Using a 3D-Printed Prosthetic to Improve Participation in a Young Gymnast

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Background and Purpose: The purpose of this case report was to investigate the application of a 3-dimensional (3D)-printed prosthetic hand to improve a child’s participation, confidence, and satisfaction in gymnastic classes, specifically, horizontal bar-related skills.

Summary of Key Points: A 9-year-old child was unable to participate in horizontal bar-related gymnastic skills due to a congenital hand deficiency. A prosthetic hand was designed, 3D printed, modified repeatedly, and incorporated into a program, which resulted in improvements in the child’s ability to participate in gymnastics.

Conclusions: Using a 3D-printed upper limb prosthetic hand improved the child’s participation, confidence, and satisfaction in her gymnastic classes permitting use of horizontal bar. To progress to higher-intensity activities, further safety measures and testing of the prosthetic hand are needed.

What This Case Adds to Evidence-Based Practice: A 3D-printed prosthetic hand was manufactured and customized allowing closely monitored, gradually increased, participation in horizontal bar gymnastics. (Pediatr Phys Ther 2021;33:E1–E6)

Key words: 3D printing, congenital upper limb deficiency, gymnastics, ICF-CY, participation, prosthetics

INTRODUCTION

Upper limb deficiency is a physical condition that occurs when a portion of a child’s upper extremity fails to form completely in utero (congenital) or when disease or injury requires amputation (acquired). In the United States, the Centers for Disease Control and Prevention estimates upper limb deficiencies occur in 4 of every 10,000 births.1 The majority of upper limb deficiencies (58%) are congenital, due to genetic, vascular, teratogenic, amniotic bands, or of unknown etiology.2 Upper limb deficiencies in children, whether congenital or acquired, can cause limitations in a child’s ability to fully participate in functional or recreational activities.3,4 Children with congenital upper limb deficiencies may have impairments such as muscular weakness, muscular contractures, and skin breakdown, all of which can limit independence in activities. Common activity limitations include difficulty with dressing and other self-care tasks, difficulty with ball skills, and difficulty with activities that involve bimanual coordination.5 Depending on the complexity of the activities and severity of the upper limb deficiency, the child’s levels of participation, confidence, and satisfaction in performing those activities can vary.

A child can be trained to use a prosthetic device to improve participation in activities of daily living and recreational activities. A significant obstacle for manufacturing an upper limb prosthetic is creating a device that mimics the dexterity needed in the upper limb as well as accommodating the growth of the child.

Using a 3-dimensional (3D)-printed prosthetic device has many positives for children with an upper limb deficiency because it can be individually customized in a time-efficient manner with low manufacturing costs.5–9 While professional body-powered prosthetics can cost several thousands of dollars and take months to produce, a 3D-printed prosthesis can cost as little as $20 to $50 and can be produced within days.10 The low cost and efficiency of production allows for creation of updated customized prosthetic devices to accommodate for the child’s growth and meet individualized needs of the child. In addition to meeting the needs of a growing child, 3D-printed prosthetics allow for quick and easy adaptations to improve participation, confidence, and satisfaction in recreational sports and activities. For example, a child might require one type of prosthesis to hold a musical instrument and a different prosthesis for catching a ball.11

Currently, many prosthetic hand designs are created by volunteers or “citizen engineers,” which are then provided to organizations such as e-NABLE, Robohand, Magic Arms, and Open Bionics. Between 2012 and 2014, organizations such as e-NABLE have created online repositories of open-source files providing an opportunity for anyone with access to a 3D printer to produce a prosthetic hand.12 If a 3D printer is not readily
available, e-NABLE also provides a list of volunteers who will print and build a hand for the cost of the materials.

3D-printed prosthetics has many positives that can benefit many, but there are negatives that should be considered. The most important is safety of the device printed. In 2016, the Food and Drug Administration (FDA) created guidelines to address the concerns related to 3D printing medical devices, stating that 3D-printed devices should meet the same regulations as their non-3D-printed counterparts. However, the guidelines are ambiguous on how nonhospital or nonclinical sites are regulated, for example, “citizen engineers.” In 2018, Diment et al reviewed the available literature and found limited evidence of the efficacy or effectiveness of using 3D-printed upper limb prosthetics in a clinical setting and could not find any articles or outcomes on the use of 3D-printed prosthetics for improving participation during recreational activities.

**PURPOSE**

The purpose of this case report was to investigate the application of a 3D-printed prosthetic hand to improve a child’s participation in beginning gymnastic classes, specifically horizontal bar-related skills. This case study was not intended to be a physical therapy clinical intervention, but rather an academic inquiry into the application of 3D-printed prosthetics using physical therapy principles as a guide. Consent was obtained from the child’s guardians and assent was given from the child. Institutional Review Board approval was obtained.

**CASE DESCRIPTION**

A 9-year-old girl with a left congenital hand deficiency was referred to the University of Jamestown Physical Therapy Program by TNT Kid’s Fitness, a nonprofit organization. TNT Kid’s Fitness provides gymnastic training for children of all abilities. The child who participated in this case report had recently joined the beginner-level gymnastic class. The child was independent and successful in all aspects of the beginning-level gymnastic curriculum; however, coaches identified that the child’s congenital left hand deficiency limited her participation during horizontal bar-related activities.

**Evaluation**

Our main objective for this case study was choosing a prosthetic design that would meet the specific demand of gymnastics, accommodate her future growth, be acceptable to the child, and be cost-efficient for the family. Once the appropriate hand was selected and produced, the following goals were developed to determine whether the application was successful: using her prosthetic hand, the child will be able to: (1) hang for 5 seconds from a low horizontal bar with knees off the ground; (2) hang for 5 seconds from a high horizontal bar with feet off the ground; (3) complete a chin-up; (4) complete a pull-over; (5) improve participation in gymnastics; (6) improve confidence in gymnastics; and (7) improve satisfaction in gymnastics. All goals were to be completed within 14 weeks, so the child could progress to more advance classes.

To understand the factors associated with her participation during gymnastic horizontal bar-related activities, investigators used the World Health Organization’s International Classification of Functioning, Disability and Health: Children and Youth Version (ICF-CY) (Figure 1). The ICF-CY is a framework by which to classify Body Structures and Function, Activity, Participation, Personal, and Environmental factors of a child.

**ICF-CY: Body Structures and Functions.** Upon examination, the child’s wrist and hand had preserved functional movements, including full wrist flexion and extension, abduction and adduction, and partial opposition between the medial and lateral side of the palm. Weakness was noted in bilateral shoulder abduction, wrist flexion, and wrist extension.

**ICF-CY: Activity and Participation.** The preserved functional movements and strength in her affected hand allowed for participation in all elements of the gymnastic class, with the exception of horizontal bar-related activities. The missing digits resulted in a mechanical disadvantage when trying to hang on the gymnastic bar or perform other bar-related skills (Figure 2a). For example, she needed to flex her wrist around the bar to attempt to hold her body weight in a hanging position. Often
Fig. 2. (a) Child's hands: Anatomically, on the lateral side of her affected hand, the base of the first metacarpal is present with a shortened appendage that included a thumbnail. Along the distal margin of her affected hand, there were small appendages where the full digits would be present. From a dorsal view, her hand forms a shallow “v.” (b) Modified Talon hand. (c) Hanging on the horizontal bar. Child is able to hang and swing on the horizontal bar using modified Talon hand and a trained spotter present.

this method of hanging leads to short hang times (3 seconds) and significant upper extremity fatigue. The short hang times prevented her attempting skills such as a “chin hold” and a “pullover,” which were required for her to advance beyond the beginner-level class.

ICF-CY: Personal and Environmental Factors. When investigators met the child, she was living with a foster family. Her foster family was supportive and encouraged her to explore various sports and recreational activities. During the gymnastic class, her participation was limited only during horizontal bar-related activities. When asked to participate in gymnastic bar-related activities, the child was initially apprehensive and was uncomfortable when other gymnasts would ask about her affected hand.

Intervention

The intervention that was targeted for this case was to design, fit, and train the child to use a prosthetic hand during horizontal bar activities in her gymnastic class. Since the child had sufficient strength, coordination, and range of motion in her affected hand, a mechanically based prosthetic hand was appropriate.

3D Printing. The e-NABLE organization Web site was used to find a prosthetic hand device that met the needs of the child. The e-NABLE site contains open-source files for 3D printing a prosthetic hand device. When choosing a specific prosthetic device, the investigators considered the preferences of the child and the mechanical capabilities of the prosthetic hand for application to horizontal bar-related gymnastic activities. Based on the preserved function in the child’s affected upper limb, a wrist-powered device was decided to be the most appropriate. The hand design chosen for the child was the Talon hand. Files for the Talon hand were downloaded and scaled to fit the child’s hand based on the e-NABLE scaling tutorials. Once the file was scaled, it was printed by a Lulzbot TAZ 6. Polylactic acid (PLA) filament was used with a nozzle temperature of 210°F, print bed temperature of 60°F, print speed of 50 mm/second, infill of 60%, and a layer resolution of 0.35 mm. The original printing and assembly process was completed in less than 2 days. Hardware
and filament used to print and assemble the original hand cost approximately $25.

**Pilot Trial.** Once the composite design was assembled, the child was asked to trial the prosthetic hand at University of Jamestown Physical Therapy Program’s research laboratory. The child’s perception and acceptance of the prosthetic hand were important to investigators to ensure the motivation of the child to use the hand. During the initial trial, overall fit, comfort, and function were assessed using feedback from the child. She practiced using the device by flexing and extending her wrist to open and close the prosthetic hand. Once she was comfortable performing the movements necessary to open and close the prosthetic hand, she completed functional tasks such as picking up a water bottle and catching a tennis ball. Once functional tasks were attempted, the child grasped and released on a parallel bar and simulated a hanging position with force through the fingers of the hand. Based on the trial, investigators determined that the child responded well to using the prosthetic hand and appeared motivated to continue the trial in the gymnastic setting. Additionally, the prosthetic hand was capable of supporting a simulated hanging position without any discomfort to her affected hand and the structure of the prosthetic hand remained intact.

**Experimental Trials in Gymnastics.** In her first 8-week session, the child participated in the “beginner” class with required criteria to advance to the next level (Appendix 1). As her class transitioned to the bar, the child was assisted by a student physical therapist in donning her prosthetic hand to ensure comfort and fit. The child trialed the prosthetic hand initially by testing her ability to perform and maintain a dead hang position on the horizontal bar (Figure 2c). She also trialed swinging and a “chin hold” at the horizontal bar using the prosthetic hand. In her second 8-week session, the child used the prosthetic hand to perform low bar pull-ups and to learn the “pull-over” skill. A trained spotter was present throughout all of her trials to ensure safety.

**Measurement.** To determine whether the prosthetic hand improved participation in horizontal bar-related skills, 3 data points were collected with and without the prosthetic hand. First, hang time was measured in a dead hang position to determine whether the prosthetic device increased hang time. The next 2 data points were observing if the child could successfully complete 2 specific gymnastic skills of a “chin-up” and a “pull-over.” The “chin-up” is successfully completed if a child can pull her chin to the bar and hold for 5 seconds. The “pull-over” is considered successful when the child can swing and rotate their body around a low horizontal bar. A “pull-over” consists of grabbing the bar with fingers facing away, stepping forward with one leg and swinging the opposite leg to create momentum to rotate the body over the bar finishing with arms extended and maintaining an upright position before dropping to the floor.

In addition to gymnastic improvements, the child was asked to (1) rate her ability to participate in gymnastics with and without the prosthetic hand; (2) rate her level of confidence in completing bar-related activities and advancing class levels with and without the prosthetic hand; and (3) rate her level of satisfaction with gymnastics with and without the prosthetic hand (Appendix 2).

**Prosthetic Redesign.** The Talon hand used in this case report was printed using PLA. PLA is a hard plastic that provided the strength needed for the child to safely use the prosthetic hand during horizontal bar-related gymnastic activities. Manufactures of the 3D printing filament provide tensile strength of their product, but the documented strength does not translate to an assembled prosthetic hand composed of multiple printed components that are withstanding variable forces. There are other types of filament that will increase the strength of the device, but cost was a necessary consideration for the project to be viable.

Printing parameters determined how the prosthetic hand withstood the forces of hanging and rotating on a gymnastic horizontal bar. The original design of the Talon hand worked well for a functional grasp, but did not tolerate the forces applied when the child was hanging from the gymnastic bar. This resulted in one redesign and reprinting of parts after 2 weeks of use during gymnastic classes (Figures 2b and 3a). To correct for layer separation, parts of the hand were printed in a different orientation that positioned the PLA layers parallel to the forces created when hanging and rotating on the gymnastic horizontal bar (Figures 3b and 3c). The prosthetic hand was...

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![Fig. 3. Prosthetic redesign. (a) Child wearing the modified Talon hand. Yellow arrow indicates the modification to prevent phalanges from full extension. Red arrow indicates the location of layer separation when hanging with the prosthetic hand. (b) A simplified visual model representing the original print. The white and blue lines represent the individual layers of the 3D print. The yellow circle represents a pin holding the proximal phalange to palm of hand. The orange arrow represents the direction of the force produced by the body weight on the pin during hanging on the bar. Directional force from the body weight separated the layers (blue and white lines) of the finished 3D-printed hand. The red line indicates the separation of printed layers when force was applied. (c) A simplified visual model representing the revised printing orientation. Printed layers (blue and white lines) are now parallel to the downward force produced by body weight resulting in no separation of printed layers.](Image)
also modified to strengthen the weak points of the hand, which included the connection between the digits and the palm as well as the attachment point of the tension cord at the tips of distal digits. The modification did restrict the range of motion of the digits, but did not affect the child’s ability to grasp the gymnastic bar. This modified version of the Talon hand was able to support the weight of the child for increased hang time and also allowed for the child to swing and complete a “pull-over.” A more detailed structural analysis of the prosthetic hand will need to be completed if the child advances to more complex gymnastic horizontal bar skills. Once the modifications were made, the hand did not need a redesign for the duration of the case study spanning the time of 14 weeks (1 hour per week).

The redesigns of the prosthetic hand did not increase the overall cost of the project. Cost was minimized by redesigning only individual 3D-printed parts of the hand. The more expensive hardware could be reused from the previous design, which resulted in an additional cost of $5 to $10 for the extra printing filament. It took less than 24 hours to print and reassemble the redesigned 3D-printed prosthetic hand. Including the original and the redesigns, the total cost of the prosthetic hands was less than $40 and was completed in less than 3 days’ time.

RESULTS

Results of using the prosthetic hand for horizontal bar-related gymnastic skills are in the Table. The child was able to increase hang time using the prosthetic hand on the low and high bars to 28 seconds. Using the prosthetic hand, she was able to successfully complete a “chin hold,” which allowed her to pass the “beginner”-level class. She was also able to complete the “pull-over,” but did require some assistance from the coaches, preventing her from passing the “advanced beginners” class. The child also responded to a 5-point Likert survey given by investigators with noted improvements in her participation, confidence, and satisfaction while using the prosthetic hand. Participation increased from (2) poor participation without the prosthetic to (4) good participation with the prosthetic. Confidence increased from (2) slightly confident without the prosthetic to (4) mostly confident with the prosthetic. Satisfaction with gymnastics increased from (2) slightly satisfied without the prosthetic to (4) mostly satisfied with the prosthetic.

DISCUSSION

For this child, application of a 3D-printed prosthetic hand resulted in positive outcomes in horizontal bar-related gymnastic activities. Due to the specific function of the prosthesis for this child, outcome measures such as the ABILHAND-Kids or the University of New Brunswick Test of Prosthetic Function were not appropriate to administer. The following considerations should be made when applying 3D-printed upper limb prosthetics for improving participation in gymnastic activities.

Safety

The material properties of the PLA plastic are available, but how the information was gathered by the manufacturers is inconsistent. The material properties do not take into account multipart assemblies that withstand various forces, thus there is a level of failure risk. Considering the possibility of failure and to maximize the safety of the child, the progression of moving from hanging on the gymnastic bar to the “pull-over” skill was completed in increments. Initially, the child hung from a low bar with her knees close to the ground and progressed to a high bar where the child’s feet were elevated off the ground. When the child was participating in gymnastic bar-related activities, a trained spotter was present.

Currently, there is little guidance on best practices to 3D print an upper limb prosthetic hand. In terms of 3D printing, the FDA has approved software for the development of medical devices; however, software restriction is specified for implantable devices and not prosthetic hands.5,11,13 With limited guidelines and regulation, caution is advised when using 3D printing for the fabrication of upper limb prosthetic hands for activities where the device could fail leading to injury. All factors of the 3D printing process should be considered to maximize the safety for an individual to use for activities beyond function grasp.

CONCLUSIONS

Using a 3D-printed upper limb prosthetic hand improved participation, confidence, and satisfaction of a 9-year-old child in her gymnastic classes. The cost-effectiveness allowed researchers the ability to modify the prosthetic hand to add the necessary strength and durability for use on the gymnastic horizontal bar. Our results were positive for the beginner activities; however, as the activities become advanced, further safety measures and testing of the prosthetic hand are warranted. A detailed analysis of durability and strength of the prosthetic hand should be made, as an individual moves from beginner activities to advanced activities.

<table>
<thead>
<tr>
<th>Using Her Prosthetic Hand, Child Will Be Able to</th>
<th>Evaluation No Prosthesis October 2018</th>
<th>Reevaluation With Prosthesis May 2019</th>
<th>Goal Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hang for 5 s on low and high bar</td>
<td>3 s</td>
<td>28 s</td>
<td>Goal met</td>
</tr>
<tr>
<td>Complete a chin hold</td>
<td>Unable</td>
<td>Independently for 5 s</td>
<td>Goal met</td>
</tr>
<tr>
<td>Complete a pull-over</td>
<td>Unable</td>
<td>Able to with minimal assistance from coach</td>
<td>Goal met</td>
</tr>
<tr>
<td>Improve participation</td>
<td>2 (poor)</td>
<td>4 (good)</td>
<td>Goal met</td>
</tr>
<tr>
<td>Improve confidence</td>
<td>2 (slightly)</td>
<td>4 (mostly)</td>
<td>Goal met</td>
</tr>
<tr>
<td>Improve satisfaction</td>
<td>2 (slightly)</td>
<td>4 (mostly)</td>
<td>Goal met</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS
Thank you to everyone for their contributions: University of Jamestown Physical Therapy Program, TNT Kids Fitness, Gregory Gass, PhD, Mitch Wolden, PT, PhD, Shelby Gusfa, PT, DPT, and Connie Miller, PT, DPT, the participating child and her family.

REFERENCES

APPENDIX 1
Skills Needed to Pass Class Levels

<table>
<thead>
<tr>
<th>Without Prosthesis</th>
<th>With Prosthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginner girls class</td>
<td></td>
</tr>
<tr>
<td>Positions</td>
<td>X</td>
</tr>
<tr>
<td>Straight arm bridge</td>
<td>X</td>
</tr>
<tr>
<td>Handstand</td>
<td>X</td>
</tr>
<tr>
<td>Cartwheel</td>
<td>X</td>
</tr>
<tr>
<td>Forward roll</td>
<td>X</td>
</tr>
<tr>
<td>Backward roll</td>
<td>X</td>
</tr>
<tr>
<td>Static chin hold</td>
<td>X</td>
</tr>
<tr>
<td>Advanced beginner girls class</td>
<td></td>
</tr>
<tr>
<td>Bridge kick-over</td>
<td>X</td>
</tr>
<tr>
<td>Handstand to bridge</td>
<td>X</td>
</tr>
<tr>
<td>Run hurdle cartwheel</td>
<td>X</td>
</tr>
<tr>
<td>Backward roll to pike stand</td>
<td>X</td>
</tr>
<tr>
<td>Handstand Forward roll</td>
<td>X</td>
</tr>
<tr>
<td>Split jump</td>
<td>X</td>
</tr>
<tr>
<td>Pull-Over</td>
<td>X</td>
</tr>
</tbody>
</table>

APPENDIX 2. Survey of Participation, Confidence, and Satisfaction
This form is for the child to fill out. It may be helpful to read it to her and explain the questions.

Participation Scale
1 = No Participation, 2 = Poor Participation, 3 = Fair Participation, 4 = Good Participation, 5 = Full Participation
- Rate your ability to fully participate in gymnastics without using the prosthetic hand.
Response __________

- Rate your ability to fully participate in gymnastics using the prosthetic hand.
Response __________

Confidence Scale
1 = Not Confident, 2 = Slightly Confident, 3 = Somewhat Confident, 4 = Mostly Confident, 5 = Completely Confident
- Rate your confidence with completing bar-related activities without your prosthetic hand.
Response __________

- Rate your confidence with completing bar-related activities with your prosthetic hand.
Response __________

Satisfaction Scale
1 = Not Satisfied, 2 = Slightly Satisfied, 3 = Somewhat Satisfied, 4 = Mostly Satisfied, 5 = Completely Satisfied
- Rate your level of satisfaction with gymnastics when participating without the prosthetic hand.
Response __________

- Rate your level of satisfaction with gymnastics when participating with the prosthetic hand.
Response __________

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