Investigating the Impact of the User Interface for a Powered Hip Orthosis on Metabolic Cost and User Comfort: A Preliminary Study

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ABSTRACT

Introduction: Powered orthoses have the potential to benefit pathologic or geriatric populations by increasing the quality of their mobility, reducing metabolic cost, and helping restore functional status. However, user interface design of powered orthoses is rarely considered, and may limit their clinical impact. The aim of this study was to design and evaluate a novel user interface for a powered hip orthosis. We hypothesized that our interface design would reduce metabolic costs, reduce skin irritation, increase user comfort, and reduce pain during ambulation when compared with an off-the-shelf (OTS) interface.

Methods: A novel, custom-fit torso user interface was designed to have extended trimlines and load the iliac crests. This allows for improved purchase over anatomic structures and potentially improves weight distribution of the powered hip orthosis. The design was compared with an OTS user interface. Subjects ambulated in three conditions: without a powered orthosis, with an OTS interface, and with the novel interface. Five healthy subjects (23.6 ± 2.2 years) with no neuromuscular limitations ambulated on a treadmill for 6 minutes at 0.8 m/s while measuring metabolic cost for three levels of torque assistance. Subjects repeated this procedure for all three conditions. After ambulating in each interface, skin was inspected at t = 0, 10, and 30 minutes. They completed the OPUS (Orthotics and Prosthetics User's Survey) Satisfaction with Device survey and reported pain on a 1-to-10 scale (0 = no pain).

Results: The novel interface reduced metabolic cost for all conditions when compared with OTS componentry. Maximal difference was at the 13% torque assistance level where the difference was 0.18 W/kg ± 0.11 (SEM) (9.48%). The novel design generally reduced pain scale and skin irritation. The average pain rating decreased from a 3/10 ± 1.17 (SEM) in the OTS condition to 2/10 ± 0.84 (SEM). The novel design generally increased OPUS Satisfaction with Device score when compared with the OTS condition; the OPUS score increased from an average of 32/45 ± 2.56 (SEM) for the OTS condition to 36/45 ± 2.1 (SEM).

Discussion: The novel design tended to reduce metabolic cost for all tested powered orthotic conditions. This may be explained by the novel design's more proximal trimlines and increased loading of anatomic structures. These features may be due to maximized biomechanical leverage and minimized compensatory motions during ambulation.

Conclusions: The user interface may impact metabolic cost of walking and user comfort. Moving forward, it should be considered an essential element of powered orthosis design. It is critical to optimize the user interface in future powered hip orthotic designs due to minimal surface area available for weight-bearing and reduced number of actuated joints. Therefore, those interested in optimizing powered hip orthotic user interface designs should focus on loading anatomic structures, including the shoulders and iliac crests, and on supporting the curvature of the lumbar spine. (*J Prosthet Orthot.* 2020;00:00–00)

KEY INDEXING TERMS: hip exoskeleton, exoskeleton, powered lower-limb orthosis, powered hip orthosis, walking assistive device

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Orthotic device development has long been predicated on the premise of passive force translation via compression, axial loading, and tension. With the advent of lower-limb powered orthosis development, a new opportunity exists to harness the principles of orthotic management and apply actuator-driven forces to limb segments.

Within the rehabilitation subset, powered orthoses have been utilized as a gait training alternative to conventional physical therapy and body weight-supported treadmill training (BWSTT). They have been used to increase mobility by assisting with functional tasks including the sit-to-stand transition and ambulation.[1,2] In clinical applications, muscular deficits frequently dictate a different control and actuation strategy, along with a different structure and mechanism for force transfer. Although the impacts of a poorly designed actuator might be immediately evident, the impact of a poorly designed user interface is less obviously characterized.

The powered hip orthosis design discussed in this study focuses on assisting ambulation in a rehabilitation setting, and assistance is localized to the hip joint. The reason for this localized assistance is 2-fold: stroke survivors rely more on the proximal hip joint for ambulation to compensate for reduced capability in distal muscle coordination,[3–5] and, due to overuse, stroke survivors tend to have increased hip muscle fatigue, which leads to limited ambulation.[6] It has been shown that elderly populations tend to rely on increased hip power during ambulation compared with the knee and ankle.[7,8] They also tend to exhibit reduced muscular strength, reduced independence, and compromised effectiveness in basic ambulation and the sit-to-stand transition.[9–11] Although those with reduced lower-limb strength and generally compromised mobility may benefit from a lower-limb powered orthosis, many commercially available at this time are heavy, bulky, and are not designed for the user's specific needs.[12] This excess mass restricts natural kinematics and makes donning/doffing difficult.[13] Localizing assistance to the hip allows for the device to be compact and close to the user's center of mass.

Previous powered hip orthoses studies have not consistently considered the impact of the orthotic interface. Some articles developed their own user interfaces.[12–14] Giovacchini et al.[12] detailed their device structure, deviating from the standard anthropomorphic structure and utilizing flexible or rigid large surface area-encompassing componentry for the user interface. Some articles attached an off-the-shelf (OTS) hip orthotic interface to their developed power orthotic system.[15,16] However, it should not be assumed that OTS components are designed to be used with a powered assistive device.

Many OTS hip orthoses are used to offer stability post hip dislocation, hip fracture, or total hip joint replacement.[17] It can be inferred that OTS hip orthoses are designed to restrict hip joint motion during ambulation as opposed to transferring net mechanical power. Typically, OTS hip orthoses consist of three parts: a pelvic section, a hip joint, and a thigh section. The purpose of the pelvic section is to suspend the orthosis over the iliac crests. Often, a metal strut with a hip joint is attached to the pelvic section and connected to the thigh section. These sections work together to restrict the available range of motion at the hip joint.

Many OTS hip orthoses have minimal coverage of the lumbar spine and pubic symphysis. They do not need to control anterior and posterior pelvic tilt, lumbar flexion and extension, and lateral trunk bending. These design characteristics, although appropriate for specific applications, are not appropriate for powered orthoses as they cause problems in transferring and controlling assistive power to the hip joint. Therefore, a novel user interface design, which is capable of harnessing additional anatomic structures for loading, is required. Extending trimlines more proximally and distally may allow for improved biomechanical leverage and may benefit the clinical powered orthosis user. It is hypothesized that a novel design based on these principles will reduce metabolic cost, reduce skin irritation, increase user comfort, and reduce pain during ambulation when compared with an OTS interface. With improved anatomic structure loading and increased total surface contact of the user interface, skin irritation will likely be reduced due to improved force distribution and reduced oscillation tendency. Similarly, increased user comfort and decreased pain during ambulation are anticipated due to improved weight distribution and the potential for axial unloading of the spinal column via an increase in hydrostatic pressure through the abdomen. The anticipated decrease in metabolic cost may be attributed to improved torso leverage and the restriction of compensatory motions, as well as improved weight distribution of the powered orthosis.

METHODS

USER INTERFACE DESIGN

The novel design was composed of four primary sections: two thigh shells, a posterior panel, an anterior panel, and two side panels (Figure 1). The thigh shells were manufactured using 4.8 mm (3/16 inch) carbon fiber-infused polypropylene (ProComp) and were designed to mimic an I-beam structure on the lateral aspect of the thigh, wrapping posteriorly and anteriorly. The thigh shells created two force couples driving hip flexion and extension when torque was applied through the powered hip orthosis.

The posterior panel was composed of two parts: 3.2 mm (1/8 inch) polyethylene against the lumbar spine and 4.8 mm (3/16 inch) of polypropylene supporting the polyethylene and extending proximally through the thoracic spine. The vertical slots in the polypropylene allowed the polyethylene panel to change its shape to match the individual's lumbar lordosis. According to van Poppel et al.,[18] supporting the lumbar curvature of the spine helps to prevent back pain and reduce muscle fatigue.

The anterior panel was constructed from 4.8 mm (3/16 inch) polypropylene and extended approximately from xiphoid to pubic symphysis. Coupled with the posterior panel, the anterior panel created a three-point force system, increasing intra-abdominal pressure and allowing for increased axial loading.[19] In addition, this three-point force system aided in the control of anterior and posterior pelvic tilt.[17,19,20]

Like the posterior panel, the lateral panels also consisted of 3.2 mm (1/8 inch) polyethylene against the subject's side and 4.8 mm (3/16 inch) polypropylene supporting the proximal

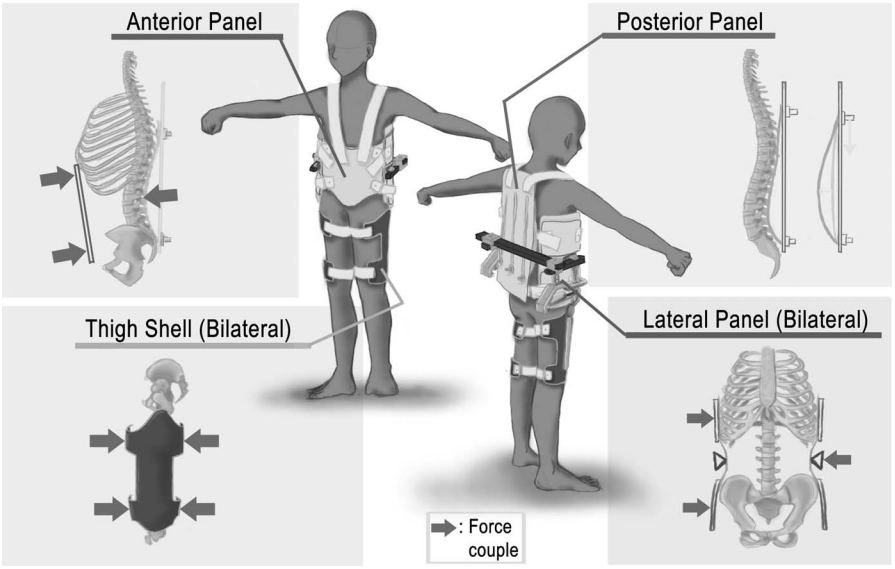


Figure 1. Four components of novel design user interface. Thigh shells were fabricated from carbon fiber-infused polypropylene. Polypropylene was used for rigid posterior, anterior, and lateral panels, and polyethylene was used for flexible inner posterior and lateral panels. A three-contact force system was employed; each sectional panel helps control the biomechanical motion of the pelvis, lumbar spine, and hip (arrows). Posterior, anterior, and lateral panels were connected with Velcro straps.

and distal ends of the polyethylene. The polypropylene was attached to the polyethylene via Velcro. The waist probe was three-dimensional printed with thermoplastic polyurethane filaments (NinjaFlex) and attached to the carbon frame. These waist probes aligned with the individual's waist groove and compressed the polyethylene over this area, anchoring the powered orthosis over the iliac crests and increasing surface area available for weight distribution.

The lateral polypropylene panels had straps and chafes connecting to the anterior and posterior panels, compressing the user's torso tissue. The lateral panels in conjunction with the waist probe created a three-point force system limiting lateral trunk bending and pelvic obliquity. Coronal plane force couples limited lateral trunk bending and pelvic obliquity. Posterior, anterior, and lateral panels were connected with Velcro straps to secure their position and to create snug fit across various body types.

POWERED HIP ORTHOSIS HARDWARE DESIGN

This powered hip orthosis was primarily composed of four parts: sensors, actuators, controllers, and the interface.[21] The powered orthosis utilized series elastic actuators (SEAs) placed bilaterally at the hip for providing power assistance in the sagittal plane with capability for 100° and 30° hip flexion and extension, respectively. In addition, a passive hinge was implemented to allow free motion in the frontal plane for both hip abduction/adduction (15° in each direction). The SEA had a series spring located in between the gearbox transmission and the output hip joint where the deflection of the spring was used to calculate the output joint torque. This aspect allowed for a closed-loop torque control to ensure that the desired torque was provided to the user. Multiple mechanical sensors were implemented on the device. An angular encoder was placed at the two hip joints. A force sensitive resistor (FSR) was placed on each heel to detect the user's heel contact. This information was used to estimate the user's position in the gait cycle. The entire device ran on a single onboard computer (NI myRIO 1900) on LabVIEW software. All of the data (joint angles, gait cycle estimation, torque command, etc.) were sampled at 200 Hz.

The entire powered hip orthotic device was attached to the main carbon-fiber frames. Three carbon-fiber frames were located on the posterior and both sagittal sides of the wearer. The posterior carbon-fiber frame element and lateral elements could move relative to each other and accommodate for various body types. The electronic hardware components were located on the back of the posterior panel, and the SEAs were mounted below the sagittal carbon-fiber frames. Thigh shells of the user interface could be attached to the metal struts at different heights to accommodate the subject's leg length. To distribute the weight of the electrical hardware on the posterior section, backpack straps were attached to the carbon-fiber frames.

When the powered hip orthosis generated a hip flexion torque, a counter moment occurred at the subject's trunk, encouraging trunk extension. Similarly, when the powered hip orthosis applied a hip extension torque, trunk flexion was encouraged. The novel design's posterior and anterior panels created three-point force couplings designed to limit trunk flexion/extension (Figure 2). The OTS interface did not have trimlines that extended as far proximally or distally as the novel design (Figure 2).

DATA COLLECTION PROTOCOL

Five able-bodied subjects (four males and one female) participated in the study approved by the Georgia Institute of Technology Institutional Review Board. The subject's average age, height, and body mass were 23.6 ± 2.2 years, 176.4 ± 6.8 cm, and 72.8 ± 8.1 kg, respectively. The custom thigh shells were used

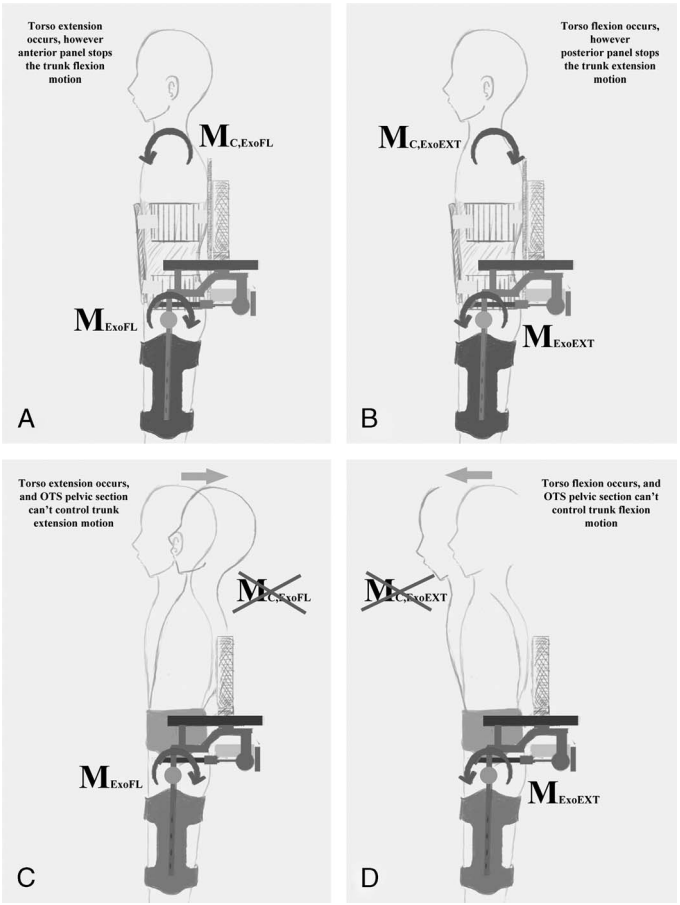


Figure 2. Moment diagram during hip flexion and extension with novel design user interface (A and B) and hip flexion and extension with OTS user interface (C and D). Moments generated to assist hip flexion (MExoFL) and extension (MExoEXT) as powered hip orthosis created an assistive torque at the hip. The novel design user interface was able to create a greater counter moment (MC, ExoFL, MC, ExoEXT) to minimize the trunk flexion/extension movement relative to the OTS device due to the trimlines that extended more proximally and distally.

for both conditions to allow isolated analysis of the torso design variable (Figure 3). Therefore, for the purposes of this manuscript, the OTS condition refers to use of the OTS pelvic band used in conjunction with the thigh shells described in the "User Interface Design" section of this article.

After each subject signed the written consent form, the subject fasted for 6 to 8 hrs. Then, metabolic data were collected during a six-minute rest period, a six-minute ambulation condition without the powered orthosis, and a six-minute ambulation condition with the powered orthosis providing zero impedance using the VO2000 system (MedicalGraphics, United Kingdom). Data were then collected over a 6-minute interval with the powered orthosis providing active flexion and extension torque equal to 13% of the peak biological level (low) and 26% of the peak biological level (high). These values were determined by the mechanical restrictions of the hardware during the time of testing. Walking speed was set to constant 0.8 m/s across all conditions as protocol was limited in maximum velocity by the device hardware. After ambulation, skin inspection occurred immediately after the device was removed, 10 minutes postdevice removal, and 30 minutes postdevice removal. Although completing the skin inspection protocol, the subject rested in a chair, reported a pain score using Likert scale (1–10, 0 = no pain), and completed an OPUS Satisfaction with Device survey (items 1–9). After all the visible skin irritations were resolved, the subject repeated the same protocol under the second interface condition (Figure 4).

RESULTS

METABOLIC COST

The novel design tended to reduce metabolic cost for all conditions (zero impedance, 13% torque assistance, and 26% torque assistance) compared with the OTS interface (Figure 5). The change between the OTS and novel design conditions was 0.10 W/kg ± 0.16 (SEM) for zero impedance condition, 0.18 W/kg ± 0.11 (SEM)

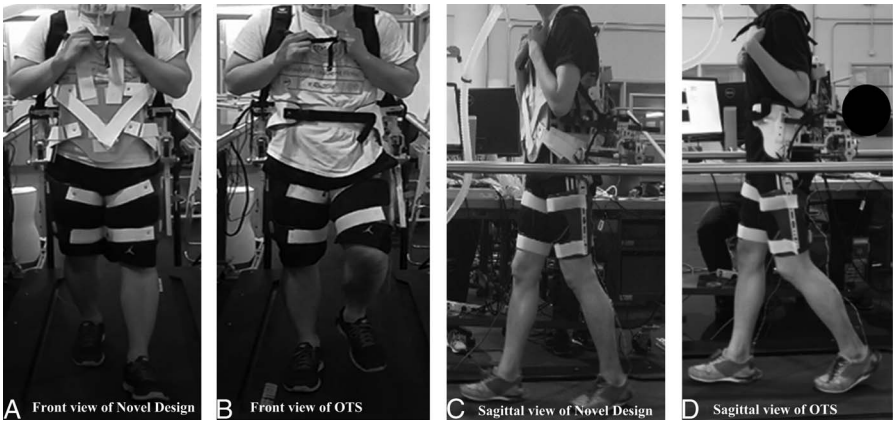


Figure 3. Front and sagittal view of novel design and OTS user interface conditions. For each condition, novel design user interface (A and C) and OTS user interface (B and D) were attached to the carbon-fiber frame form the power assistive component. To distribute the weight of the electrical/mechanical hardware at the posterior section, backpack straps were attached to the carbon-fiber frames. Because the study focused on the torso user interface, the novel design's thigh shells were used for both novel design and OTS conditions (see Supplementary Digital Content 1, http://links.lww.com/JPO/A40, Supplementary Digital Content 2, http://links.lww.com/JPO/A42, Supplementary Digital Content 3, http://links.lww.com/JPO/A41, Supplementary Digital Content 4, http://links.lww.com/JPO/A43).

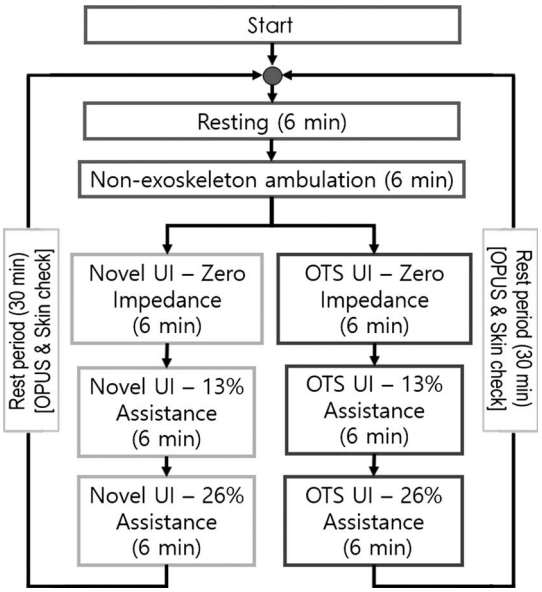


Figure 4. Algorithm of the experiment process. Both novel design user interface and OTS user interface conditions were randomly selected between the subjects to minimize subject bias. Once one condition was completed, subjects rested for 30 minutes while finishing the skin inspection protocol, pain score, modified OPUS survey, and user feedback. After the rest, subjects repeated the same process for the other condition starting from collecting metabolic cost data during resting period.

for 13% assist condition, and 0.14 W/kg ± 0.08 (SEM) for 26% assist condition. The maximum difference was at the 13% torque assistance level where the difference between interfaces was 9.48% (Figure 5).

PAIN SCORE

Two subjects found the novel design less painful, one subject found it more painful, and two did not find it painful in any condition (Table 1). The average pain score for the OTS interface was 3/10. The average pain score for the novel design interface was 2/10.

OPUS SATISFACTION WITH DESIGN SCORE

Two subjects were more satisfied with the novel interface design than the OTS design. One subject was more satisfied with the OTS interface than the novel design interface. One subject was equally satisfied with the design of both interfaces. One subject did not complete the survey. The average OPUS score for the OTS interface was 32/45. The average OPUS score for the novel design interface was 36/45 (Table 1).

SKIN INSPECTION

At t = 0 minute, SC01, SC02, and SC05 all had redness and pressure indentations underneath the shoulder straps for both the novel and OTS conditions. At t = 10 minutes, SC01, SC02, and SC05 had persistent redness; however, it was less severe than at t = 0. Redness and irritation for these three subjects dissipated by t = 30 minutes.

In the OTS condition, SC03 showed proximal trimline marks at the waist groove along with dark redness and strap marks at the shoulder at t = 0 minute. At t = 10 minutes, shoulder marks and redness dissipated; however, trimline marks near the waist groove persisted beyond t = 30 minutes check. In the novel design condition, SC03 had shoulder strap marks and redness at t = 0 minute; however, this redness and irritation was less than the OTS condition. These marks dissipated by the t = 10 minutes inspection. SC04 had proximal trimline marks on the proximal

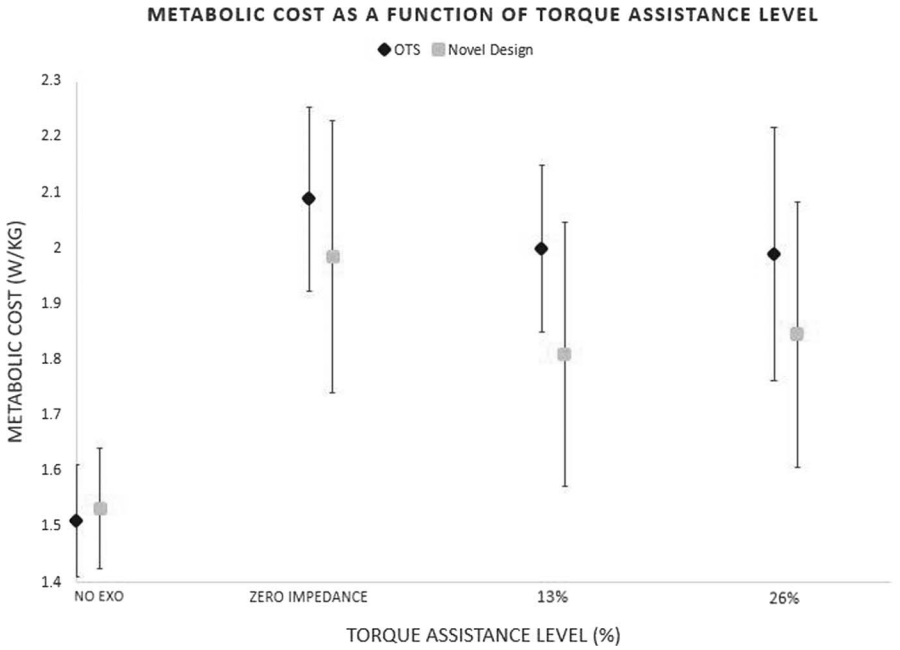


Figure 5. Metabolic cost as a function of powered orthosis condition and assistance torque. Metabolic cost data for the no-powered orthosis, zero impedance (no assistive torque), 13% of assistive torque, and 26% of assistive torque conditions between novel design (shown in ■) and OTS (shown in ♦) user interface settings are shown in the graph. The maximum difference was at the 13% torque assistance level where the difference was 9.48%. The baseline condition is shown to indicate consistent performance of the metabolic equipment during testing.

Table 1. Pain scores and modified OPUS scores

	Pain Score		Modified OPUS Score	
	Novel Design	OTS	Novel Design	OTS
SC01	3/10	7/10	41/45	27/45
SC02	2/10	3/10	30/45	26/45
SC03	5/10	4/10	N/A	N/A
SC04	0/10	0/10	38/45	40/45
SC05	0/10	0/10	35/45	35/45
Average	2/10	3/10	36/45	32/45

OPUS score for SC03 is excluded due to failure to complete the survey. The average OPUS score for the novel design interface was 4 points higher than the average score for the OTS interface.

pelvic section trimline in the OTS condition but had no shoulder marks. There was no redness or irritation under the shoulder straps. SC04 had no redness or irritation with the novel design condition. SC02 had redness on his back distal to the scapula and just proximal to the waist groove for both the novel design and OTS conditions. The redness and irritation reduced over time; however, it persisted beyond the t = 30 minutes inspection for both conditions (Table 2).

SUBJECTIVE USER FEEDBACK

All subjects reported the novel design was heavier. SC03 reported the OTS device wobbled too much and it was too large. SC04 reported they were able to feel that the weight of the device was localized to the shoulder for the OTS condition.

DISCUSSION

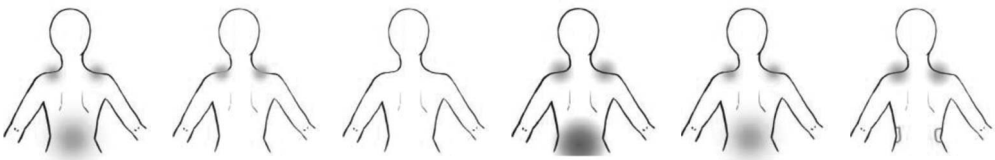
This study demonstrated that there is potential for the user interface in powered orthotic design to impact clinically relevant outcome measures and metabolic cost. Reviewing relevant literature results in a stark lack of clinically relevant outcome considerations. Within user interface design considerations, there were several terms consistently present: adjustable, lightweight, safe, and rigid.[22–25] Among several articles, only Giovacchini et al.[12] and Asbeck et al.[13] discussed the most basic tenets of orthotic device design: surface area and material selection. Giovacchini et al.[12] and Bortole et al.[23] discussed subjective user feedback regarding the user interface and examined the skin for irritation. Validation of custom user interface design as opposed to stock OTS products would serve to improve future powered orthotic design protocols by encouraging a systematic component-based evaluation approach.

The novel interface design tended to reduce the metabolic cost (W/kg) for all tested conditions when compared with the OTS interface. The maximum difference occurred with 13% assistance (0.18 W/kg ± 0.11 [SEM]). The tendency to reduce metabolic cost associated with the novel design may be explained by the improved biomechanical leverage and control exerted by the novel design. The novel design had extended proximal and distal trimlines, which improved control over the subject's torso and limited the ability to move the torso in order to compensate for the torque applied by the powered orthosis. Reduced compensatory motions may have reduced metabolic cost during ambulation. The reduced redness noted during the skin inspections may provide additional evidence that the novel design was able to reduce compensatory movements.

The novel design was substantially more adjustable than the OTS interface. With extended trimlines, the novel design allowed for force coupling capable of controlling trunk flexion and extension. Therefore, when a hip flexion torque was applied in the novel design, the interface was capable of resisting compensatory trunk extension, and, with the application of a hip extension torque, it was capable of resisting compensatory trunk flexion.

The novel design was also able to improve the total contact through the torso via adjustment of the lumbar curvature and extended posterior panel. The posterior aspect of the novel design, in conjunction with the anterior panel, allowed for application of hydrostatic loading principles. This potentially allowed for increased spinal column support by compression of the surrounding soft tissues of the abdomen. Load was effectively shifted away from the shoulders and onto the iliac

Table 2. Table of skin observation when T = 0, 10, 30 mins

	Novel Design Condition			OTS Condition		
	t = 0 min	t = 10 min	t = 30 min	t = 0 min	t = 10 min	t = 30 min
Common finding of skin condition among subjects						

Subject's skin conditions are observed as soon as the device is removed (T = 0 min). Additional observations were performed 10 mins post-device removal (T = 10 mins), and 30 mins post-device removal (T = 30 min). Most of the subjects show redness and strap marks at the shoulders, and the OTS user interface subjectively leaves more significant redness and marks relative to the novel design user interface. Subjects wore the device for approximately 18 mins in each novel design user interface and OTS user interface conditions.

crests with the waist probes. This adjustability made it possible to optimally fit the powered orthosis to different body types. The OTS interface adjustability was limited to adding soft padding to improve contact and shift weight distribution off of the shoulders. Improved weight distribution may have contributed to a reduced average pain score and increased OPUS satisfaction with device scores.

The adjustable lumbar curvature and adjustable loading of the iliac crests had the potential to reduce device pistoning and inefficient transfer of torque to the subject's hip joint. During the posttesting protocol, one subject reflected on lower-back pain while wearing the OTS orthosis, commenting on continuous impacts on the lumbar spine. This did not occur while using the novel design, perhaps indicating that the novel design was effective in reducing device movement relative to the subject's torso in the sagittal plane. This reduced oscillation compared with the OTS condition may correlate to reduced pain and improved satisfaction with the interface design.

Considering the pain scores, OPUS Satisfaction with Device survey results, and skin inspection protocol results, there are several key design features that should be incorporated in future powered orthotic designs. Utilizing the iliac crest as an axial load-bearing structure allows for improved weight distribution and proximity to the center of mass. Extending trimlines from the xiphoid process to the pubic symphysis may allow for improved compensatory motion control and biomechanical leverage. Maintaining total contact throughout the lumbar spine may prevent excessive device oscillation, improve user comfort, and provide increased proprioceptive feedback.

Although the novel design demonstrated promising results compared with the OTS design, there were still limitations. Ideally, the novel design would have successfully transferred the majority of the powered orthosis' weight to the iliac crests. However, redness at the shoulders of the subjects in the novel design was more common than redness over the iliac crests. This indicates that the design should be modified to allow for more significant load transfer to the iliac crest. This could be accomplished through probe redesign or using a thinner polyethylene membrane. In addition, although the device was adjustable on the posterior and lateral panels, the anterior panel was not able to be adjusted to the individual subject. Ideally, future iterations of interface design would allow for this panel to be lengthened and shortened to allow for consistent contact from the xiphoid process down to the pubic symphysis.

This preliminary study only examined the effect of the user interface on five subjects at a single walking speed under three assistance conditions. This is acceptable for a preliminary study. However, it would be valuable to increase the number of subjects, expand the number of assistance levels, examine the effect of a velocity profile rather than a single speed, or use a self-selected walking speed. Based on these limitations, it is not possible to generalize these results to nonhealthy subjects or is it possible to comment on how performance may change with variable cadence during daily activities. These study expansions would provide added value but were beyond the limited scope of this preliminary feasibility study. Subjects in this study were all healthy and young. Only two of the five subjects had a BMI classified as overweight and none were obese. These limitations in demographics and body types leave room for further examination in future studies with pathologic populations, geriatric subjects, and more diversity in body type. Future studies will continue to highlight essential areas of consideration in powered orthotic user interface design.

CONCLUSIONS

The novel user interface design presented in this study demonstrated a number of key advantages compared with an OTS interface, despite the small sample size. Utilizing a custom-fit user interface developed based on orthotic design principles resulted in important, clinically relevant trends, including decreased metabolic cost, increased user comfort by reducing pain and local redness, and increased OPUS Satisfaction with Device scores. Optimizing user interface design has the potential to increase the impact of powered hip orthoses and level of acceptance in clinical and rehabilitation applications through increased comfort and reduced metabolic cost. Future powered orthosis designs should begin integrating the user interface as an integral portion of development and seek to identify the interface as a statistically significant design metric when optimizing metabolic cost and other clinically relevant metrics.

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