand (values collapsed across time) for forearm circumference (p = 0.04), active ROM UD (p = 0.03), and active ROM RD (p = 0.03). There were no significant hand × time interactions, however, for wrist flexion strength (F1, 4 = 1.48; p = 0.29), wrist extension strength (F1, 4 = 0.05; p = 0.84), active ROM UD (F1, 4 = 0.65; p = 0.5), active ROM RD (F1, 4 = 1.77; p = 0.25), and forearm skinfold values (F1, 4 = 4.24; p = 0.11).

All five families and children participating in this study completed a short survey. The survey was developed to estimate the impact of this prosthetic device on items related to quality of life, daily usage, and types of activities performed. The survey has not been statistically validated but provides useful information related to daily usage. After 6 months of using the prosthetic hand, four children reported using the hand 1 to 2 hours a day and one reported using the hand 4 to 6 hours a day. Furthermore, children reported using the prosthetic hand just for fun (n = 5), for activities at home (n = 4), to play (n = 5), for school activities (n = 4), and to perform sports (n = 1).

DISCUSSION

The main finding of the present investigation was that use of a low-cost 3D-printed transitional prosthetic hand significantly increased forearm circumference (before, 16.70 ± 1.86 cm, and after, 17.80 ± 1.48 cm), wrist active ROM for flexion (before, 54.60° ± 14.48°, and after, 68.40° ± 14.29°), and extension (before, 40.40° ± 37.75°, and after, 47.00° ± 36.42°) on a small
sample of children with upper-limb deficiencies. Muscle strength of the wrist flexors (before, 14.07 ± 14.8 kg, and after, 17.72 ± 3.78 kg) was not statistically greater than the nonaffected hand (before, 17.89 ± 7.74 kg, and after, 19.08 ± 8.47 kg). This finding may have resulted from the small sample size (n = 5) and the great variability in force production among our research participants (Figure 2).

The use of transitional prosthetic devices to restore and preserve strength and ROM in children with upper-limb reduction deficiencies has been described by previous investigations.6,7 For example, Bryant et al.6 developed a transitional terminal device with the purpose of restoring opposition, sensory functions, and control of grip strength in 12 children between 2 and 11 years of age with congenital aphalangia or adactylia. The terminal device consisted of an opposition post strapped to the forearm by Velcro straps. The authors indicated that the use of the opposition post preserved sensory feedback and improved grip strength and overall function. Although no quantitative data were reported for the complete data set, the authors reported a pinch on the affected side of 7.7 kg compared with 4.54 kg on the nonaffected side for a 14-year-old research participant.

In addition, Shim et al.7 reported a case of a 52-year-old woman with thumb and index finger disarticulation who used a transitional hand prosthesis made of low-temperature thermoplastic designed to increase strength and ROM of the three remaining fingers and to prevent phantom pain. After restoring strength and ROM in the affected hand, the research team designed the final wrist-driven hand prosthesis.

The increase in circumference and wrist ROM found in the present investigation suggests that a low-cost 3D-printed prosthesis can be effectively used as a transitional or initial device in children with traumatic or congenital upper-limb deficiencies (Figures 2 and 3). The increases in circumference and active ROM for flexion and extension of the affected wrist after using a low-cost 3D-printed transitional prosthetic device suggests added benefits to the use of this type of device beyond gains in function. These findings also suggested that transitional prostheses may play an important role in patient rehabilitation and prescription of standard prostheses.6,7 The transitional prostheses used in previous investigations6,7 were constructed using standard methodology and were customized to the patients’ needs and particular hand morphology. Some individuals from

### Table 2. Mean ± SD for anthropometric, active range of motion, and strength measurements before and after 6 months of using the 3D-printed hand prosthesis

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Nonaffected</th>
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<th>Affected</th>
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<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
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<tr>
<td>Forearm circumference, cm²</td>
<td>18.30 ± 2.08</td>
<td>18.70 ± 12.04</td>
<td>16.70 ± 1.86</td>
<td>17.80 ± 1.48</td>
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<tr>
<td>Skin folds, mm</td>
<td>7.40 ± 2.41</td>
<td>7.60 ± 2.51</td>
<td>8.60 ± 2.07</td>
<td>7.60 ± 2.07</td>
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<tr>
<td>Active ROM flexion, °</td>
<td>76.40 ± 6.43</td>
<td>76.20 ± 5.54</td>
<td>54.60 ± 14.48</td>
<td>68.40 ± 14.29</td>
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<tr>
<td>Active ROM extension, °</td>
<td>76.00 ± 5.61</td>
<td>76.20 ± 5.22</td>
<td>40.40 ± 37.75</td>
<td>47.00 ± 36.42</td>
</tr>
<tr>
<td>Active ROM UD, °</td>
<td>30.20 ± 7.29</td>
<td>36.40 ± 10.36</td>
<td>16.80 ± 13.31</td>
<td>19.80 ± 9.26</td>
</tr>
<tr>
<td>Active ROM RD, °</td>
<td>31.60 ± 9.53</td>
<td>33.00 ± 2.65</td>
<td>16.20 ± 13.26</td>
<td>25.60 ± 11.13</td>
</tr>
<tr>
<td>Wrist flexion strength, kg</td>
<td>17.89 ± 7.74</td>
<td>19.08 ± 8.47</td>
<td>14.07 ± 14.8</td>
<td>17.72 ± 3.78</td>
</tr>
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ROM, range of motion; RD, radial deviation; UD, ulnar deviation; ANOVA, analysis of variance.

* The results of the two-way repeated-measures ANOVA for forearm circumference showed a significant two-way interaction for hand × time and significant main effects for time and hand.

* A two-way interaction for hand × time and a significant main effect for time were also found for active ROM flexion and extension.

* Main effects for hand were found for active ROM RD and UD.

Figure 2. Individual changes for forearm circumference and strength for wrist flexors before and after a 6-month period of using the 3D-printed transitional hand prosthesis.
3D-printed transitional hand prosthesis. Flexion and extension before and after a 6-month period of using the 3D-printed transitional hand prosthesis. A 3D-Printed Transitional Hand Prosthesis for Children

Recent advances in manufacturing technology allow the production of 3D-printed prosthetic hands from a customized digital file. Recently, Zuniga et al. validated a distance fitting methodology for a popular open-source 3D-printed prosthetic hand named Cyborg Beast. This prosthetic prototype or transitional prosthetic device can be fitted at a distance according to the patient’s needs and manufactured using small, cost-effective desktop 3D printers. Conceivably, a 3D-printed device, such as the Cyborg Beast, in conjunction with a licensed prosthetist, could provide a 3D-printed transitional prosthetic hand to those around the globe in need at very low cost. It has to be noted, however, that the durability of 3D-printed prostheses and environmental factors that affect them, such as temperature, can restrict large-scale use of this type of device. In the present investigation, three of the five children participating in the study reported breaking or malfunctioning of the 3D-printed hand prosthesis. The main problem with the current materials used for 3D-printed prostheses, such as PLA polymers, is the lack of thermal stability at elevated temperatures. In the presence of moisture and at high temperatures, PLA degrades considerably, affecting the durability and function of these devices. Furthermore, there are no standards for manufacturing 3D-printed prostheses, which makes it difficult to obtain a reliable print. Although durability, environment, and lack of 3D-printing standards are factors to consider when using 3D-printed prostheses, practicality and cost effectiveness represent promising new options for clinicians and their patients.

Children have a high rejection rate for upper-limb prostheses. It is feasible that low-cost, open-sourced 3D-printed prosthetic hands as described in the current study could be used as transitional devices in preparation for a standard or more sophisticated hand prosthesis. The 3D printing technology for the development of hand prostheses is at a very early stage in development, and the supervision of a certified prosthetist is crucial for the proper development and use of these devices. Thus, it is strongly encouraged to include certified prosthetists and other health care professionals in the development, fitting, and testing of 3D-printed prosthetic devices. Furthermore, future investigations should examine the functionality, durability, safety, and development of 3D-printing standards for these types of prosthetic devices.

ACKNOWLEDGMENT

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REFERENCES

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