Automated Sizing of 3D Scan-Based Robotic Exoskeleton Braces

Krishna Sarvani Desabhotla[1,2], Alexander G. Steele[2,3,4], David Eguren[2,3], and Jose L. Contreras-Vidal[1,2,3,4]

[1]Department of Biomedical Engineering, University of Houston
[2]Laboratory for Non-Invasive Brain Machine Interface Systems
[3]NSF IUCRC BRAIN University of Houston
[4]Center for Neuroregeneration, Houston Methodist Research Institute

Abstract— **Robotic-assisted gait therapy is becoming an increasingly common method of providing lower-limb gait assistance; however, there are limited options for pediatric populations who suffer from limited mobility issues. We propose a pediatric gait rehabilitation and mobility system with custom 3D printed braces built from lower limb 3D scans. Such a system can be manufactured and reprinted effectively to grow with a child without the traditional cost associated with assistive device replacements. Our initial design consisted of 3D printing carbon fiber braces based on user measurements, but issues with breathability and friction lead us to transition to an entirely 3D printed brace built from 3D scan dimensions and joint positions. The process to create a complete set of braces for a single user typically takes 5-6 hours. We are currently working on a technique that enables a template brace created from one 3D scan to readjust and reorient to another with minimal steps through the integrated use of static and dynamic variables to define the various brace elements to create custom fitted braces within minutes. This process can be applied to various exoskeletons, orthotics and prostheses as well as any field requiring customizable manufacturing.**

I. Background

Robotic-assisted gait therapy has emerged as a method of providing lower-limb gait therapy in a customizable manner that allows for longer training duration, repeatable walking patterns and is safe for physical therapists. Lower-limb exoskeletons are capable of providing gait therapy and mobility assistance outside of research and clinical settings. Unfortunately, the options for pediatric users are limited. Therefore, we are developing a gait rehabilitation and mobility system for children with cerebral palsy, spinal cord injury (SCI), spina bifida and other mobility limiting conditions [1].

A. Need for Flexibility

Cerebral Palsy is the leading cause of pediatric mobility limitations, occurring in 2-3 per 1,000 children in the U.S. annually [2] and has a global prevalence of 17 million individuals [3]. Children with cerebral palsy often present with musculoskeletal abnormalities that make the development of a generic rehabilitation system difficult. We have developed a method of creating device braces based on user-specific anatomy. The custom braces are intended to add improved fit and increased torque transfer between the user and the device. The braces incorporate design patterns that increase breathability to reduce sweating that could lead to rubbing and skin irritation in populations with high levels of skin sensitivity. Additionally, the braces provide the connection between the device actuators, which are located in each hip, knee and ankle joint and provide torque assistance in the user's sagittal plane. As a child grows, a new set of braces can be manufactured, and when attached to the device would provide the necessary increase in length required between joints.

II. Initial Design

Initial attempts to create custom braces, that could also act as a framework to connect actuators, featured a carbon fiber hand layup method with a 3D printed framework interior. The interior framework was based on a 3D scan of the user's legs. A vacuum pump seal held the carbon fiber in place around the 3D printed framework while epoxy cured to seal the brace shape. This method produced braces that closely resembled a user's anatomy, but the hand layup method resulted in large pockets that were later filled with epoxy. The braces did not provide breathability and also resulted in rubbing during use.

The decision was made to transition to an entirely 3D printed brace reinforced with materials such as Kevlar to increase the structural integrity while retaining a light weight.

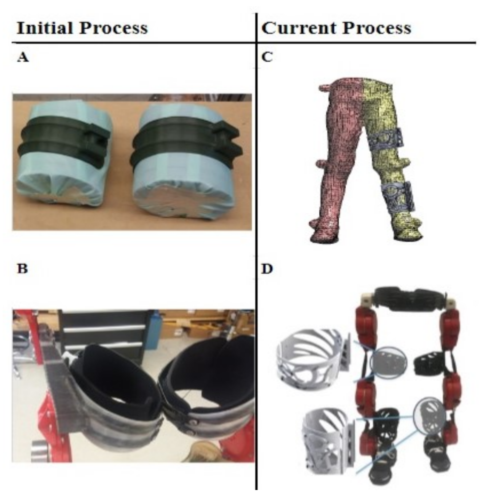

Fig. 1: The braces were originally built using foam formed to subject measurements **(A)**. The brace was 3D printed with carbon fiber and assembled with the exoskeleton **(B)**. We currently use a 3D scan of subject to design custom braces **(C)** that are then 3D printed with a nylon and Kevlar composite and assembled **(D)**. [1], [4]

III. Methods

A. 3D Scanning

3D scanning was done with the legacy 3D Systems iSense scanner^{TM} - a cost-efficient, structured-light-based handheld device fitted for Apple^{TM} devices. Since users may not be able to stand for the 3D scanning process, an alternative method was developed and tested with able-bodied subjects. Subjects were seated with hips and heels supported and legs outstretched, allowing access to the full leg for scanning. Joint and angle information was determined by placing a marker on the joints. Completed scans were stored as a mesh in .stl format.

B. Brace Design

The main concern for designing a pediatric exoskeleton brace is finding a balance between user comfort, structural reliability and minimizing interference with range of motion. These considerations lead to geometries that are not easily machined and require 3D printing.

It is important to account for breathability, so our brace incorporates an open design without compromising structural integrity, with a skin safe ethylene-vinyl acetate (EVA) foam placed between the brace and the skin to maximize comfort.

To design the brace in SolidWorks^{TM}, the 3D scan mesh is converted to a surface, which is used to define the brace surface and the joint angles that are used to build the braces as shown in Fig.1.

The brace structure and joint markers, the various brace elements, such as the fitment system, the required connections to the exoskeleton, and design elements for increased breathability are defined using static variables. This process is time-consuming, requiring 5-6 hours to create a set of braces for a single user.

C. 3D printing

Because of the complex geometry and the low production volume of the exoskeleton braces, rapid prototyping by 3D printing was selected as the creation method. The Markforged^{TM} 3D printer has the capability to incorporate a continuous fiber inlay into the part, which provides a strength to weight ratio similar to aluminum when using a carbon fiber inlay [5]. Additionally, since different continuous materials can be selected for the inlay, the parts can be tailored to the use case.

Due to the cyclical loading applied to the braces, Kevlar inlay was chosen, because it has similar material properties in tension to carbon fiber but is not as brittle in compression making it ideal for this use [5]. 3D printing of the braces provides flexibility to iterate the design to maximize subject comfort during use.

IV. Current Work

Our aim is to create a process that minimizes brace creation time by creating a template brace that will reorient and adjust to an imported scan with minimal steps.

We developed a proof of concept for the brace transfer process that uses both static and dynamic variables for defining various brace elements instead of orienting objects in reference to 3D space as is common practice in solid modeling. Static variables are used for attachment elements that connect to external systems and remain constant, independent of scan dimensions. Dynamic variables are defined from scan surface dimensions and are used to define design elements that need to adjust according to the subject's size.

By changing the reference surface and joint locations of the template brace from one scan to another, the custom fitted brace can be created within minutes.

Future work would address current limitations of the 3D scanning process such as considerations of scanner accuracy, that seated thigh width might be greater than standing thigh width, and that the process was tested on able-bodied individuals who can keep their lower limbs in the same position for the 1-2 minute duration of the scan. This would be done by expanding the proof of concept to create a complete set of braces that transfers between scans and testing the scanning and brace design process with children.

V. Conclusion

After transitioning from carbon fiber braces created from foam molds to a brace design process based on 3D scanning and 3D printing the braces, we are working on an efficient brace transfer process with automatic size and orientation adjustment by defining the braces using static and dynamic variables with joint references. This technique standardizes the design by reducing human error and drastically shortens the time it takes to create subject specific braces.

Applications for this research are not limited to exoskeletons and orthotics and prostheses, but can be applied to any field requiring customizable manufacturing.

Acknowledgment

The authors would like to thank the following institutions for their grants supporting the pediatric exoskeleton project: NSF IUCRC BRAIN, Mission Connect – A TIRR Foundation, TIRR Memorial Hermann, NSF Award CNS 1650536, and the University of Houston Chancellor's Technology Bridge Fund.

References

[1] D. Eguren, M. Cestari, T. P. Luu, A. Kilicarslan, A. Steele, and J. L. Contreras-Vidal, "Design of a customizable, modular pediatric exoskeleton for rehabilitation and mobility," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, pp. 2411–2416, 2019.

[2] D. Christensen, K. Braun, N. Doernberg, M. Maenner, C. Arneson, M. Durkin, R. Benedict, R. Kirby, M. Wingate, R. Fitzgerald, and M. Yeargin-Allsopp, "Prevalence of cerebral palsy, co-occurring autism spectrum disorders, and motor functioning - autism and developmental disabilities monitoring network, usa, 2008," *Developmental medicine and child neurology*, vol. 56, 10 2013.

[3] H. e. a. Kerr Graham, "Cerebral palsy," 2016.

[4] J. L. Contreras-Vidal, J. J. Gorges, and A. Kilicarslan, "Pct/us2017/037457, customizable orthotic/prosthetic braces and lightweight modular exoskeleton, filed december 11, 2018 under application number 16/308,964."

[5] "Markforged materials datasheet." https://static.markforged.com/markforged_composites_datasheet.pdf.