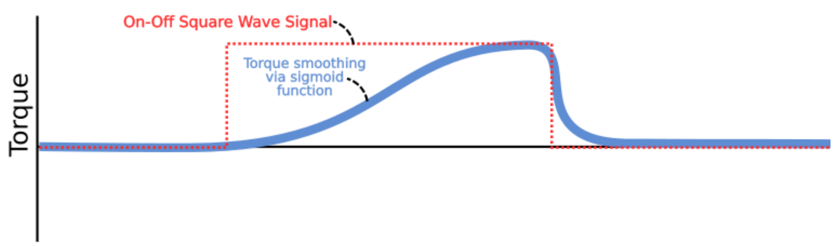
Mechanical Design Considerations:
We identified four primary design considerations to meet our goal of an untethered ankle exoskeleton capable of reducing the metabolic cost of walking in children and young adults with CP. Our first mechanical design consideration was to provide sufficient torque output to augment the ankle plantar-flexor muscles. Quinlivan et al. reported a 23% reduction in metabolic cost during walking with tethered plantar-flexor assistance in unimpaired adults for peak assistive torque providing 10-38% of the biological ankle moment [1]. Individuals, including those with CP, typically walk with ~1.0 $Nm \cdot kg^{-1}$ of peak biological ankle plantar-flexor moment [2]. Using these references as a general guide, 30% of the net ankle moment for children with CP would require up to 12 Nm of exoskeleton torque for our average target pediatric participant (12 year old, 40 kg average body mass [3]), and up to 20 Nm for our average target young-adult participant (18 years old, 67 kg average body mass [3]). Our second design consideration was to minimize the amount of mass added to the body, particularly distal portions of the lower-extremity, considering that both the magnitude and placement of the added mass impacts the metabolic cost-benefit ratio of a powered exoskeleton. For example, adding mass to the foot segment increases the metabolic cost over four times greater than when the same mass is added to the pelvis or torso [4]. Considering the youngest of our target population (5 year old's with an average body mass of 18 kg [3]), and that a 10% increase in total body mass would theoretically increase the metabolic cost of walking by 17% [5], our goal was an exoskeleton, including power supply, with a mass of 1.80 kg, where less than 0.65 kg was located on the legs. Our third design consideration was to allow normal ankle range of motion. We specified 80° as the target amount of exoskeleton articulation, which is slightly greater than necessary for locomotor activities of daily living [6]. The fourth design consideration, minimizing the physical profile of the device, was motivated by the future goal of conducting longitudinal interventions. An exoskeleton that maximizes real-world usability must not be drastically more cumbersome than existing mobility aids, including AFOs. We sought to limit the distance from the outside of the body to the perimeter of the rigid components on the exoskeleton to roughly the amount needed to fit under an item of clothing; our target was 5 cm.

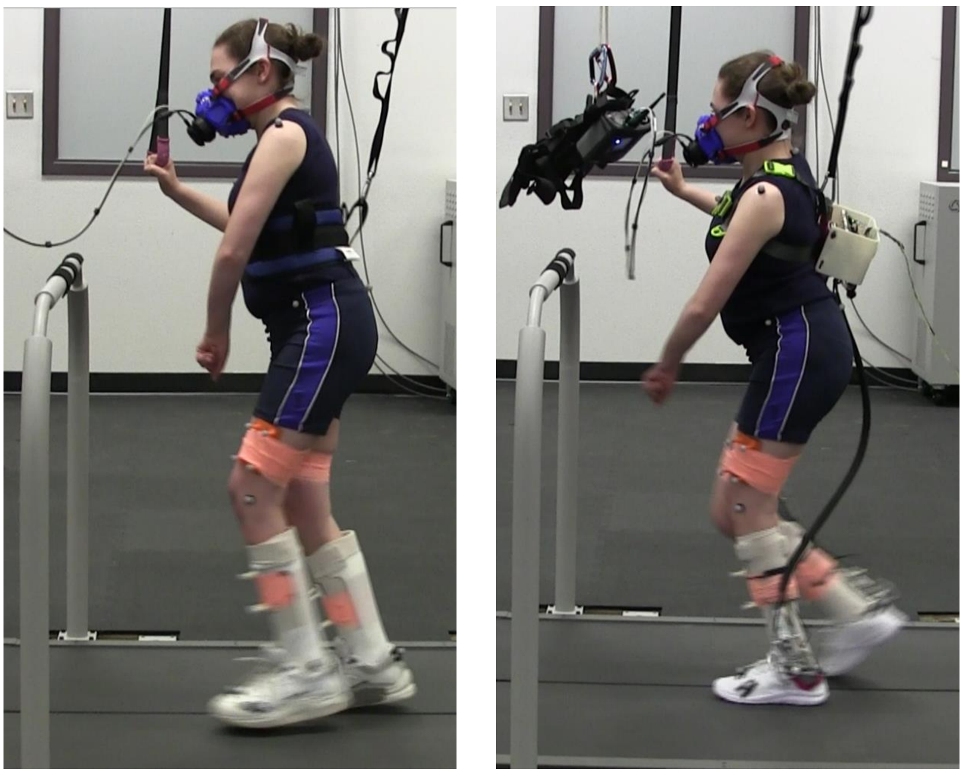
Control Design Considerations:
Three primary factors influenced our ankle exoskeleton controller design. First, abnormal ankle mechanics and gait and/or limb asymmetry requires the ability to easily and quickly adjust the timing and magnitude of powered plantar-flexor and dorsi-flexor assistance for each individual. Second, appropriate timing of external ankle assistance is essential to reducing the metabolic cost of walking [7]; ill-timed torque drastically limits improvement. Third, exoskeleton controller designs for the clinical pediatric population demand robust, yet simple and intuitive control due to elevated variability of spatiotemporal gait parameters [8], and potentially limited attention and/or cognitive function [9].



Supplemental Fig. 1. Schematic depiction of the torque signal before and after smoothing.

Exoskeleton Customization:
The customization of several components was required for creating exoskeleton assemblies for each participant. First, Bowden cable length was determined by measuring the distance along the body from the ankle joint to a location on the back where the control assembly was to be placed. Second, the lateral uprights and thermoplastic shank attachments were customized from a trace of the lower-limb. Lastly, an aluminum foot-ankle plate was fabricated for each participant; the size and shape were determined by a weight-bearing trace of each foot, and the measured height and location of the lateral malleolus. With proper fabrication of each custom foot-ankle plate, the ankle assembly's axis of rotation was aligned with the estimated axis of rotation connecting the medial and lateral malleoli of the biological ankle. Despite an initial worry that the single support would have the tendency to slide around the shank, we found that administering a self-adherent wrap around the limb prevented unwanted relative movement and unwanted rubbing of the skin.

Exoskeleton Tuning Procedure:
The general tuning procedure was as follows. Initially, the magnitude of assistance was slowly increased from zero to approximately 0.15 $Nm\cdot kg^{-1}$. As participants accommodated to assistance, the torque was increased up to a maximum of 0.35 $Nm\cdot kg^{-1}$. The research team solicited feedback from the participant regarding the magnitude of assistance and the onset-offset timing of assistance, which was adjusted for each limb by lowering or raising the foot-sensor thresholds. Torque rise-time was adjusted via the sigmoid shaping function. Parameters were generally, but not always, the same across limbs. In order to accommodate the range of neurological impairments, behavioral characteristics, and developmental ages observed within our cohort, steady-state metabolic data were informally evaluated at one or more time points during the training period to guide tuning and assess acclimation to assistance.



Supplemental Fig. 2. Picture of the GMFSC III participant that used the instrumented handle attached to a hanging rope walking in their baseline condition (left) and with the exoskeleton (right).

SUPPLEMENTAL TABLE I
CLINICAL CHARACTERIZATION OF ANKLE FUNCTION.

Patient	Ankle Function
P1	Normal passive range of motion
P2	Normal passive range of motion; bilateral reduced plantar-flexion, unilateral drop-foot during walking
P3	Normal passive range of motion; bilateral reduced plantar-flexion during walking
P4	Normal passive range of motion; bilateral reduced plantar-flexion during walking
P5	Normal passive range of motion; unilateral reduced plantar-flexion during walking

SUPPLEMENTAL TABLE II

ORDER OF TRIAL COMPLETION ON EACH PARTICIPANT'S FINAL VISIT.

Trial Order	**P1**	**P2**	**P3**[a]	**P4**	**P5**
First	Zero-Torque-Ctrl	Baseline (AFO)	Zero-Torque-Ctrl	Baseline	Zero-Torque-Ctrl
	Exo-assisted	Exo-assisted	Exo-assisted	Exo-assisted	Exo-assisted
		Zero-Torque-Ctrl			
Last	Baseline	Shod	Baseline	Zero-Torque-Ctrl	Baseline

Trial order was randomized across participants. [a]Metabolic data from the Zero-Torque-Ctrl trial for P3, 5 years old, were recorded on a separate visit as the exo-assisted trials due to participant compliance. To compare across conditions, the relative change in metabolic cost during the Zero-Torque-Ctrl trail relative to a baseline trial recorded on that same visit was presented as an absolute change relative to the baseline trial recorded on the same visit as the exo-assisted trials.

SUPPLEMENTAL TABLE III

PERCEIVED EXERTION AND WALKING CONDITION PREFERENCE

	PCERT Score[a]		**Preferred walking condition**
Participant	**Baseline**	**Exo-Assisted**	
P1	3	7	Baseline
P2	1	2	Exoskeleton
P3	2	4	Exoskeleton
P4	1	4	Undecided
P5	1	2	Exoskeleton

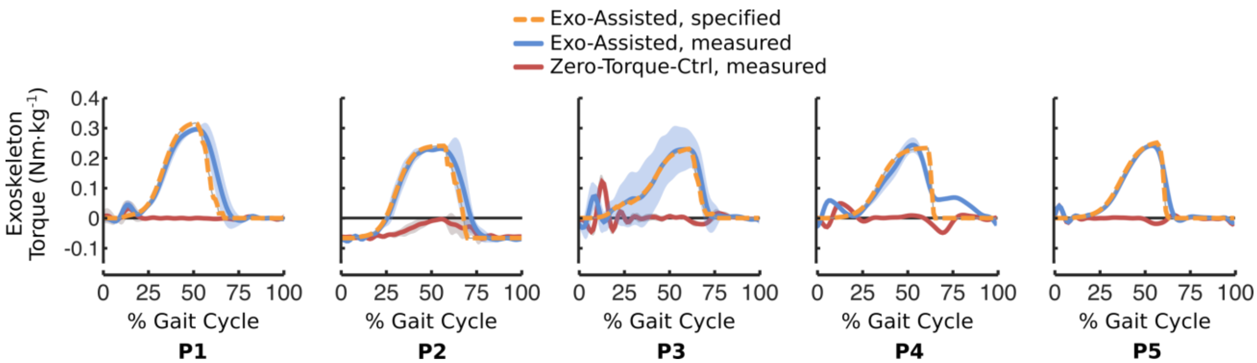
[a]PCERT: Pictorial Children's Effort Rating Table[10]. Exo-Assisted PCERT scores were from the condition that resulted in the greatest reduction in metabolic cost for participants with multiple exo-assisted trials.

SUPPLEMENTAL TABLE IV

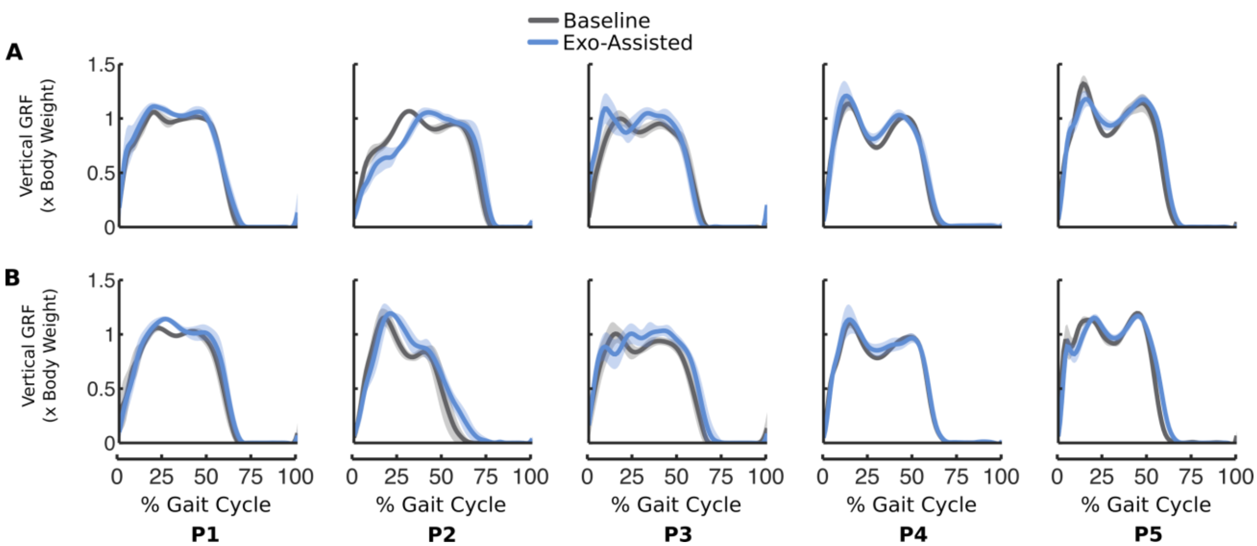
PARTICIPANT COMMENTS WHEN ASKED IF AND/OR HOW THE EXOSKELETON HELPS THEM WALK.

Participant	**Participant comments**
P1	No response provided
P2	"Can I please take the [exoskeleton] home?"[a]
P3	"The exoskeleton makes it easier to bring [my] foot forward with each stride, [I] feel less likely to trip and more stable."
P4	"Exoskeleton gives a good mix of balance, assistance, and movement."
P5	"Exoskeleton assistance helps and feels better while walking."

[a]It was very difficult obtain a straight answer from this 5-year-old participant with developmental delay. The participant replied with this comment when asked, "Would you like to take your powered braces home?"



Supplemental Fig. 1. Left limb exoskeleton torque data. Individual plots of exoskeleton torque for each participant's left limb across the gait cycle during baseline (gray) and exo-assisted (blue) walking. Shading depicts ± 1.0 standard deviation. Data are from the trial that resulted in the largest reduction in metabolic cost for participants that walked with multiple magnitudes of assistance.



Supplemental Fig. 2. Ground reaction forces. Right (**A**) and left (**B**) vertical ground reaction forces during baseline (gray) and exo-assisted (blue) walking. Shading depicts ± 1.0 standard deviation. Data are from the trial that resulted in the largest reduction in metabolic cost for participants that walked with multiple magnitudes of assistance.

Exoskeleton Bill of Materials:
Each exoskeleton cost ~ $4,700 to fabricate, including all purchased components, material, and machining expenses. Excluded in this estimate was the considerable design, iteration, and fabrication time that took place during development.

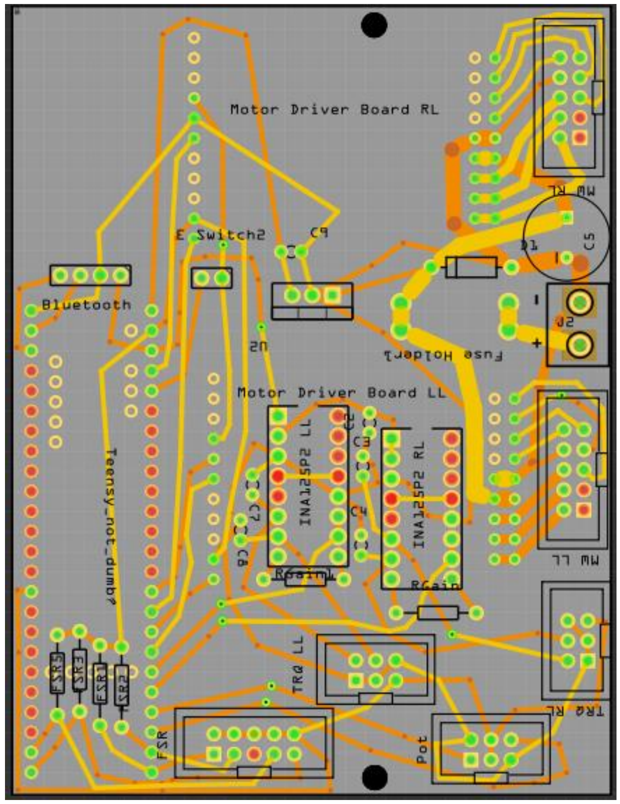
Part Name	Vender	Quantity	Part Number/Material
Ankle Orthotics			
Foot Plate	McMaster Carr	2	89015k37
Torque Sensor	Tansducer Techniques	2	TR-500
Ankle Pulley Left	Custom	1	See CAD package
Ankle Pulley Right	Custom	1	See CAD package
Shank Upright	McMaster Carr	2	8975k585
14mm Thrust Bearings	McMaster Carr	4	6655k52
10-32 x 3/16in Button Head Screws	McMaster Carr	8	91255a025
10/32 x 5/16in Flat Head Screws	McMaster Carr	8	91253a025
M5 Nylon Locknut	McMaster Carr	2	90576a104
Ankle Cable Block	Custom	2	See CAD package
Thermoplastic Cuff	Kydex	2	0.008 in Kydex
Cuff Padding	Cleverbrand Inc.	2	1/8 in sponge neoprine
Cuff Strap	Secure Cable Ties	2	24 x 2 in webbing straps
Bowden Cable Transmission			
Barrel Adjuster	Juscycling	8	M5 adjuster
Ferrule	Jagwire	8	5mm ferrule
M5 Nut	McMaster Carr	8	90592a095
Bowden Cable Housing	Clarks	4	Break cable housing
Bowden Cable Wire	McMaster Carr	2	3461t44
Motor Assembly			
Large motor, EC-4-Pole 120W	Maxon	2	311536
Large gearhead	Maxon	2	166945
Small motor, EC-4-Pole 90W	Maxon	2	323218
Small gearhead	Maxon	2	370782
Motor Bracket	Custom	2	See CAD package
Motor Pulley	Custom	2	See CAD package
M2 x 6mm Button Head Screws	McMaster Carr	12	91239a704
M2 x 8mm Button Head Screws	McMaster Carr	2	91239a705
M3 x 8mm Button Head Screws	McMaster Carr	2	91239a113
Battery	E-Flight	1	22.2v 910mAh 30C
Control Plates			
Motor Cable Block	Custom	2	See CAD package
Motor Assembly	Custom	2	See CAD package
M5 x 6mm Button Head Screws	McMaster Carr	16	91239a220
M2 x 6mm Button Head Screws	McMaster Carr	4	91239a704
PCB	Custom	1	See PCB

Exoskeleton CAD Files
CAD files are available to download here:
https://drive.google.com/drive/folders/1ZKYzHZhp1lv2wdMAKoO2i9XDxI0RMEv1?usp=sharing

Exoskeleton Control Code
The code used to operate the exoskeleton is available here:
https://drive.google.com/drive/folders/1ZKYzHZhp1lv2wdMAKoO2i9XDxI0RMEv1?usp=sharing

Custom PCB

The custom PCB file, pictured below, is available here:
https://drive.google.com/drive/folders/1ZKYzHZhp1lv2wdMAKoO2i9XDxI0RMEv1?usp=sharing



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