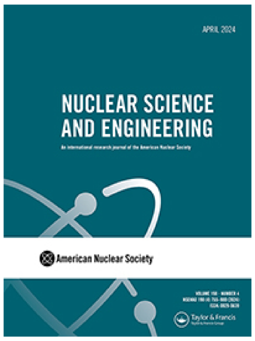

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User Impressions and Gait Analysis of Exoskeleton Device Usage in Generalized Tank Farm Activities

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Abstract — *Tank farm workers involved in nuclear cleanup activities perform physically demanding tasks, typically while wearing heavy personal protective equipment (PPE). Exoskeleton devices have the potential to bring considerable benefit to this industry but have not been thoroughly studied in the context of nuclear cleanup. In this paper, we examine the performance of exoskeletons during a series of tasks emulating jobs performed on tank farms while participants wore PPE commonly deployed by tank farm workers. The goal of this study was to evaluate the effects of commercially available lower-body exoskeletons on a user's gait kinematics and user perceptions. Three participants each tested three lower-body exoskeletons in a 70-min protocol consisting of level treadmill walking, incline treadmill walking, weighted treadmill walking, a weight lifting session, and a hand tool dexterity task. Results were compared to a no exoskeleton baseline condition and evaluated as individual case studies. The three participants showed a wide spectrum of user preferences and adaptations toward the devices. Individual case studies revealed that some users quickly adapted to select devices for certain tasks while others remained hesitant to use the devices. Temporal effects on gait change and perception were also observed for select participants in device usage over the course of the device session. Device benefit varied between tasks, but no conclusive aggregate trends were observed across devices for all tasks. Evidence suggests that device benefits observed for specific tasks may have been overshadowed by the wide array of tasks used in the protocol.*

Keywords — *Tank farm, nuclear cleanup, exoskeleton, gait kinematics, inverse kinematics.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Workers across the U.S. Department of Energy's Environmental Management (DOE-EM) sites perform a variety of physically challenging tasks on a daily basis, often while wearing extensive personal protective equipment (PPE) designed to protect them from external hazards. In this paper, the terms "tank farm" and "cleanup activities" refer to sites containing radioactive waste and activities to remove such waste, respectively. Tank farm workers are generally required to perform a variety of maintenance and sampling work tasks and traverse across large tank farm sites while wearing heavy PPE. In some cases, workers must wear a self-contained breathing apparatus (SCBA), which requires a large oxygen tank to be carried on the back for the full duration of the worker's shift. The DOE-EM Office of Technology Development is sponsoring research into wearable robotic and exoskeleton devices to determine the feasibility of deploying exoskeletons at their tank farm sites. The work described in this paper represents one study executed as part of that program.

To narrow the scope of this study, members of the research team performed multiple visits to a DOE-EM

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tank farm site, interviewing and surveying workers and management. The interviews and surveys aimed to identify challenges and needs pertaining to cleanup work. The survey responses reported walking long distances and standing for extended periods of time while performing maintenance tasks with heavy equipment as the most common and physically demanding activities. Based on the responses, the scope of this study was constrained to the lower body. The tasks analyzed in this study align closely to the workers' reported challenges and include a variety of walking activities and a standing hand tool task. The selected exoskeletons were commercial devices available at the time of the study and identified to be designed to benefit at least one of the relevant activities mentioned above. The selected exoskeletons are Lockheed Martin Corporation's ONYX, Dephy Inc.'s ExoBoot, and Noonee's Chairless Chair. Each is described below (see Fig. 1).

I.A. Lockheed Martin ONYX

The ONYX is a powered knee-assist device manufactured by the Lockheed Martin Corporation. A motor mounted on the lateral side of each knee provides torque to assist the knee based on information gathered by a controller about the user's movements from sensors on the foot, legs, and pelvis. Because the torques applied can be relatively large, the physical interfaces to the user are also large. The device weighs approximately 14 lb and must be carefully aligned to minimize discomfort. Two large batteries are required to power the device and must be mounted somewhere on the user's torso. The ONYX is expected to be most beneficial to the user during walking and carrying heavy loads.

I.B. Dephy ExoBoot

The ExoBoot (Dephy Inc.) is a powered ankle-assist device weighing approximately 3.4 lb/side. A motor and transmission system is placed near the lateral side of the ankle joint, and the device connects to a custom boot and the user's shin. A small battery is integrated into the top of each device. A controller uses information from sensors in the device to determine the timing and amount of assistive plantar flexion torque that is applied. The ExoBoot is expected to assist the user during walking, specifically loaded walking.

I.C. Noonee Chairless Chair

The Chairless Chair (Noonee) is a body-mounted chair, ideal for use in places where conventional chairs are not practical. The device attaches to the posterior aspect of a user's legs, keeping it out of the way when not in use and allowing for quick, hands-free deployment. The device also allows adjustments to set different sitting heights. The Noonee attaches to a user's normal shoes or boots using bootstrap anchors and to the waist with a Velcro belt and weighs approximately 4.4 lb. The Noonee is suitable for tasks that would permit the user to complete them while seated.

II. PRIOR WORK

Exoskeleton devices have become readily available for industrial use only in the past few years, and the number of available devices is still relatively small. The most commonly used devices tend to be targeted at very specific, repetitive tasks. Studies have examined the effects of exoskeletons in construction,[1] automotive

(a) ONYX (b) Dephy ExoBoot (c) Noonee Chairless Chair

Fig. 1. Lateral view of the ONYX, Dephy ExoBoot, and Noonee exoskeleton devices from left to right fitted to the lower body. The participant is wearing the boots from the Dephy ExoBoot unit in all fittings.

manufacturing,[2] military,[3] and healthcare industries[4,5]; however, few studies have tested the efficacy of exoskeletons in supporting environmental cleanup activities. The work at tank farms and across the DOE-EM complex tends to be diverse and is often less repetitive than what is frequently performed in factories and other settings where exoskeletons are commonly deployed. The unique PPE required at tank farms is also an important factor when considering the efficacy of exoskeletons, as some devices may not be compatible with the required PPE. In this study, we test the exoskeletons in a protocol intended to simulate a tank farm work shift while the participant is wearing PPE common to environmental cleanup sites.

Ankle assistive devices, similar to the Dephy ExoBoot, have been shown to reduce the metabolic cost of walking.[3] In laboratory studies, the effectiveness of these devices is typically tested with level and incline walking tasks. The Dephy ExoBoot has also been shown to improve a participant's stability and impact their strategy when completing a balancing task, which is valuable when considering the safe implementation of these devices outside of a controlled laboratory environment.[6] While studies have examined the metabolic effects of the ExoBoot,[3,7,8] few have considered the user's perception of the device. Peng and colleagues[9] examined the impact of actuation timing on a user's perception of the usefulness of a powered ankle exoskeleton during a walking task. Their results highlight clear individual differences in sensitivity to the device, and participants adjusted their gait patterns accordingly.

Understanding user perception of exoskeletons is vital as it provides useful insights regarding overall comfort and trust in the device. User preference is a dynamic quantity that often changes over time as an individual continues to use a device.[10] Preference can be dependent on a variety of factors including fatigue, sensitivity, and practice. It is important to consider user preference as it can have significant impacts on device adoption, regardless of any physical benefits.

While the ONYX and ExoBoot were designed to assist with dynamic tasks (e.g., walking), Noonee's Chairless Chair was built to support more stationary tasks in environments where a conventional chair may not be feasible. Studies have shown that the Noonee reduces musculoskeletal load in the lower leg.[11] There is also evidence that the passive exoskeleton can reduce physical loading on the lower back muscles.[12] However, these benefits may be accompanied by increased stress in the knee and hip joints, making it important to consider the postural control and weight distribution when using this device. Users have perceived the Noonee to be beneficial during assembly work, but less so during dynamic tasks like walking.[13] When considering the implementation of such devices at tank farms, testing the device in a real-world protocol containing both walking and standing tasks provides information about the user's perception and the kinematic effects of the device over the duration of a simulated work shift. These data can provide insights into the trade-offs and appropriate use cases of devices in environmental cleanup activities.

When examining the efficacy of military exoskeletons, Leova and colleagues[14] noted that the ONYX is particularly useful in assisting soldiers who must traverse long distances of inaccessible terrain by reducing tension in leg muscles and increasing endurance. The ONYX may provide similar benefits to tank farm workers who must walk long distances while carrying heavy PPE. Researchers have also examined how the use of powered exoskeletons impacts both cognitive and physical workload.[15] When examining the effectiveness of an exoskeleton similar to the ONYX device, Bequette and colleagues[15] found that most participants had faster reaction times when the exoskeleton was unpowered. However, their findings also highlighted the individual differences between participants when considering both physical and cognitive impacts of lower-body exoskeletons. Several individual factors, such as fitness level and anthropometry, could impact how a participant interacts with an exoskeleton.

Understanding the user's perception of exoskeletons and the effects they have on the user's gait kinematics is an important consideration that should be evaluated prior to the deployment of such devices. The goal of this study was to explore the impact, whether positive or negative, of commercially available exoskeletons worn during a simulated tank farm shift. We were not expecting one device to perform favorably across all tasks; rather, we were evaluating the performance of the exoskeletons in order for DOE-EM sites to make informed decisions when considering future exoskeleton implementation.

III. METHODS

A generalized set of tasks emulating physically challenging tank farm activities was derived from the tank farm survey responses. The study tasks include walking over level and inclined terrain, walking while carrying heavy toolboxes/loads, performing tasks with hand tools, and lifting loads from the ground to the waist level and vice versa while carrying a SCBA tank on the back to replicate PPE loading experienced by tank farm workers. A protocol was designed with these tasks in a specific order that would tax participants while performing these activities in a controlled laboratory setting. Details of the study protocol with the laboratory setup and relevant training for the usage of each device are provided in Secs. III.A and III.B, respectively.

III.A. Experiment Design and Setup

The study protocol included a mix of different types of walking, weight lifting, and a hand tool dexterity task performed while stationary with 5-min rest periods in-between tasks. An outline of the complete laboratory controlled set of tasks in sequence designed for this study is shown in Table I. Each task in the study protocol, with the exception of the less physically demanding hand tool dexterity test, was separated by a 5-min rest period to minimize overexertion to the participant.

An instrumented treadmill was used for the walking activities where participants were required to (1) level walk: walk on level slope for 10 min to replicate walking at the job site or between workstations, (2) weighted walk: walk on level slope for 10 min while carrying a 15-lb kettlebell to replicate carrying a toolbox or load, and (3) incline walk: walk at a 15-deg incline for 10 min to replicate walking up a moderate slope. Participants started the weighted walk with the 15-lb load in their dominant hand and were allowed to switch hands as needed during the task. All level and inclined walking tasks were performed at the participant's self-selected pace previously determined during the participant's screening session. Details of speed selection during screening and the device training sessions are provided in Sec. III.B.

TABLE I

Study Protocol: Outline of Tasks Performed in Sequence

Task	Duration (min)
Rest	5
Level walking	10
Hand dexterity test	10
Weighted walking	10
Rest	5
Weight lifting	10
Rest	5
Incline walking	10
Rest	5
Total time	70

The hand tool test was designed based on the standard calibrated hand tool dexterity test apparatus from the Lafayette Instrument Company.[16] Participants removed 12 sets of bolts and nuts attached in three rows from the left side of the apparatus and attached them on the right side. The hand tool test was placed in front of the participant, approximately 3 in. below elbow height. Participants were free to sit or stand during this task as the device allowed. This was not a timed activity; participants were allowed ample time to complete the task and wait in place until the preallocated time of 10 min for this activity passed. The apparatus is generally used to assess user skill with tools[16] based on the time it takes for them to complete the test. However, in this study, the tool was used to replicate a task requiring the worker to use a variety of hand tools while standing or sitting, as the device allowed, for a considerable amount of time with a heavy SCBA tank on their back.

The weight lifting task included lifting weights from the ground to a table at a height of 29 in. and from the table to the ground every 10s for a total of 10 min. Initially, three 15-lb kettlebells were placed on the ground in a line followed by three 20-lb kettlebells placed in a line on the table. The 6-ft-long table was positioned parallel to the line of kettlebells on the ground with its nearest edge 0.5 ft from the ground kettlebells. Participants would move along the line transferring the 15-lb kettlebells first from ground to table in sequence, then the 20-lb kettlebells from the table to the ground, and then repeat in the reverse order transferring the weights again every 10s at a fixed cadence.

The treadmill used in the laboratory setup was an AMTI instrumented treadmill with two front-back positioned tracks capable of providing a variable incline of up to 20% grade to simulate workers walking on flat or hilly terrain. The treadmill included 6-axis force plates on the front and rear tracks to measure the center of pressure (COP) and ground reaction forces (GRFs). Hand rails were attached on the front, left, and right sides of the treadmill, and an emergency stop button was also available in front of the participant for safety purposes. The hand rails were marked with colored tape at appropriate locations to help the participant stay centered on the treadmill when walking. A VICON motion capture system (Version 2.12.1) was utilized to track the participant's body movement during each of the tasks. Retro-reflective markers were attached on the participant's lower body with adhesive tape. With the above setup, the participant's body motion and GRF data were collected during each session.

Each participant completed four data collection sessions, one for each device condition designated as (1) noExo: without any exoskeleton device, (2) ONYX: wearing the ONYX device, (3) Noonee: wearing the Noonee Chairless Chair device, and (4) ExoBoot: wearing the Dephy ExoBoot device. The order of these device sessions differed for each participant. Participants were required to carry a SCBA tank on their back mounted on a harness (3M Scott 60-min duration, 25 lb, TC-13F-96 CBRN) to simulate tank farm PPE requirements during all tasks, across all device condition sessions. In ONYX sessions, a custom battery holder was mounted on each side of the SCBA harness to hold the ONYX batteries during testing. The batteries were assumed to have a negligible contribution on the moment created about the spine by the added weight. Participants wore the Dephy boots as standardized footwear for all device condition sessions. An illustration of a participant wearing the ONYX device ready for weighted walking task set up on the treadmill carrying a 15-lb kettlebell and instrumented with VICON motion capture markers is shown in Fig. 2.

During each device condition session, participants completed a questionnaire after every task to record their immediate perceived exertion, comfort, and helpfulness/hindrance when using the device for the task. Perceived exertion levels were recorded using the Borg CR10[17] scale, and comfort and helpfulness/hindrance responses were recorded using an 11-point negative-to-positive scale.

Fig. 2. A participant on the treadmill getting ready for the weighted walking task. The participant is wearing the ONYX device and SCBA tank and has reflective markers placed on the lower body.

At the end of each device condition session, participants were asked to rank the helpfulness of the device for each of the tasks. This questionnaire was designed to identify any changes in the participant's opinion on device helpfulness on each of the tasks once all the tasks were completed to attenuate any bias in opinion due to in-session exertion level or tiredness and to understand the participant's impression of the device helpfulness on tasks at an emulated end of work day.

Last, at the end of the study (completion of all device condition sessions), participants were asked to rank the devices from best (1) to worst (4) based on comfort and overall helpfulness for all tasks, as well as the device's helpfulness for each task individually. This questionnaire was designed to identify the participant's overall opinion on which device was most suitable for the full protocol and compare devices to each other.

III.B. Screening and Device Training

Each recruited participant for the study initially went through a screening session where they were briefed about the study details and the laboratory setup. Participant consent was obtained before proceeding with the study, and participants were free to stop participating in the study at any time. Participants were fitted with each device following the guidelines provided by the respective device manufacturer. While wearing each of the devices, participants walked on a level treadmill for 5 min each. The treadmill speeds in each device case were incremented in small steps, and the participants were instructed to select a speed characterized as a "brisk walk" that they could "maintain for 30 minutes." After the speed selection was completed for all device level walking conditions, the overall lowest speed was chosen for the participant's level and weighted walking data collection sessions for all devices. The process was repeated for the incline walking speed selection.

The study had three vastly different exoskeleton devices; thus, each participant completed a separate training session for each of the devices prior to completing the designed data collection session with the emulated tank farm tasks. Each device training session allowed the participant to familiarize themselves with the device and practice a condensed version of the tasks in the study protocol. Device training consisted of three instances of 10 min of level treadmill walking, two instances of 10 min of inclined treadmill walking, and a weight lifting and hand tool dexterity task each 10 min in duration spaced out by rest periods. Participants were trained in a sitting exercise for 10 min specifically for the Noonee Chairless Chair device. The complete set of training tasks in sequence is presented in Table II. After a device training session occurred, participants were given a minimum of 24 h of rest before the data collection session took place.

III.C. Participant Recruitment

Participants were recruited through an internal daily newsletter sent to all Sandia National Laboratories (SNL) employees. Age range, sex, and information regarding prior experience with SCBA was gathered to select participants who closely represented the demographics of a tank farm workforce. Three volunteers were selected for the study, as shown in Table III. The relatively small study enrollment was due to the extensive time required to complete each participant's study sessions (eight sessions were required per participant, with each session lasting 1 to 3 h). Because of the small participant pool, the results will be evaluated as individual case studies and not aggregated for population-level statistical analysis.

The study was approved by SNL's Human Studies Board (SNL000366). Participants provided informed written consent and met all inclusion criteria prior to beginning the study. The inclusion criteria were participants must have been able to fit into all three exoskeleton devices without exceeding the manufacturer prescribed weight limits; must walk for 30 min with a 25-lb load; must lift up to 20 lb; and must be free of any unhealed musculoskeletal injuries and/or chronic joint or muscle pain, musculoskeletal or neurological disorders, and cardiovascular and pulmonary disorders that could affect balance or gait.

TABLE II

Device Training Protocol: Outline of Training Tasks Performed in Sequence

Task	Duration (min)
Level walking	10
Rest	5
Weight lifting	10
Rest	5
Level walking	10
Rest	5
Incline walking	10
Rest	5
Sitting with Noonee	10
Level walking	10
Rest	5
Hand dexterity test	10
Incline walking	10
Total time	105

TABLE III

Demographics of Study Participants

Identifier	Sex	Age Range	Weight (lb)
A	Male	40 to 49	194.9
B	Female	<39	180.3
C	Male	>50	236.5

IV. DATA PROCESSING AND ANALYSIS

The VICON motion capture marker data for each of the walking activities in this study were labeled and gap filled using the VICON Nexus software (Version 2.12.1). Scaled models of each participant were created in OpenSim (Version 4.3).[18] Inverse kinematic results were computed with the scaled models to generate gaits for all walking activities for each device condition for each participant. For each participant and device condition, 20 individual walking steps from each leg were segmented for each of the walking activities from footplate mappings obtained using the force plate GRF and COP data. The hip, knee, and ankle joint angles at each gait percentage were analyzed across device conditions to assess differences in gait from the baseline noExo device condition of each participant.

Several metrics of interest were identified as indicators of comfort/ease of walking and to compare gait profiles across device conditions for each of the participants on each walking activity. The identified metrics include stride length measured as the maximum distance the heel travels from heel strike to toe-off, the percentage of gait spent in the stance phase, the peak extension angle and the corresponding percentage of gait cycle for the hip, the peak flexion angles and their corresponding percentage of gait during stance and swing of the knee, the peak dorsiflexion and plantarflexion angles and their corresponding percentage of gait during stance for the ankle, and the range of motion (ROM) for each activity and device condition for each participant.

It was hypothesized that the above metrics will be affected by the noExo, ExoBoot, Noonee, and ONYX device conditions and by the level, weighted, and inclined walking activities. A multifactor analysis of variance (ANOVA) was fit for each metric on the aggregate data from 20 steps of the left leg segmented from each walking activity for each of the participants in the study. The interaction effects of these factors are interpreted when they highlight a difference in behaviors across treatments. Post hoc–dependent t-tests were evaluated when appropriate. To examine how individuals were affected by the experimental conditions, 95% confidence intervals for each individual over specific contrasts were calculated. With a small participant pool, we examine each participant response individually and emphasize here that while pooled data can provide information on general metric trends, individual data provide insight on the different ways that participants may have responded to the device condition.

We also acknowledge here that the exoskeleton devices considered in this study were designed to benefit either specific joints or different activities. However, the goal of this study is to identify and assess any differences in gait across the device conditions and different types of walking activities identified to be the most physically challenging activity at tank farm sites while wearing heavy PPE. In addition to considering the effects of the intended design goal of these devices, the goal is also to identify any unintended effects that may exist and affect day-to-day activities of workers at these sites.

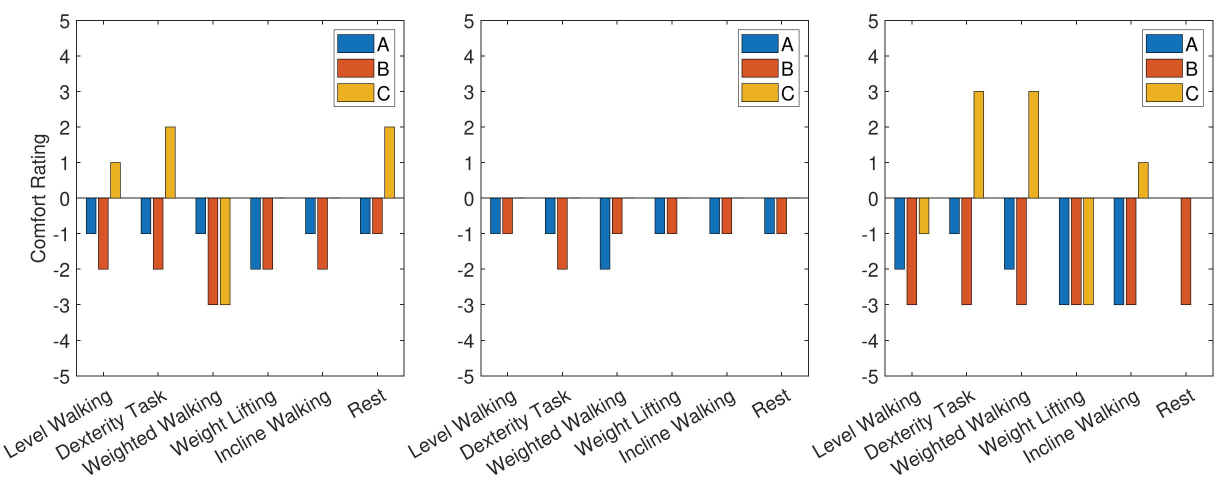
V. RESULTS

V.A. Subjective Feedback

Although this work considers the three participants as separate case studies, there are a few trends across participants that will be highlighted. Otherwise, the following discussion looks at each participant's questionnaire response separately and compares the participants' experiences using each device.

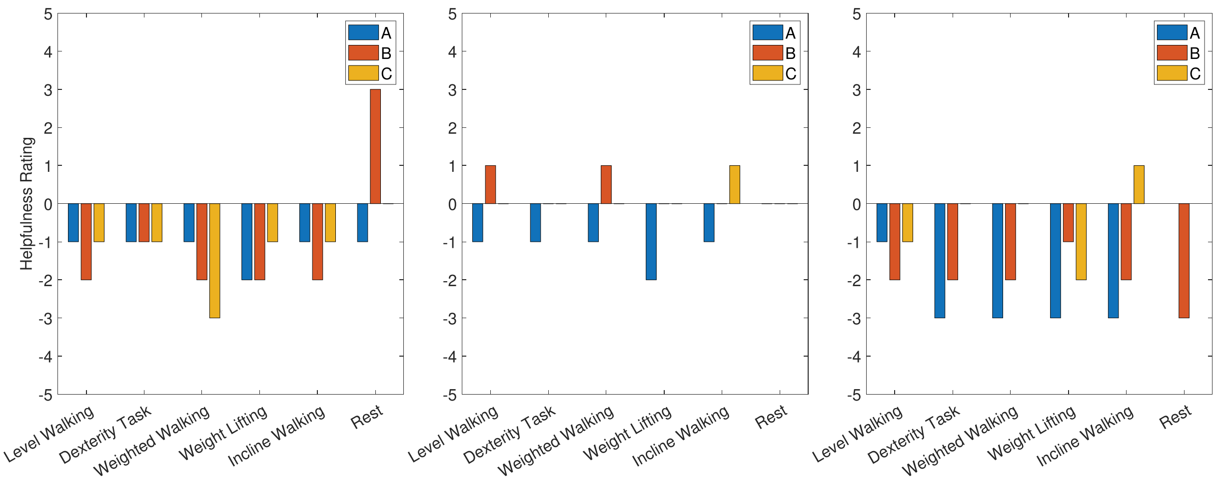
Comparing the responses between Figs. 3 and 4, helpfulness was ranked generally higher than comfort for all activities, and both comfort and helpfulness had generally negative responses. The Dephy ExoBoot was consistently ranked as marginally helpful or hindering, but there were no strong feelings (see Fig. 4b). Participants C and B perceived levels of exertion show similar increase while wearing the ONYX over time (see Fig. 5d), whereas there was no obvious trend of increasing or decreasing exertion reported by Participant A. Participant B also reported increasing exertion levels over time while using the Noonee Chairless Chair (see Fig. 5b). Participants A and B had overall lower exertion rankings than Participant C but reported lower comfort scores for all devices with the exception of Participant B's comfort score for the Noonee Chairless Chair during inclined walking.

Participant A preferred to not use an exoskeleton, which is to be expected in a portion of the population [see Table IV, "a) Participant A"]. When comparing devices, this participant showed a consistent preference for the ONYX for all active tasks. However, this participant consistently reported the lowest comfort scores when compared to the other participants. This correlates with the participant's helpful/hindrance scores. Notably, the participant scored the ExoBoot and the ONYX as the most hindering among the participants.



(a) Noonee (b) ExoBoot (c) ONYX

Fig. 3. End of task response: comfort rating from each participant for each task during (a) Noonee, (b) ExoBoot, and (c) ONYX device condition session. Positive scores indicate the device was comfortable during the given task, and negative scores indicate the device was uncomfortable during the given task. Scores of zero appear as empty bars.



(a) Noonee (b) ExoBoot (c) ONYX

Fig. 4. End of task response: helpfulness/hindrance rating from each participant for each task during (a) Noonee, (b) ExoBoot, and (c) ONYX device condition session. Positive scores indicate the device was helpful for a given task, and negative scores indicate the device was hindering to the given task. Scores of zero appear as empty bars.

Participant B's response revealed consistent preferences between the exoskeletons [see Table IV, "b) Participant B"]. The Dephy ExoBoot was the most favorable device for most tasks, whereas the ONYX was the least favorable among the devices. The ONYX was the only device that the participant reported a negative perception when compared to not using an exoskeleton. In other words, Participant B would have preferred to wear the other two devices or not use a device rather than use the ONYX. It is interesting to note that this participant preferred the ExoBoot for all walking tasks, which is the activity that the device is primarily marketed to assist. However, Participant B thought the ExoBoot was only marginally helpful for level walking and weighted walking on level ground.

Participant C was the only participant that gave positive rankings for comfort for any device (Fig. 3). Participant C reported the only positive comfort score on Noonee and ONYX. This participant also thought the ExoBoot was helpful for incline yet he "didn't notice the device for any task." Participant C did not prefer the Chairless Chair from Noonee as it was consistently ranked the "worst for the task" across every task [see Table IV, "c) Participant C"]. This was the largest participant in our study, and he voiced his distrust of the device to the research team during his time wearing the device after the training session. Similar to Participant A, this participant preferred not to use exoskeletons for common tasks but preferred the ONYX for more taxing tasks (i.e., lifting weight from the ground and walking uphill). This participant thought the ONYX was helpful overall but did not like wearing it for static tasks where the device is not being actively used. Interestingly, this participant recorded less negative comfort scores for all the devices but also felt high levels of exertion for all devices.

V.B. Gait Kinematics

Figure 6 presents a summary of observed differences in each gait analysis metric for each participant, activity, and device condition from their respective noExo baseline device condition case. Color-shaded boxes with arrows indicate a statistically significant change from the noExo baseline device condition, where red indicates a statistically significant decrease and green indicates a statistically significant increase of the metric. The column for ankle percent gait of peak dorsiflexion during stance is omitted as it showed no statistically significant change for any of the participants, activities, and device conditions. The metrics ankle peak plantarflexion angle and its corresponding percentage gait are ignored for all device conditions in inclined walking.

V.B.1. Participant A

Gait analysis revealed that Participant A presented similar differences in level and weighted walking gait from the baseline in general for all device conditions. Stride length increased with statistical significance in both these activities across all device conditions except for the Noonee in weighted walking where it remained unchanged from its corresponding baseline case. The hip

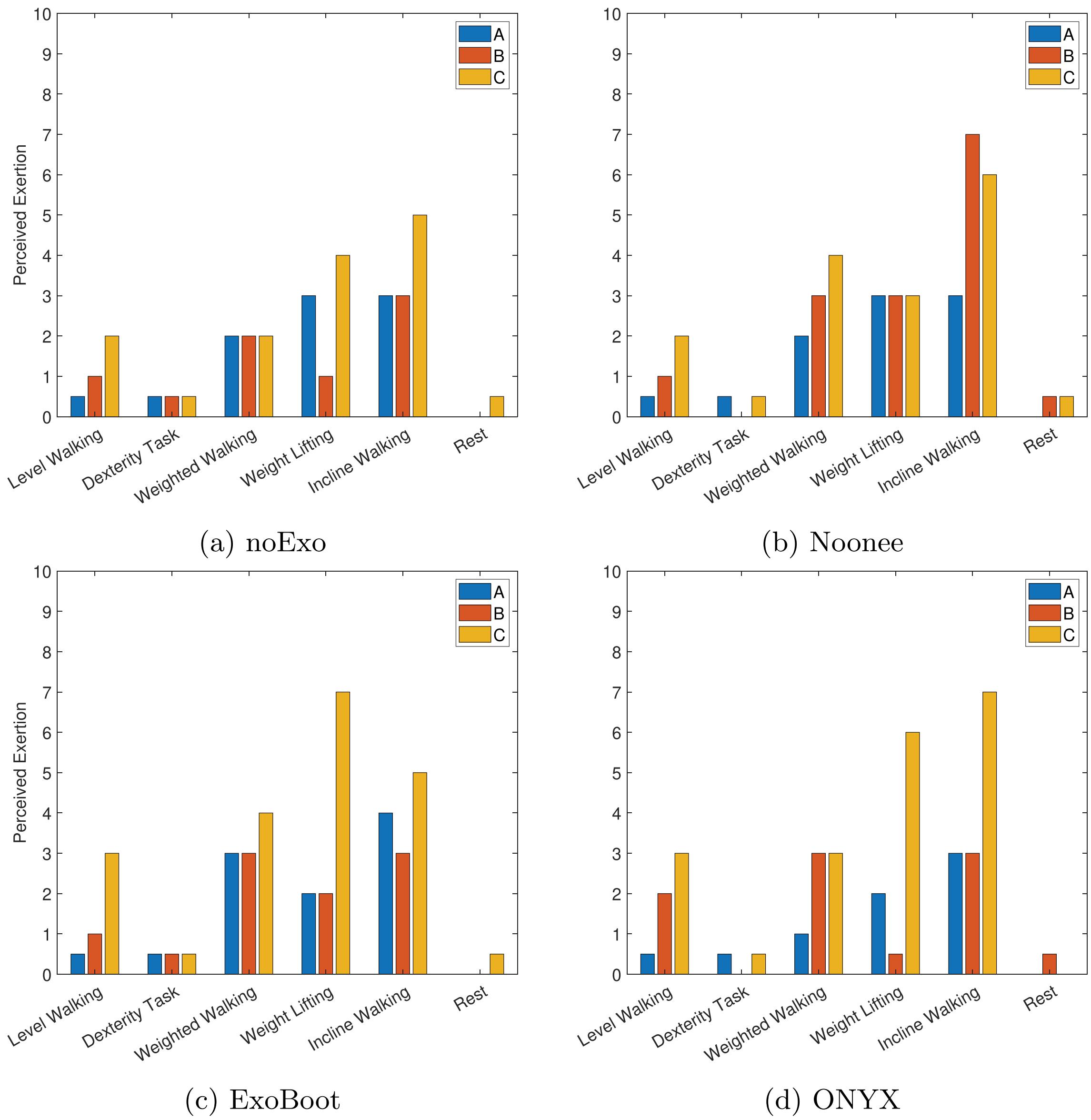


Fig. 5. End of task response: perceived exertion rating from each participant for each task during (a) noExo, (b) Noonee, (c) ExoBoot, and (d) ONYX device condition session, using the Borg CR10 scale. Scores of zero appear as empty bars.

and the knee ROM showed a statistically significant increase for the ExoBoot across both walking conditions while the rest remained unchanged. The ankle ROM showed a statistically significant decrease across all device conditions. Participant A rated comfort and helpfulness consistently as negative for all devices. The ONYX device was perceived to be the most uncomfortable and hindering during weighted walk. From the obtained results, no direct correlation could be established in the participant's gait change with device conditions and the perceived comfort and helpfulness scores. However, the knee gait profile suggested that the knee remained hyperextended with all device conditions compared to the baseline case with a statistically significant decrease in peak knee flexion during stance and swing with the exception of the ExoBoot device in weighted walk. The discomfort and hindrance perceived by the participant with the devices and the added weight in weighted walk may be explained with the knee gait profile suggesting that the participant may have been trying to cope with the added weight by unloading the added device weight onto the aligned femur and tibia with the knee hyperextended and eventually to the ground. The effect was the highest for the heaviest device, ONYX, with the added weight being carried in weighted walking.

TABLE IV

End of Study Response: Device Rankings by Comfort and Task Helpfulness

a) Participant *A*

	ExoBoot	ONYX	Noonee	No Exo
Comfort	2	4	3	1
Overall Helpfulness	4	2	3	1
Walking	2	3	4	1
Dexterity Task	3	4	2	1
Weighted Walking	3	2	4	1
Weight Lifting	3	2	4	1
Incline Walking	3	2	4	1
Rest	4	3	2	1

b) Participant *B*

	ExoBoot	ONYX	Noonee	No Exo
Comfort	1	4	2	3
Overall Helpfulness	1	4	2	3
Level Walking	1	2	4	3
Dexterity Task	3	4	1	2
Weighted Walking	1	2	4	3
Weight Lifting	2	4	3	1
Incline Walking	1	3	4	2
Rest	2	4	1	3

c) Participant *C*

	ExoBoot	ONYX	Noonee	No Exo
Comfort	2	3	4	1
Overall Helpfulness	2	1	4	3
Level Walking	3	2	4	1
Dexterity Task	2	3	4	1
Weighted Walking	3	2	4	1
Weight Lifting	3	1	4	2
Incline Walking	3	1	4	2
Rest	3	1	4	2

For inclined walking, the participant consistently rated the ONYX as being the most uncomfortable and hindering. However, gait analysis revealed that the stride length increased with statistical significance with the ONYX; no significant difference in hip or knee ROM was observed from the baseline. The results suggest that the perceived discomfort and hindrance may have been due to the same reasoning as the weighted walking case with the added temporal effects of increased perceived exertion during inclined walking. Other notable observations include the ExoBoot having a statistically significant increase of the stride length, hip ROM, and knee ROM, whereas the Noonee presented a statistically significant decrease of the stride length and hip ROM in inclined walking. The ExoBoot presented a decreased knee peak flexion during stance while reduced knee flexion for both the stance and swing phases were observed for the Noonee.

V.B.2. Participant B

Although participants walked on the treadmill during level and weighted walking at the same set speed specific to each device condition, the gaits observed for Participant B presented significant differences in level and weighted walking. In level walking, the stride length decreased with statistical significance for all device cases while it either increased or remained unchanged in weighted walking. The knee ROM had a mixed response of no change, decreasing, and increasing for the ExoBoot, Noonee, and ONYX, respectively, in level walking, while a statistically significant consistent increase was observed for all devices in weighted walking. The ankle ROM was observed to remain unchanged for the ExoBoot and Noonee and to decrease for the ONYX in level walking while it increased for the ExoBoot and Noonee and remained unchanged for the ONYX in weighted walking.

Device-specific observed trends include significant gait improvements from level to weighted walking across the board for all devices in terms of stride length and in terms of hip, knee, and ankle ROM. Such drastic improvement across the board may be attributed to temporal effects and the order of the activities. The participant may have acclimated to each of the devices and their added weight during level walking, presenting noticeable ROM and stride length increases with time in weighted walking. However, we note here that the Participant B survey responses on device comfort did not show any significant improvements from level to weighted walking for any of the devices, warranting further study on this observation. The participant also rated the ExoBoot to be the most comfortable in both activities without any change, yet gait analysis revealed increases in stride length, knee ROM, and ankle ROM from level to weighted walking. The significant decrease in knee peak flexion during stance and swing in the weighted walking case in all device conditions suggests that the participant may have been unloading the additional weight from the kettlebell and the devices onto the bones more effectively with a hyperextended knee.

The hip extension was also found to decrease with statistical significance in both level and weighted walk for the ONYX. With the ONYX being considerably heavier than the other devices, this observation is however consistent with the participant consistently ranking ONYX with the lowest comfort and helpfulness scores, suggesting that the device weight may have had an effect on the participant's gait and perceived impressions.

In inclined walking, stride length was observed to remain unchanged for the ExoBoot but showed

					Hip			Knee					Ankle			
Subject	Activity	Device	Stride Length	Stance as a percent of stride	Peak Extension Angle	% Gait of Peak Extension Angle	ROM	Peak Flexion Angle During Stance	% Gait of Peak Flexion Angle During Stance	Peak Flexion Angle During Swing	% Gait of Peak Flexion Angle During Swing	ROM	Peak Dorsiflexion During Stance	Peak Plantarflexion During Stance	% Gait of Peak Plantarflexion During Stance	ROM
A	Level Walking	ExoBoot	↑		↓	↓	↑	↓	↑	↓		↑	↑	↑		↓
		Noonee	↑	↓	↑			↓		↓	↓		↓			↓
		ONYX	↑		↓			↓		↓	↓		↓	↓		↓
	Weighted Walking	ExoBoot	↑		↓	↓	↑	↓			↓	↑	↑	↑		↓
		Noonee						↓	↑	↓	↓	↑	↓			↓
		ONYX	↑		↓			↓		↓	↓		↓			↓
	Incline Walking	ExoBoot	↑		↓	↓	↑	↓				↑	↑			↓
		Noonee	↓	↓	↑		↓	↓			↓		↑			↓
		ONYX	↑		↓	↑		↓	↑	↓						↓
B	Level Walking	ExoBoot	↓			↓	↑		↓				↓	↑		
		Noonee	↓		↑					↓		↓	↑	↑	↓	
		ONYX	↓		↓	↑	↑	↓			↑	↑	↓			↓
	Weighted Walking	ExoBoot					↑	↓		↓	↑	↑	↑	↑		↑
		Noonee	↑	↑	↑	↑	↑	↓		↓		↑		↓		↑
		ONYX			↓		↑	↓		↓	↑	↑				
	Incline Walking	ExoBoot				↓	↑	↑		↓	↑					↓
		Noonee	↓	↓		↓	↑	↓	↓	↓	↓	↑	↓			
		ONYX	↓	↓	↓		↑	↑		↑		↑	↓			↓
C	Level Walking	ExoBoot	↑		↑			↑		↑	↓	↓	↑	↓		↑
		Noonee			↑			↓	↑	↓	↓	↓	↑	↓		↑
		ONYX	↑		↓	↑	↑	↓	↓	↓	↑	↑	↓	↓		
	Weighted Walking	ExoBoot	↑		↑	↓	↑	↑		↑	↓	↑	↓	↓		↑
		Noonee	↓		↑	↓		↓	↑	↓	↓	↓		↓		↑
		ONYX	↑		↓		↓	↓		↓		↑	↓	↓		↓
	Incline Walking	ExoBoot			↑	↓			↓	↓		↓	↑			
		Noonee	↓		↑			↑		↓		↓	↑			↑
		ONYX			↓		↑		↓	↓	↑	↑	↓			

Fig. 6. Results from inverse kinematics calculations. Red- and green-shaded boxes with arrows indicate a statistically significant change from the no exoskeleton condition. Red shading indicates a significant decrease, and green shading represents a significant increase from the control condition.

statistically significant reduction for the Noonee and ONYX devices. The stance phase was also found to significantly decrease with the Noonee and ONXY devices. Participant B in general did not favor any of the devices during incline walk in terms of comfort and helpfulness; the Noonee and ONYX in particular were scored to be most hindering during incline walk in the survey response consistent with these gait analysis findings. However, the hip ROM in inclined walking was observed to increase significantly for all device conditions compared to the baseline case due to increased hip flexion in swing, which may have been as a result of fatigue. The knee peak flexion in inclined walking was increased during stance by the ExoBoot and during both stance and swing by the ONYX that could be due to the additional device weight.

V.B.3. Participant C

Similar to Participant A, Participant C also showed identifiable gait similarities in general in level and weighted walking for each device condition. In both walking activities, the stride length showed a statistically significant increase over the baseline for the ExoBoot and ONYX. Device condition effects on the hip peak extension, and knee flexion during stance and swing showed identical trends over the baseline. The comfort and helpfulness scores for level walk remained within ±1, suggesting that the participant did not hold any strong perception on the devices. However, the scores changed considerably in weighted walking, which suggests a device acclimation temporal effect on the participant. Taking a closer look at a device-specific assessment, Participant C's perception on comfort increased for the ONYX but decreased for the Noonee moving from level to weighted walking. The perception change on the Noonee can be observed in stride length analysis where it remained unchanged from the baseline in level walking but significantly decreased in weighted walking. The stride length and knee ROM for the ONYX increased with statistical significance over the baseline in both level and weighted walking; no gait change metric could be identified correlated to the perceived comfort improvement of the ONYX between these two activities. Compared to Participants A and B, gait analysis results for Participant C does not show a hyperextended hip or knee during walking, suggesting that the participant did not have to adapt their gait to unload the added device weight on their body. Participant C was considerably taller and heavier than the other individuals in the study. Regardless, the ONYX device consistently presented reduced hip peak extension for all participants in all walking cases.

In inclined walking, survey responses from Participant C showed that the ONYX was perceived to be the most comfortable and helpful. Gait analysis revealed a statistically significant increase in the hip and knee ROM while the stride length remained unchanged from the baseline. Ankle peak dorsiflexion showed a statistically significant reduction for the ONYX while it increased for the ExoBoot and Noonee. The participant had a neutral perception of comfort and helpfulness of the ExoBoot. The ankle ROM remained unchanged, and the peak hip extension increased from the baseline case for the ExoBoot in inclined walking.

Based on the gait analysis results, Participant C in general seemed to favor the two powered devices over the Noonee. Perception of the ONYX improved over time with the activities while the ExoBoot generally remained unchanged. The perception of the Noonee deteriorated from level to weighted walking and then remained neutral for inclined walking; the Noonee was the only device that recorded a statistically significant decrease in stride length for both weighted walking and inclined walking for Participant C.

A detailed presentation of the distribution of the gait analysis metrics for each of the individual participants is also provided as supplemental data to this paper for the reader's convenience. The three columns in each plot represent level, weighted, and inclined walking in order. For each type of walking activity, device conditions with statistically significant differences from the baseline noExo condition are shown by black horizontal lines on top.

VI. DISCUSSION

The observations made in this study with the small pool of participants presented a diverse set of responses when using the three different exoskeleton devices in the study protocol tasks. Participant A consistently preferred to not use any of the exoskeleton devices while Participant B presented mixed responses of finding the ExoBoot helpful and the ONYX unhelpful and uncomfortable for the generalized set of tasks. Participant C, who was the heaviest and tallest of the pool, exclusively preferred using the powered devices with an emphasis on the ONYX for taxing tasks. Gait analysis of the participant walking activities supported some of these participant perceptions while contradicting a few others, suggesting that the participant perception of the devices failed to consistently reflect the actual gait changes regardless of improving or deteriorating from the baseline. Inconsistent gait changes in each device condition compared to the baseline over time also suggested that adaptation may still have been occurring for some of the participants regardless of the extensive training session with each of the devices.

Aggregating results from a device perspective revealed two specific observations that heavily relied on participant attributes. Participant C was the heaviest and tallest in the pool and struggled to trust the Noonee Chairless Chair consistently ranking it the lowest in the comfort and helpfulness index; Participants A and B, on the other hand, presented mixed responses across the different activities. The ONYX device was the heaviest of all the tested devices in this study. The hip peak extension angle decreased for all participants for all walking conditions for the ONYX. Gait analysis and subjective feedback revealed that Participants A and B, having a relatively smaller height and weight, may have struggled carrying the added weight; Participant C, with significantly larger height and weight in comparison, rated the ONYX as comfortable and helpful in weighted and incline walking. These observations clearly identified the effect of a device property on the device adaptability by a user based on their physical attributes. Further work is required to establish if adaptability to the Noonee device with time can improve usability for users such as Participant C or how demanding a task needs to be, if at all, for a specific a device design benefit to stand out for a given user.

The protocol in this study included at least one task that each of the chosen devices was specifically designed to benefit. Even though previous research on these devices has positively quantified task-specific benefits, we highlight our results showing that such benefit may not hold true in a real-world setting where users often have to complete a diverse set of activities in a given work day, underscoring the task-specific nature of currently available exoskeletons. The intended perception and adaptability to the device by the user for its specific task is diluted by other motion or activities in a work day that the device was not designed for. In addition, our results also validated the variability in adaptation to these devices by users of different demographics that is often seen with exoskeleton studies.

VII. CONCLUSION

The results described above are consistent with the variability across participants that is often seen in exoskeleton studies. For reasons that are still not well understood, individuals adapt to devices in diverse ways that are often hard to predict. One implication of this finding for end users is that it should not be assumed that all workers will adapt to a device in the same way. Some may benefit from a device while other others do not, and this is especially true of powered devices that provide active assistance. This variability, coupled with the cost and complexity of powered exoskeletons, makes the current use of these devices in many applications challenging.

Data presented in this work suggest the possibility of temporal trends in a user's perceived level of exertion while wearing the device, specifically over long periods of time. Additional work is needed to confirm the presence of these temporal trends.

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