The Economic Value of Augmentative Exoskeletons and their Assistance

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Understanding the success of augmentative exoskeletons is critical to their impact on society. Many exoskeletons are developed to address impairments stemming from neuromotor pathology, which provides guidance for understanding their abilities; however, for augmentative exoskeletons that assist able-bodied users, a clear metric of success remains an open question. In this study, we leverage an approach from economics--the Vickrey second-price auction--to quantify the economic value added by lower-limb exoskeletons during uphill walking. In our protocol, participants describe the monetary compensation needed to continue walking uphill for consecutive bouts of two minutes. To incentivize truthful descriptions of participant's “price to walk,” their compensation amounts were provided as bids in Vickrey auctions before each bout. We compared these data across different conditions to determine the marginal value of the exoskeleton weight, assistance, and weight + assistance. Our approach found that the total value of the exoskeleton and its assistance was modest ($3.40/hr, SD: $3.35/hr); while most participants found the assistance itself valuable ($19.76/hr, SD: $19.43/hr), this value was nearly offset by the cost of wearing the exoskeleton weight (-$18.59/hr, SD: $18.28/hr). Our approach and results demonstrate that economic value can be a powerful tool to develop exoskeletons that maximize user benefit.

Introduction

Powered lower-limb exoskeletons have the potential to transform human mobility by extending the locomotor abilities of their wearers. These technologies augment lower-limb function by providing mechanical assistance to the joints of the legs in tandem with the human neuromotor system, and thus can make physically demanding tasks less challenging for both able-bodied and impaired individuals. Assistance provided by modern exoskeletons have been shown to reduce the caloric demands and muscular effort required for walking (*1–9*). Consequently, exoskeletons may have beneficial implications for recreational users and workers in factory, military, or supply chain environments. In addition, exoskeletons can reduce muscle activation, and thus may reduce joint loading (*10–13*), potentially extending the physical capabilities of aging individuals. Rehabilitation-focused exoskeletons may also restore the mobility of people with neuromotor deficits who face weakness and impairments in balance, coordination, and joint mechanics following upper motor neuron disease (*e.g.* stroke). Exoskeletons can be used to assist the gait of these individuals, with several commercially-available lower-limb exoskeletons having been approved by the U.S. Food and Drug Administration.

The metrics by which we assess exoskeletons drive their design, control, and potential impact. For rehabilitative applications, the design of these technologies has a clear physiological objective: the restoration of impaired gait function. These exoskeletons are often considered successful if they restore able-bodied kinematics or kinetics, which provide clear physiological goals on which to base exoskeleton design and control decisions (*8, 12, 14–16*). However, for augmentative applications in which the user is typically able-bodied, the metrics of success are less clear. Currently, augmentative exoskeletons are developed based on their ability to meet a physiological objective; the "gold standard" for exoskeleton success is the reduction of metabolic expenditure during locomotion (*i.e.* a reduction of the calories burned) (*17*). This objective is both intuitively meaningful and objectively measurable (*18, 19*). Modern exoskeletons have reduced the metabolic rate relative to unassisted walking by an average of approximately 14% (*1–6, 20*). This objective has led to the rise of promising 'human-in-the-loop' (HILO) optimization techniques, which directly modulate exoskeleton assistance based on the metabolic reductions experienced by the wearer (*21–27*). Recent work has established experimental infrastructure that illustrates the tight coupling between metrics of success and exoskeleton development. An example of this infrastructure includes tethered emulator systems (*7, 28*), whose purpose is to inform exoskeleton design and control based on their ability to reduce the metabolic expenditure of their wearer. Numerous studies investigating the biomechanical underpinnings of metabolic cost reductions have also been conducted to find more optimal exoskeleton assistance settings (*20, 22, 29, 30*). Finally, other metrics include net-joint torque reduction (*11*) and muscle activation reduction (*10, 12*), which are commonly used, easier-to-measure proxies for improvement in energetics.

Though the physiological benefits of exoskeletons have been demonstrated using metabolic metrics, these benefits have not widely translated to wearer perception of enhanced endurance and strength. These perceptions are important, as for augmentative exoskeletons to reach their potential in society, users will need to voluntarily accept these technologies into their lives. They thus must be developed to provide a perceivable benefit to their wearer, in addition to objective assessment of their impact. Our recent work has shown that during exoskeleton-assisted walking, the average user cannot yet perceive the benefit of most systems available today (*31–33*). That is, the metabolic rate needed to be reduced by 23% (N = 10) before exoskeleton users could reliably perceive this improvement (whereas most modern exoskeletons reduce the wearer's metabolic rate by 14% compared to unassisted walking (*17*)). These results agree with prior studies that showed humans were relatively insensitive to small changes in exertion in other exercise contexts (*34*). Intuitively, if the user is unable to perceive the metabolic reduction provided by an exoskeleton, this value may be difficult to incorporate into decision-making during exoskeleton design, translation, and adoption. Consequently, assessing and developing exoskeletons based on reductions in metabolic rate could result in systems that are not perceived as valuable by users, despite significant energetic benefits (*3, 23, 30, 35–37*).

An alternative method for measuring success in exoskeleton development is to quantify the perceived *economic value* provided to the wearer during its use. Economic value, measured in monetary currency (*e.g.* US dollars), is assigned by the wearer and can reflect the multifaceted nature of exoskeleton user experience. Although exoskeletons can provide assistance that improves energetics, that assistance often comes at a cost to the wearer. Exoskeletons can add discomfort, weight, and audible noise, in addition to having aesthetic implications. While exoskeletons may potentially have universal positive value, the heterogeneity of the metabolic response to exoskeleton assistance, coupled with the known variety of responses to new innovations within the social sciences (*38*), could also imply a wide range of valuations for wearing an exoskeleton. If the user is able to assign economic value to the experience of exoskeleton use, they are able to inherently balance and quantify these trade offs. Thus, we posit that exoskeletons that maximize economic value may have a greater likelihood for adoption and use. Prior work in management science has established that the perceived value of different technologies has a significant impact on user intent to adopt those technologies into their daily lives (*39–43*). When potential exoskeleton users, manufacturers, and others are weighing the choice to adopt or purchase an exoskeleton, the consciously perceived benefits must outweigh these costs. Thus, the perceived economic value of exoskeleton use is a potentially powerful metric for designing and controlling exoskeletons that quantifies meaningful, individualized benefits to wearers.

In this study, we introduce a tool for measuring the perceived economic value of exoskeleton use as a metric to evaluate their performance and user experience. We define and use this tool to quantify the economic value—termed *Marginal Value (MV)*—provided by bilateral ankle exoskeleton use during uphill walking. We leveraged the Vickrey second-price auction to measure participants' "price to walk," which was then aggregated and compared across conditions to obtain our economic value metric (*i.e.* MV). Our experiment revealed that while there was insignificant positive value of exoskeleton use across subjects, there was a large disparity between subjects. Some subjects reported substantial value provided by the exoskeletons, which represents an opportunity target these "responders" in future work. The near-zero net MV from the exoskeleton stems from two competing effects: the MV of the powered assistance alone was substantially positive, but it was counteracted by the cost from wearing the device itself. The use of MV offers advantages over the more common metabolic rate metric, including its accessibility, in that it does not require specialized equipment, and its intuitiveness, as users and manufacturers are more likely to understand the value of monetary currency over biomechanical quantities (*e.g.* calories burned or muscle power). Our approach is also generalizable, and can be used to measure the value of not only different types of exoskeleton assistance, but also various technologies, activities, or experimental conditions.

Background on Vickrey auctions

Within the field of economics, the Vickrey second-price auction (*44*) provides a well-studied incentive structure for quantifying the economic value of abstract concepts. In a seller's Vickrey auction, participants compete via bidding to sell a good. The winner of the auction is the participant that bids the lowest amount to sell the good. However, the winner will earn the amount bid by the second-lowest bidder. The Vickrey auction is also "sealed-bid" in that each participant's bids are not revealed publicly. This second-price paradigm incentivizes subjects to bid their true perceived value for the good (*44–46*) rather than attempt to guess (and slightly underbid) all other bidders' lowest bids. Auction participants would be discouraged from bidding higher than what they believe the good is truly worth, for fear of losing the auction to a competitor with a lower bid, and the second-price nature breaks the link between the auction winner and their actual bid. Conversely, they will have no incentive to underbid below their true value since they would risk selling for a "loss" if they won the auction. Thus, the Vickrey auction provides a quantitative measurement for the value of arbitrary goods or services by measuring an individual's willingness to buy or sell (*46, 47*). The specific incentive structure is thus less prone to biases when quantifying the value of a good when compared to alternative methods such as direct feedback (*48, 49*). Prior researchers have also used Vickrey auction metrics to measure the value of abstract concepts or actions, such as food safety (*50*), GMO-free foods (*51*), the stigma resulting from HIV (*52*), personally identifiable information (*48*), and smartphone battery life (*53*). In particular, Coursey *et al.* employed the Vickrey auction to quantify the willingness of participants to endure performing an unpleasant task, such as tasting a bitter liquid (*54*). These examples highlight the promise of the Vickrey auction to quantify the perceived economic value provided by experiences, including exoskeleton use.

Results

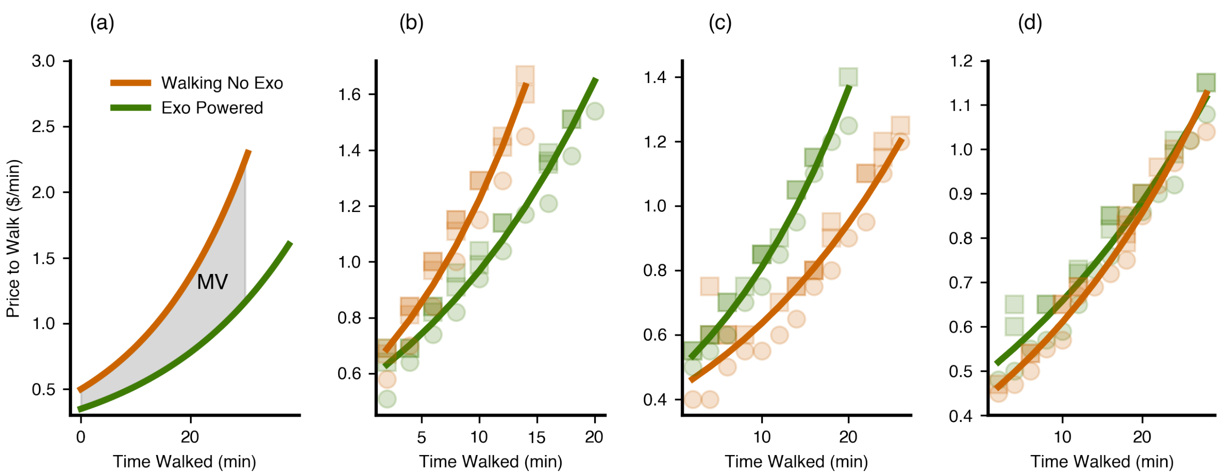

Figure 1: (a) Generic examples of price to walk curves for the walking-no-exo condition (green) and the exo-powered condition (orange) from different subjects. The marginal value (MV, the value of the exoskeleton assistance) is given by the area between the curves. In actual trials, the price to walk curves are estimated by fitting first order exponentials to subject bids. Circles denote winning bids, while squares denote losing bids. The participant in (b) shows a clear benefit from the device, the one in (c) shows a clear detriment, and the one in (d) is more ambiguous.

Within each trial, participant bids invariably trended upwards as participants became more fatigued and this trend was well represented by a first-order exponential. During each trial, participants either walked with normal walking shoes **(‘walking-no-exo’)**, with the exoskeleton applying assistance **(‘exo-powered’)**, or with the exoskeleton donned but applying no power **(‘exo-powered-off’)**. Across all three walking conditions, the average bid for each two-minute interval was \$0.75, with a standard deviation of \$0.39. The maximum bid was \$5.00, while the minimum bid was \$0.10. As participants continued to walk during each trial, their bids increased at varying rates (Fig. 1). The first-order exponential model exhibited an R^2 of 0.87 ± 0.11, averaged over all con-

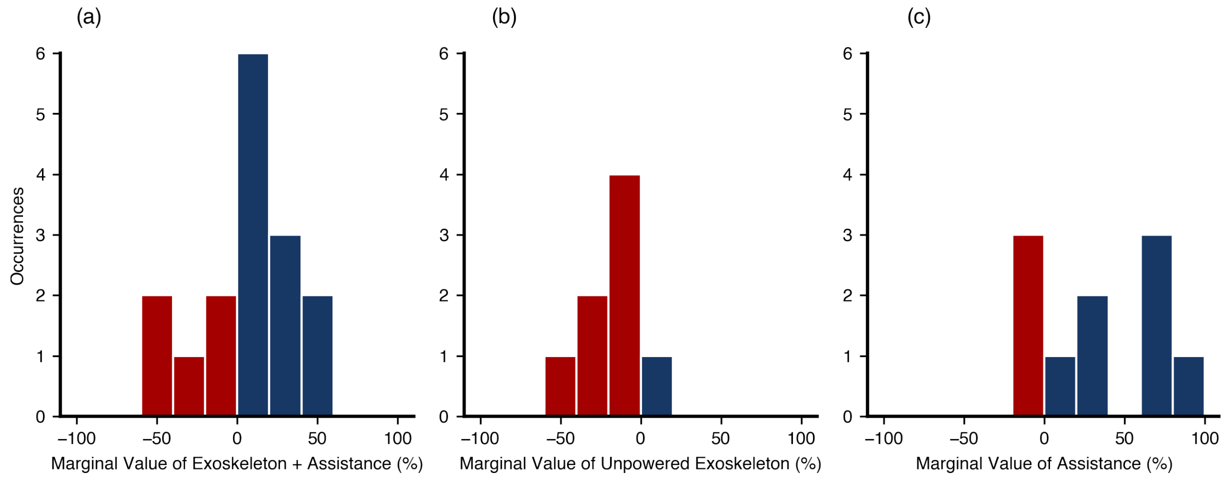

Figure 2: Histograms of the Marginal Values (MVs) for the different conditions. Positive MVs, indicating that value was added to the wearer are in blue, while negative MVs, indicating that costs were imposed on the wearer, are in red. (a) The MVs of exoskeleton + assistance for all sixteen subjects. The average MV was 5.81%, with an SD of 31.1%. (b) The MVs of the unpowered exoskeleton for the twelve subjects who participated in this condition. Aside from one subject, all participants experienced notable economic costs from this condition, reflected by the average MV being significantly negative (average: -31.8%, SD: 45.0%). (c) The MVs for the exoskeleton assistance alone (average: 33.8%, SD: 38.1%). While the average MV of the exoskeleton + assistance was not significantly positive, the assistance alone conferred a significant benefit.

ditions experienced by the sixteen participants. These first-order responses denote the user's price to walk curves for each condition (the curves for the walking-no-exo and exo-powered conditions are shown in Fig. 1a). The area between the walking-no-exo and exo-powered curves denotes the Marginal Value (MV) of the exoskeleton and its assistance, which is the value obtained by the participant from the exoskeleton's use. Participant price-to-walk curves broadly demonstrated three potential outcomes; namely, a clear economic benefit from the exoskeleton's assistance (higher walking-no-exo curve than exo-powered curve, Fig. 1b, positive MV), a clear economic penalty (lower walking-no-exo curve than exo-powered curve, Fig. 1c, negative MV), and a negligible economic effect (similar walking-no-exo and exo-powered curves, Fig. 1d, near-zero MV).

Our approach was able to quantify the intuitive effects of added mass and assistance. Across subjects, the MV of the exoskeleton + assistance was positive but not significant, while the MV of the unpowered exoskeleton was significantly negative, and the MV of the assistance itself was significantly positive. The average inter-subject MV of exoskeleton use was 5.82%, with a standard deviation (SD) of 31.14% (N=16, Fig. 2a). The exoskeleton + assistance thus provided only a small value benefit to the average participant. Using a t-test, the average MV of exoskeleton + assistance (5.82%) was not significantly different from zero ($p = 0.24$). However, as denoted by the high standard deviation, some participants received large benefits from the device's assistance, while others

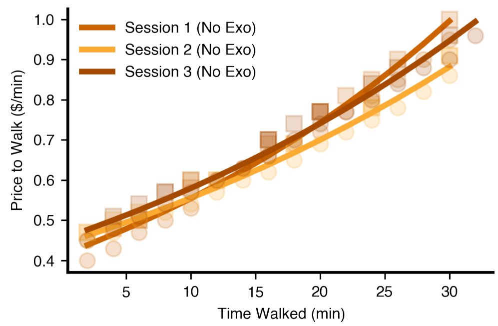

Figure 3: Representative price-to-walk curves for a single 'repeater' subject across different days. The agreement across the curves demonstrates the test re-test reliability of our approach. These sessions were completed over a seven day span.

experienced an economic penalty from exoskeleton use. The average MV for the unpowered exoskeleton was -31.8% with a standard deviation of 45.0% (N=13, 2b). Using the same t-test as in the exo-powered condition, we found this change to be significantly different from zero ($p = 0.03$). Additionally, the powered assistance alone from the exoskeleton provided a significant increase in value (mean: 33.8%, SD: 38.1%, $p = 0.01$, N=13, Fig. 2c).

The integral of each price to walk curve yields the cumulative price to walk for each condition (Fig. 10). The average cumulative price for the walking-no-exo condition was $\$29.23 \pm \$28.11$ (Fig. 10a), for the exo-powered condition $\$25.38 \pm \$13.87$ (Fig. 10b), and for the exo-powered-off $\$49.68 \pm \$54.34$ (Fig. 10c). Changes in participant value due to the different walking conditions can be measured by comparing the associated cumulative prices.

We also characterized the repeatability of our measurements with a subset of participants to verify that the changes in price to walk detected due to the changing walking conditions were attributable to the difference in perceived difficulty between conditions and not due to participant day-to-day variability (a representative repeater trial is shown in Fig. 3). For the four subjects that repeated the walking-no-exo condition at least once, the average intra-subject standard deviation of the cumulative price for the walking-no-exo condition was 3.38%, expressed as a percentage of each subject's average walking-no-exo cumulative price. This quantity represents the day-to-day fluctuation in the value demanded to walk, in addition to any user or experimentally derived noise.

Discussion

In this work, we use the Vickrey second-price auction as a method to capture the economic value or detriment provided by exoskeletons and their assistance. As part of our broader goal of emphasizing the user's role in the design, control, and evaluation of exoskeletons (*32, 55*), the intent of this work is to quantify the success of these technologies through a user-centered metric which encompasses the different aspects of the user experience, including exertion, weight, comfort, and assistance. To this end, the wearer specified their "price to walk" during a series of Vickrey auctions from which we quantified the economic value of different conditions. Our approach is particularly relevant for assessing the success of augmentative exoskeletons, which do not have a clear, clinically-relevant, biomechanical or physiological objective (as in the case of prostheses or orthoses). Our work is motivated by the belief that obtaining accessible and relevant metrics of success is critical to the successful development and adoption of exoskeletons in the real world. This motivation is supported by a history of strong interconnection between the assessment of exoskeletons and their design and control architectures (*21–27*). Our strategy quantifies success using monetary currency, as opposed to biomechanical or physiological quantities that may be more difficult for users, manufacturers, and those outside of the exoskeleton research field to interpret.

Our results showed that the economic value provided by the exoskeleton assistance was comparable to the cost incurred by wearing the unpowered system. We obtained these results by quantifying the marginal value (MV) between two conditions, and by varying which two conditions were compared, we isolated the value of the exoskeleton + assistance, the assistance alone, and the detriment of the unpowered exoskeleton. The average cumulative price of walking uphill for 30 minutes without the exoskeleton was $29.23 ($58.46/hr SD: $57.49/hr). The MV of wearing the unpowered exoskeleton—that was not providing assistance—was -31.8%, which translates to a monetary cost of $18.59/hr (SD: $18.28/hr) for wearing the unpowered system. When assistance was applied by the exoskeleton, the MV increased to just above zero ($3.40/hr, SD:$3.35/hr) when compared to not wearing the exoskeleton. The marginal value added by the assistance alone was 33.8%, which translates to an added value of $19.76/hr (SD: $19.43/hr). Thus, the assistance applied by the exoskeleton offset the cost of wearing the system, and the net benefit was modest but positive. These results suggest that modern augmentative ankle exoskeletons may not provide a substantial benefit to their wearers during short-term uphill walking. This is particularly surprising because of the lightweight, refined design of the exoskeletons used, and the high physiological demands of the uphill walking task (*56, 57*), which we chose to increase the observed value of the exoskeleton (*i.e.* to improve the signal-to-noise ratio in our measurement of economic value).

Our approach and metrics can be used to guide the development of exoskeletons in new ways. Exoskeleton controllers can potentially be directly engineered to maximize the MV added (in dollars) from the assistance of the exoskeleton during walking. Similarly, exoskeletons can themselves be designed to minimize the economic cost they impose on the wearer, which includes not only weight, but also other factors such as inertia and discomfort.

This information can be obtained using the MV of the unpowered exoskeleton when compared to the walking-no-exo condition. Additionally, this study suggests that exoskeleton development may be improved by identifying the users who innately receive greater economic value from wearing the system. We found that nine participants obtained substantial positive economic value from wearing the system ($27.8\% \pm 16.3\%$, corresponding to $\$16.25/\text{hr}$ $\pm$ $\$9.53/\text{hr}$), even though the average across all participants was lower. Such "responders" may be more willing to adopt exoskeletons in the face of potential drawbacks, including cost and added mass, among others. Understanding why some users obtain this value would enable the targeting of these individuals to maximize the translation and impact of augmentative exoskeletons. For example, models such as the diffusion of innovation (DOI) theory within the social sciences categorize individuals based on their willingness to adopt a new innovation (*38*), such as exoskeletons. It is possible that the individuals who obtained positive value within our study fall into the "early adopter" category, and are more willing to find value in exoskeleton use. Future investigations could focus on the separation of these individuals *a priori* based on the social characteristics within DOI theory, or based on other human factors, such as fitness level or perceptual abilities (*32*). Furthermore, investigations of whether users can be "trained" to receive a greater economic value from the exoskeleton are promising avenues of future study.

Participant results were consistent when repeated across days, supporting the quality of our measurements. Four participants repeated the walking-no-exo condition across several days, and the inter-day variance of the cumulative prices was low ($0.67, Table 4). This consistency supports the ability for our approach to quantify perceived changes in value, with potentially minimal effect from inter-day confounding factors. Using this inter-day variance, we estimated the Minimum Detectable Change (MDC), defined as the minimum change in value not caused by chance. The MDC for the MV measurement was 9.4% (95% confidence interval, difference between two measurements, standard deviation 3.4%). To identify which subjects had a noticeable change in value, we compared each participant's MV against the inter-day variability's 95% confidence interval ($\pm 9.4\%$); nine of 16 subjects had MVs exceeding this threshold in the positive direction, while four subjects exceeded it in the negative direction.

Our auction strategy avoids several potential limitations of more direct methods to quantify value, such as a Likert scale test, direct feedback, or auctions without a real monetary payout (*58*). The locomotion task implemented in our approach does not necessitate extreme fatigue and can remain relatively short, avoiding confounding factors (*e.g.* boredom or opportunity cost). Additionally, the incentive structure of the auction links participant bids to a specific consequence (*e.g.* walking uphill), and are thus less prone to biases, such as self-enhancement or social desirability, while still remaining intuitive (*48, 49*).

Individual bids and, subsequently, cumulative prices varied widely across subjects. Since participants were able to set their own bids, this added inherent variability across subjects. This variation may have resulted from each participant having different internal valuations of their time, which could have been driven by differing socioeconomic status, athleticism, opportunity cost, or other factors. This large discrepancy motivated the creation of the marginal value (MV) metric, which normalizes by each participant's 'baseline' cumulative price from the walking-no-exo condition, expressing the change as a percent of the walking-no-exo condition.

We anticipate that the conclusions drawn in this study extend to other augmentative ankle exoskeletons, although further study is needed to quantify the value from other technologies. The ankle exoskeletons from this work were developed for commercial use, and represent a "best-in-class" technology; the system's refined design is lightweight, untethered, and provides substantial net-positive energy during each stride (13.4 ± 2.9 J). We expect that other, similar exoskeletons would have comparable marginal values, and thus may also not provide a substantial economic benefit to their wearers. Additionally, although the task of uphill walking does not represent all possible uses for augmentative exoskeletons, it enables an opportunity to quantify value provided by the exoskeleton during an intuitive application where it can provide substantial benefit. We expected that the increased energetic difficulty of uphill walking (*56, 57*) would enable the exoskeleton to more readily demonstrate its value to the wearer. Furthermore, we chose the uphill walking task to reduce experimental duration as the greater difficulty would cause participant bids to rise more quickly. We expect that for less strenuous tasks, exoskeletons will show reduced marginal value; this hypothesis is supported by the results of a separate study we conducted (see Supplementary Information) in which the MVs of the exoskeleton + assistance were lower for level-ground walking when compared to uphill walking.

The changes in exoskeleton conditions caused intuitive changes in value, supporting the validity of our economic value metric. That is, we believe the different exoskeleton conditions (walking-no-exo, exo-powered-off, and exo-powered) likely drove the changes in value measured, and these changes agree with the biomechanical demands of the conditions. The MV of the exo-powered-off condition was strongly negative, denoting a cost to wearing the system. This result is expected, since without assistance, wearing an exoskeleton is akin to wearing shank weights during locomotion, which would necessitate greater mechanical work from the triceps surae and cause an upstream increase in (by ~ 16.8 W based on the results from (*36, 59*)). Additionally, when the assistance was added, the value increased to just above zero, indicating the assistance was useful in offsetting the challenge of wearing the unpowered system during uphill walking.

The MV for the exo-powered condition may shift with repeated sessions, as the participants adapt to the assistance. Prior work has found that training sessions across multiple days yield greater reductions in metabolic rate in naive users (*3*). Accordingly, the MV for the exoskeleton may adjust as well while the user adapts to the experience of wearing an exoskeleton. For this initial investigation, we sought to understand the immediate economic value obtained from a first-time experience of exoskeleton use, analogous to a user assessing an exoskeleton when making the decision to adopt (*i.e.* a "test drive"). To calculate the MV, we thus conducted a single exo-powered session with a brief adaptation period of a few minutes. Future work is needed to understand any adaptation of value that may occur over time, which would have implications in the longer-term value of these technologies.

The use of simulated bidding agents may have influenced the results but we expect the overarching conclusions of the study would not be affected. In our auction protocol, we used simulated bidding agents ("robo-bidders") to model human behavior, rather than implementing our approach with multiple human subjects. The intent for this choice was to reduce the logistical challenges of our approach, which would otherwise have required multiple treadmills and exoskeletons. To mitigate any effect of the simulated nature of the other participants, the human participant was informed that the robo-bidders were humans participating in the experiment in remote locations. The behavior of the robo-bidders—defined by a parameter that governs the rise and fall of their bids—was derived from pilot data obtained from human participants. To reduce the likelihood that the human participants could infer the robo-bidder behavior model, the robo-bidder bids were corrupted with noise. The use of robo-bidders also enabled us to standardize the interaction between the human participant and the other auction participants. Any series of auctions would naturally establish an equilibrium between the participants; thus, by using robo-bidders, we were able to control for this equilibrium, which strengthens our ability to compare across subjects. In addition, the use of robo-bidders enables our results to more readily be compared across other researchers, institutions, and exoskeletons that are assessed using comparable methods. The code to implement the robo-bidders is provided in [TBD].

During the experimental protocol, participants responded with bids as instructed, but we are unable to know for certain that their bids were truly honest (*i.e.* truthfully reflecting their internal sense of value). Our study relies on participants honestly reporting their bids, which is theoretically guaranteed as an optimal strategy by the nature of the Vickrey second-price auction for rational actors (*44*). In addition to the natural structure of the Vickrey auction, which incentivizes truthful bidding, we minimized the potential influence of dishonest bidding by setting the auction interval to two minutes (as opposed to a shorter duration). We chose the two minute duration to increase the effort required, and thus minimize potentially 'dishonest' exploratory bidding, which would corrupt the price to walk curves. Additionally, subjects continuously received verbal instructions to always bid honestly as the best strategy, which has been demonstrated to increase the likelihood of honest bidding (*60*). Finally, participants received the expected monetary compensation that resulted from their winning bids, which similarly incentivizes truthfulness.

Conclusion

We have developed a method to quantify the economic value of augmentative exoskeletons, and used these methods to assess the value provided by bilateral ankle exoskeletons during uphill walking. Our results underscore the challenge of developing exoskeletons that provide a clear, meaningful benefit when augmenting the healthy human neuromotor system. The value of the assistance provided by the exoskeletons was modest, and just offset the cost of wearing the unpowered system. Our results also suggest that more work is needed to identify why some participants received substantially greater value from the exoskeleton assistance, which could be used to identify or train individuals for maximizing the real-world impact of these technologies. Finally, the economic value metric we have developed can be readily used to compare different design and control strategies to develop exoskeletons that are maximally valuable to their wearers.

Methods

Participants

In this study, sixteen able-bodied participants (N = 16, 5 female, 9 male; age = 26.3 $\pm$ 4.61 years; mass = 77.1 $\pm$ 13.4 kg, Table. 1) walked using bilateral ankle exoskeletons on a treadmill. All participants provided written informed consent before participation. The study protocol was approved and overseen by the Institutional Review Board of the University of Michigan Medical School. Participants had no prior experience walking with the bilateral ankle exoskeletons featured in this study.

Experimental Protocol

Exoskeleton Apparatus

Our approach quantifies the value of bilateral ankle exoskeletons that were designed to improve the energetic efficiency of human walking (ExoBoot, Dephy Inc. Maynard MA, Fig. 4). The commercially-available system utilizes an onboard brushless electric motor and flat cable transmission (for a mean transmission ratio $\sim$15:1, see Supplementary Fig. 6.) to apply ankle assistance during walking. The exoskeletons have a single powered degree of freedom (dorsi-plantar flexion) and a passive, unactuated degree of freedom (inversion-eversion). The

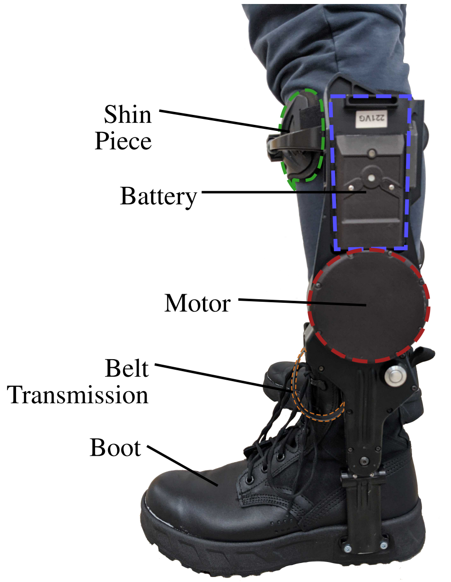

Figure 4: The Dephy ExoBoot used in this experiment. An electric motor applies plantarflexion torques at the ankle via a belt transmission.

transmission is unidirectional, which enables the system to apply plantar flexion assistance torque but it cannot provide dorsiflexion assistance. Each side of the exoskeleton applies a torque profile (Fig. 5a) that provides a burst of positive power (Fig. 5b) during the terminal stance phase of gait, augmenting the propulsive effort provided by the triceps surae. The average energy provided by the exoskeleton during the gait cycle is $13.4 \pm 2.9J$. During swing phase, the exoskeleton is able to add slack to the belt drive, thereby preventing any unwanted resistance to the foot; this capability stems from the unidirectional nature of the design. Gait progression, inferred from heel-strike timing events, was used to schedule how assistance was provided during each step. Similar exoskeletons have been shown to lower the user's metabolic expenditure during walking as well as reduce the biomechanical power requirements at the ankle and other joints of the legs (*1, 29, 36*). The walking assistance controller was developed by Dephy Inc. as part of their commercial system. As one of the first commercially available exoskeletons, the Dephy Exoboot was chosen for its ease of use, robustness, and representation of the state-of-the-art.

Vickrey Auction Protocol

The Vickrey auction (*44*) is a powerful economic tool for determining the true value placed on goods or actions. In this type of auction, participants compete to purchase (or sell) a good or item. For each participant, the auction's

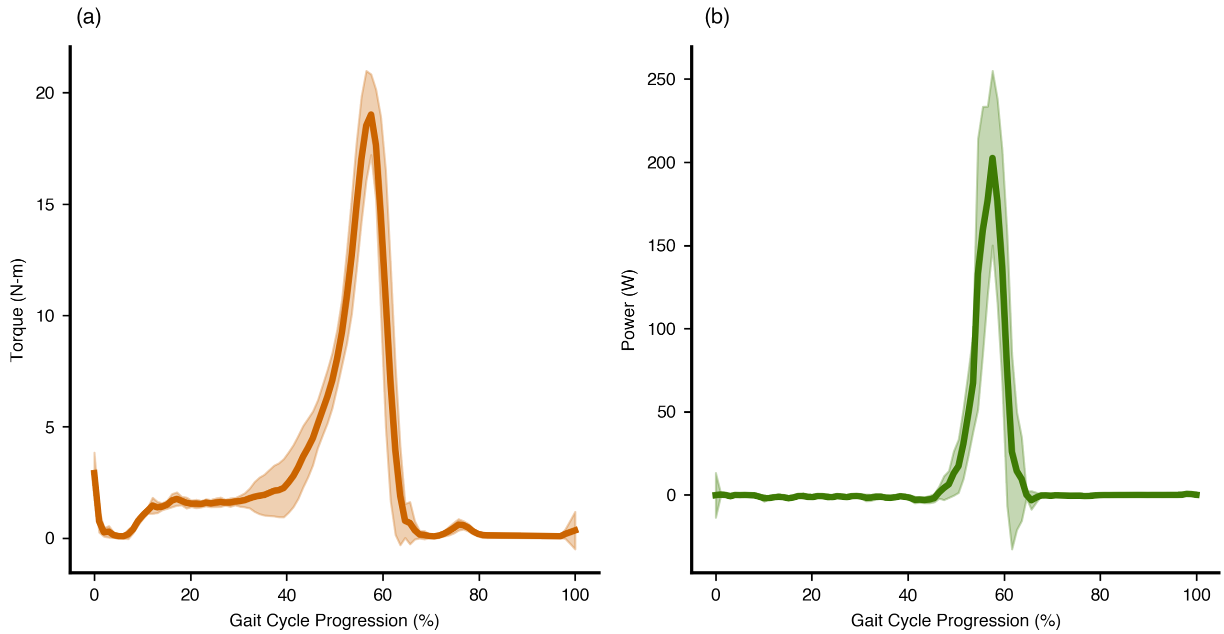

Figure 5: (a) The torque profile applied by the bilateral ankle exoskeletons during the uphill walking task. The torque applied stems from the proprietary control strategy implemented by Dephy Inc and represents the state of the art. The mean profile is shown in solid orange, with a single standard deviation shown by the shaded region. Torque was quantified by using the measured q-axis motor current and the experimentally-derived, q-axis torque constant to calculate motor torque (*61*), and then multiplying that value by the instantaneous transmission ratio. Gait cycle progression is defined as beginning and ending at sequential ipsilateral heel-strikes. (b) The power applied by the exoskeletons at the ankle during the walking trial. Power was calculated by multiplying the current-derived torque profiles in (a) by measured ankle angular velocities. The mean profile is shown in solid green, with a single standard deviation shown by the shaded region. The average energy provided by the exoskeleton, obtained by integrating the power curves over time is 13.4 ± 2.9 J.

structure is designed such that the optimal strategy for obtaining the item is to truthfully represent their internal value with their bid (*e.g.* to bid an amount equal to the true worth of the item). This optimality stems from the *second-price* nature of the auction (*44–46*), in which the winner is the participant who bids the highest (or lowest, as in the selling implementation used in this study). However, rather than paying the highest bid, the winner of the auction instead pays the *second-highest* bid. Participants do not know the value of competing bids (sealed-bid). In theory, bidders are disincentivized to bid less than their true value, as they run the risk of not winning the auction (not acquiring the good). Similarly, participants should not bid more than their true value, which otherwise could cause them to pay more than the value of the item. The second-price nature breaks the link between the auction winner and their specific bid. The inverse is also true for the case of selling an item (second-lowest bid is paid, lowest bid wins); thus, the incentive structure that elicits truthful bidding still holds in the seller's auction. Due to the presence of this optimal strategy, the Vickrey auction provides a method for quantifying the value of abstract

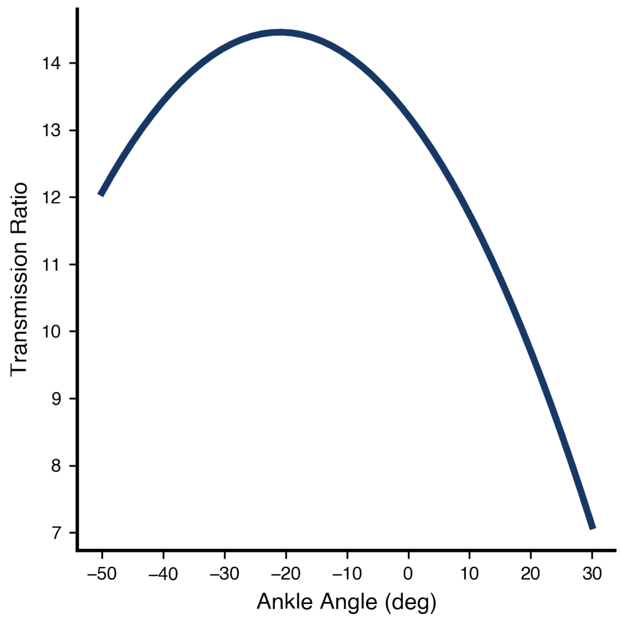

Figure 6: The transmission ratio curve of the exoskeleton device used in this experiment. Positive ankle angles denote dorsiflexion and negative angles denote plantarflexion. The curve was modeled as a second-order polynomial, and was obtained by taking the derivative of the best-fit third order polynomial that relates motor angle to ankle angle.

concepts (*46, 47*). In our protocol, we use the Vickrey auction sequentially to repeatedly sample individuals' valuations of their time during uphill walking. The participants bids across the sequential auctions denotes the wearer's "price-to-walk" curve.

Walking Protocol

Participants received guidance on the Vickrey auction protocol prior to the experiment. During this time, participants read a lay explanation of the Vickrey auction. Subsequently, participants underwent two mock Vickrey auctions, where the optimal strategy of truthful bidding was explained. Subjects were also repeatedly informed of the optimality of the honest-bid strategy to improve the number of honest bids provided (*60*). In the first mock auction, participants were presented with a miscellaneous office supply item and told to bid honestly on it as if they were competing to purchase it in a real Vickrey auction. Each participant wrote down their bid on an index card, while the researcher wrote down some artificial competing bids. The participant then revealed their bid, and the experimenter explained which bid won (the highest bid) and what the cost would be (the second-highest bid). Next, participants were told to imagine they were participating in the actual study, in which they would compete to sell their walking time in exchange for monetary compensation. Participants were prompted to consider bidding

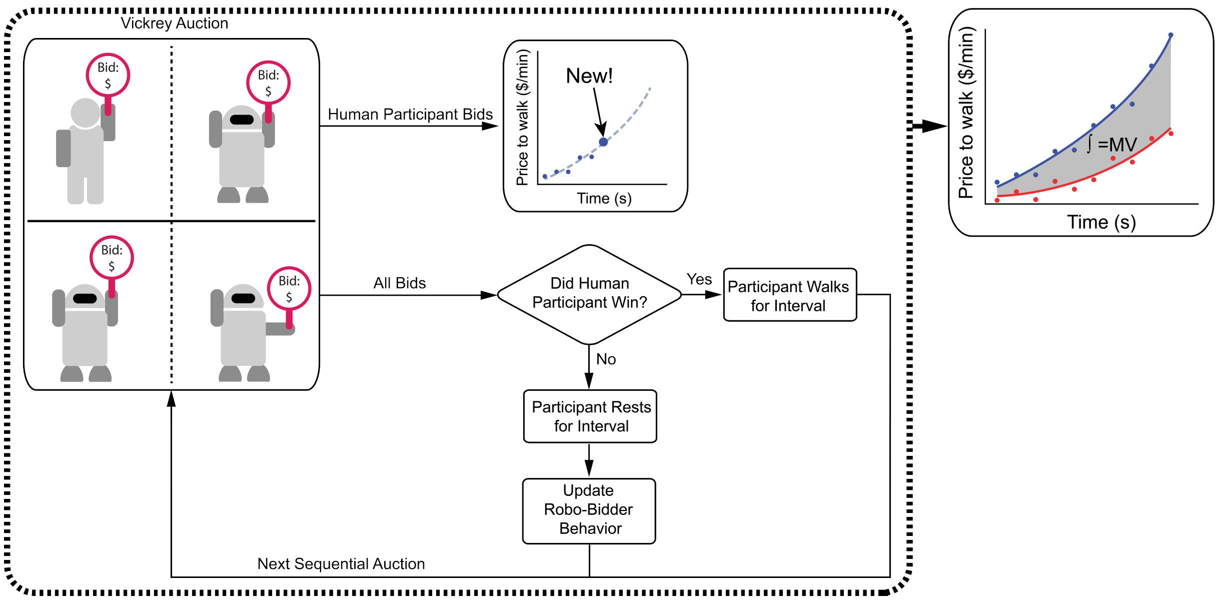

Figure 7: The experimental Vickrey auction protocol. In this protocol, human participants compete against computerized bidders (depicted in the 2×2 grid) in sequential Vickrey auctions for the prize of monetary compensation in exchange for undergoing a strenuous locomotion task. A human participant, shown in the upper-left quadrant, competes against computerized ('robo-') bidders, represented by the robots in the remaining three quadrants. Every two minutes, the human participants verbalize their bids to their experimenter, which are recorded and compared to the bids from the computerized opponents; the lowest bid is the winner of the auction, and the payout is the second-lowest bid. The second-price nature of the auction elicits truthful bids/prices from the participants. Should the human win, they accrue the payout and walk for the two-minute interval; should they lose, they instead miss out on the payout and rest until the next interval. Regardless of whether the human won or suffered a loss, their bid is aggregated to form their price to walk curve. This process repeats for roughly an hour. As the human walks more, they become more fatigued, causing their price to walk to increase; a trend well-modeled by a first-order exponential according to the observed data. Among other conditions, participants competed while wearing normal shoes ('no-exo' condition) and while receiving powered assistance from the exoskeleton ('exo-powered'). The integral of the difference between the price-to-walk curves for the no-exo and exo-powered conditions is the value added from the device's assistance.

based on an hourly wage, although they were also told that any truthful bid would be accepted. Again, participants wrote down their bids while the researcher aggregated the competing bids. As in the previous mock auction, the participants revealed their bids, and the experimenter walked them through which bid won and the payout.

Following familiarization with the exoskeleton and auction mechanics, participants competed in sequential Vickrey auctions to sell their time while walking uphill. The protocol was organized into a set of Vickrey auctions experienced in series, each lasting two minutes. If the participant won the auction, they would walk for the two minute interval, and they would rest if they lost the auction. During walking, participants walked on a split-belt treadmill with a 10° incline (Fig. 7). Unlike in the mock auctions, the participants would accrue and receive monetary compensation according to the Vickrey auction protocol. At the end of each interval, the winning bid (second-lowest bid) was revealed. The sequential auctions lasted a randomly-specified duration between 50 and 70 minutes, with a mean duration of 60 minutes; participants walked on average a total of 31.3 minutes $\pm$ 11.5 minutes. The duration uncertainty was added to discourage subjects from waiting until their bidding competitors were “exhausted” to inflate payouts. The two-minute interval duration was chosen to minimize subject exploratory behavior. In total, participants experienced approximately 25 - 35 Vickrey auctions in series. By aggregating each subject’s bids across the series auctions, the resulting price to walk curve captured the participants’ valuation of their time to complete the experiment, which can be used to provide insight into the value provided by the exoskeleton in this application.

Our protocol was broken up across several days to reduce the effect of fatigue from the experiments. The order of the testing was randomized across participants. On one day, subjects completed the Vickrey auction protocol with normal shoes (*i.e.* the walking-no-exo condition); these data establish their baseline price to walk curve and cumulative price. On a different day, subjects instead walked with powered exoskeleton assistance (*i.e.* the exo-powered condition). Participants were not explicitly told that the exoskeleton would provide assistance; instead, they were told that the exoskeleton was applying a randomized torque profile that would either help or hinder their locomotion. This was done to reduce the chance that participants would experience a placebo effect and perceive the exoskeleton as valuable due to information provided by the experimenter. By comparing the price to walk curves from the walking-no-exo and exo-powered conditions, we obtained a measurement for the value provided by the exoskeleton in this task. If undergoing the exo-powered condition on the second day, subjects were given time to re-familiarize and experience the exoskeleton’s assistance.

In addition, each subject was randomly assigned to additional experimental sessions to investigate other attributes our approach. Participants were randomly assigned to groups that either quantified the inter-day variability of the price-to-walk measurements, or investigated the additional condition of walking with the exoskeleton without assistance (*i.e.* the exo-powered-off condition). Due to the number of experimental sessions required, particpants were assigned to only one of these groups. Of the sixteen total participants, ten participants walked in the exo-powered-off condition, while four participants repeated the walking-no-exo condition at least once (the remaining two subjects were not able to participate in the additional sessions). Within the experimental group that repeated the walking-no-exo condition, three participants repeated the condition twice more, while the last participant repeated the condition once. The intent of investigating the exo-powered-off condition was to support that the price-to-walk curves captured the cost of wearing the additional exoskeleton weight, when no assistance was provided. The goal of repeating the walking-no-exo condition was to provide insight into the test re-test variability of the price to walk curves and how they may be affected by inter-day confounding factors.

Robo-bidders

For a live Vickrey auction, multiple participants are needed; however, this constraint adds practical challenges in coordination and logistics. To this end, we utilized computerized bidding agents (robo-bidders) as a substitute for other human participants in the Vickrey auctions. The mechanics of the robo-bidders are modeled on the bidding behavior of three pilot subjects. The robo-bidders bid with prices following a first-order exponential function of the number of intervals spent walking. This model captured the effect of fatigue and increased their bids as the robo-bidder won the auction. If the robo-bidder did not win the auction (meaning the human participant won), their bid remained constant. Gaussian white noise (zero mean, standard deviation $0.01) was added to corrupt the robo-bidder bids, to reduce the likelihood that the human participant would intuit the robo-bidder model. Robo-bidder behavior at time t_k during simulated walking was governed by the following equation:

$$y_k(t) = k \cdot e^{(b \cdot t_k)} + \sigma, \tag{1}$$

where y_k was the robo-bidder's price, k was the initial price, b was the rate at which the price increases, is time, and σ was drawn from normal distribution $\mathcal{N}(0, 0.01)$. Parameters k and b were set differently for each robo-bidder; full implementation details can be found in [TBD]. Having robo-bidders instead of human auction participants reduced the logistical difficulty of executing the Vickrey auction experiments over time, while still replicating modeled behavior of a human participant. Naturally, the robo-bidder bids competed in parallel with the human subject and approached an equilibrium behavior, which affected the total walking time of the human participant. In the application of auctions in series, an equilibrium would also likely be established between multiple human participants. The human participants were not initially made aware of the fact that they were competing against computerized opponents. They instead were told that they were competing in live Vickrey auctions against other humans located remotely, with the experimenters communicating live. This was done to prevent the participants from attempting to learn and exploit the price to walk curves of the robo-bidders in an attempt to maximize profits beyond the strategy of honest bidding. Participants were debriefed on the true nature of the robo-bidders at the conclusion of their participation in the experiment.

Analysis

Marginal Value

Our outcome metric is the marginal value (MV) that stems from difference in two price to walk curves obtained for different experimental conditions. Each price to walk curve was fit with a first-order exponential response of the form:

$$Y(t) = k \cdot e^{(b \cdot c \cdot t)}, \tag{2}$$

where Y is the participant's price, k is the initial price, b is the rate at which the price increases, c is a scaling factor equal to the participant's win-rate, and t is time. The scaling factor is necessary to control for the different durations of walking experienced by the participants (*i.e.* variations in the number of auctions won). After correcting for this win-rate, these curves are integrated and subtracted, yielding the area between the two curves. This area represents the marginal value added—in US dollars—from one exoskeleton condition compared to another. The expression for the MV is as follows:

$$MV = \overbrace{\int_{t_1}^{t_2} k_1 \cdot e^{(b_1 \cdot t)}\, dt}^{\text{exo condition 1}} - \overbrace{\int_{t_1}^{t_2} k_2 \cdot e^{(b_2 \cdot t)}\, dt}^{\text{exo condition 2}}, \tag{3}$$

where k_1, b_1 correspond to the first exoskeleton condition in the comparison, k_2, b_2 correspond to the second condition, and t_1, t_2 are the bounds of the time domain for the integrals—0 and 30 minutes respectively, which roughly corresponds to the average time each participant walked in each trial. The MV is then equivalent to the value added or removed by the exoskeleton during a continuous thirty minute, uphill walking task. We commonly normalized the MV by the cumulative price from the walking-no-exo condition to obtain a percentage change. However, this metric can be converted to compare any two experimental conditions or other candidate control strategies that researchers wish to evaluate in terms of economic value.

Table 1: Participant characteristics.

Participant	Gender	Weight (kg)	Age	Height (cm)
1	F	83.64	24	160.02
2	M	99.2	27	176
3	M	84	22	186
4	M	90.7	25	182.9
5	M	80.7	26	177.8
6	F	72.58	29	170.18
7	M	80	34	180.3
8	M	74.8	34	74.8
9	M	68.03	25	170.18
10	M	70.3	22	185.4
11	M	67.13	25	167.6
12	M	104.3	36	193
13	F	74.84	23	177.8
14	M	70.3	21	172.7
15	M	61.2	23	163
16	F	52.4	25	162.6

1 Supplementary Information

1.1 Supplementary Text

1.1.1 Level-ground study

We conducted a separate, smaller study in which two participants (Subjects 2 and 7) underwent the main study's protocol, but on level-ground instead of at a 10° incline. This was done to investigate how their MVs changed when the walking was made easier and more representative of exoskeleton use in the community. Both participants' MVs diminished when the task was level-ground walking—Subject 2's MEV dropped from 36.35% to -28.10%, while Subject 7's MEV dropped from 26.68% to 12.62% (Fig. 13). These results suggest that for everyday mobility tasks, which are likely to be more similar in difficulty to level-ground walking than uphill walking, energetic exoskeleton assistance may have less value to potential adopters. Furthermore, augmentative exoskeletons may thus provide maximal value during highly strenuous tasks. Future work should investigate if these results are consistent across more subjects and different walking conditions.

Table 2: Powered condition cumulative prices and marginal values.

Subject	MV (%)	Exo Powered ($)	Walking No Exo ($)		
			Day 1	Day 2	Day 3
1	1.07	13.34	13.48		
2	36.35	42.36	66.55		
3	26.14	15.46	20.93		
4	-13.85	17.66	15.09	15.94	
5	-8.00	25.03	23.16		
6	2.45	26.88	27.55		
7	49.27	36.53	72.02		
8	55.83	62.77	142.09		
9	11.70	11.40	12.91		
10	11.47	11.18	12.63		
11	14.86	17.36	20.64	19.81	20.71
12	-59.43	30.99	19.44		
13	-32.35	35.16	26.57		
14	18.04	11.51	14.04		
15	-46.56	33.42	21.97	23.30	23.14
16	26.08	14.86	19.24	20.23	20.85

Table 3: Powered-off condition cumulative prices and marginal values.

Subject	MV (%)	Exo Powered Off ($)	Walking No Exo ($)
1	-0.53	13.56	13.48
2	-26.44	84.15	66.55
3	-3.53	21.31	20.59
4	-0.10	15.10	15.09
5	-7.40	24.88	23.16
6	17.44	22.75	27.55
7	-40.51	199.66	142.09
9	-26.64	16.34	12.91
12	-119.94	42.76	19.44
13	-111.95	56.31	26.57

Table 4: Cumulative prices for participants who repeated the walking-no-exo condition

Subject	Average Cumulative Price ($)	St. Dev. Cumulative Price ($)	St. Dev. Cumulative Price (% of Average)	Prices ($)		
				Day 1	Day 2	Day 3
4	15.52	0.43	2.75	15.09	15.94	
11	20.39	0.41	2.01	20.64	19.81	20.71
15	22.80	0.59	2.59	21.97	23.30	23.14
16	20.11	0.66	3.30	19.24	20.23	20.85

1.2 Supplementary Tables

1.3 Supplementary Figures

Declarations

Author's contributions

RLM, GCT, DM, and EJR designed the study; RLM performed the experiment and analyzed data with input from GCT, DM, and EJR.; RLM, GCT, and EJR wrote the paper. EJR directed the study and all authors approved the final version of the manuscript.

Availability of data and materials

All data needed to evaluate the conclusions of the paper are available in the paper or the Supplementary Materials.

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Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

All experiments were carried out with informed consent at the University of Michigan, with approval from the Institutional Review Board of the University of Michigan Medical School (IRBMED).

Consent for publication

Not applicable

Acknowledgements

Not applicable

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Acknowledgments

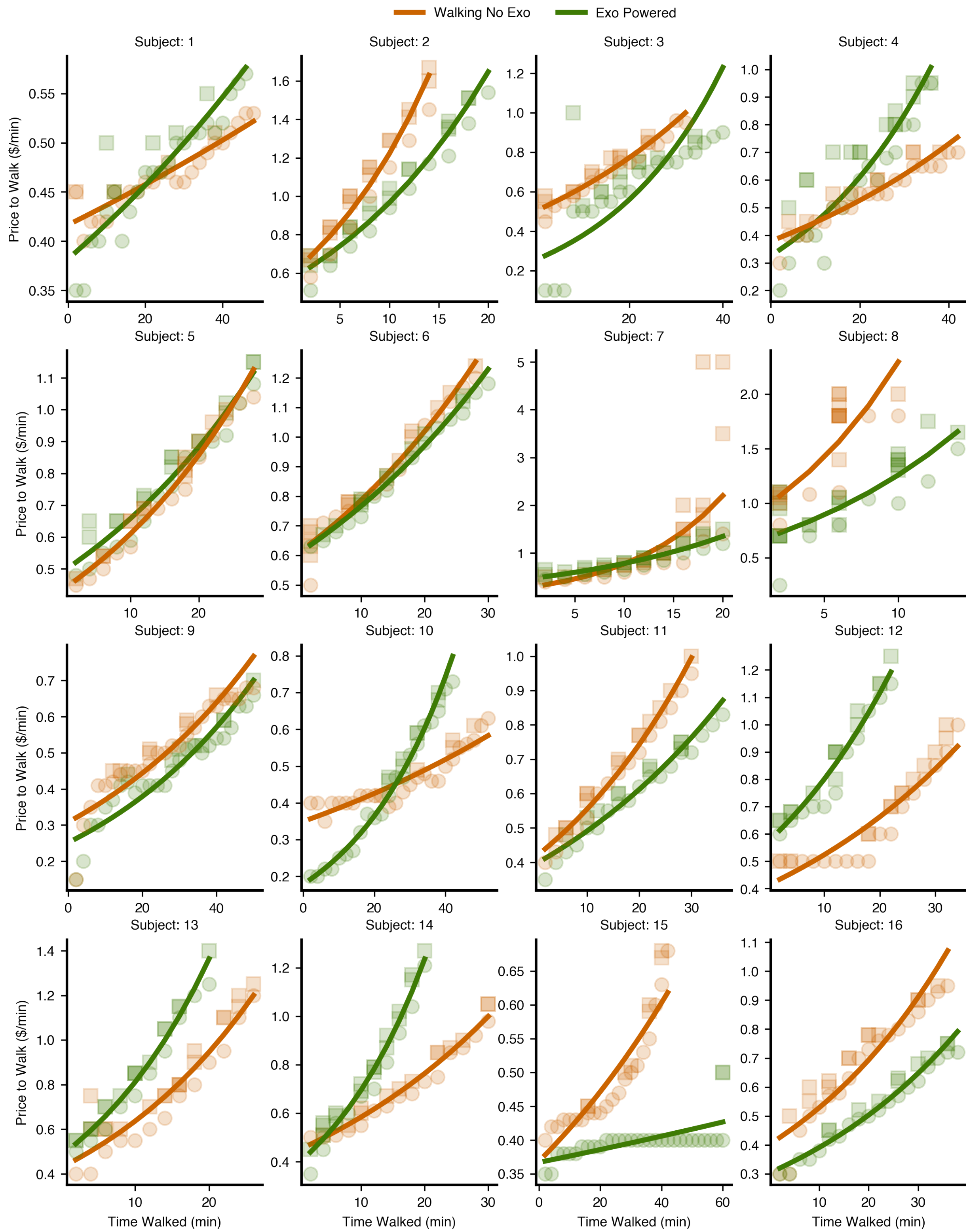

Figure 8: The price to walk curves for the exo-powered (orange) and walking-no-exo (teal) from all sixteen subjects. Circles denote winning bids, while squares denote losing bids.

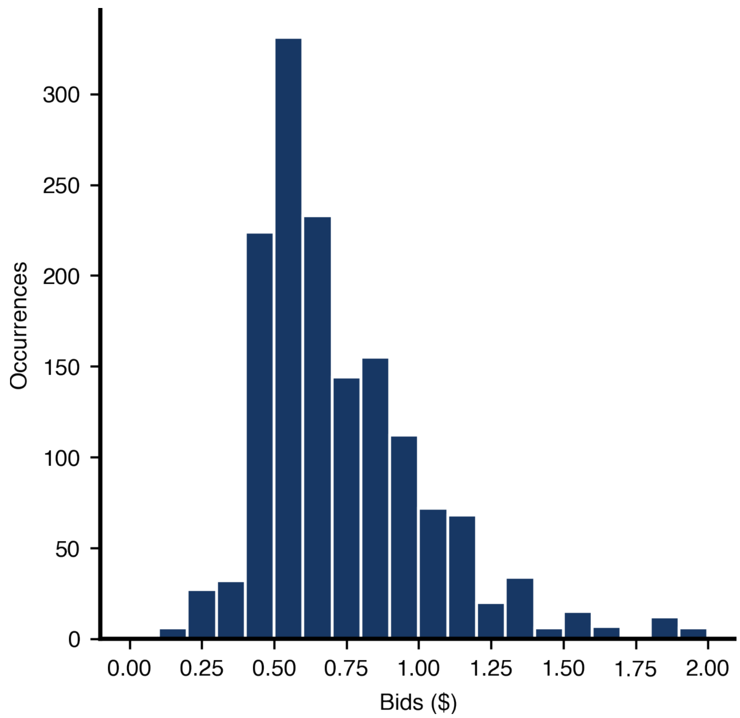

Figure 9: A histogram of all the subject bids for the two-minute intervals across all tested conditions. The average bid was $0.75, with a standard deviation of $0.39.

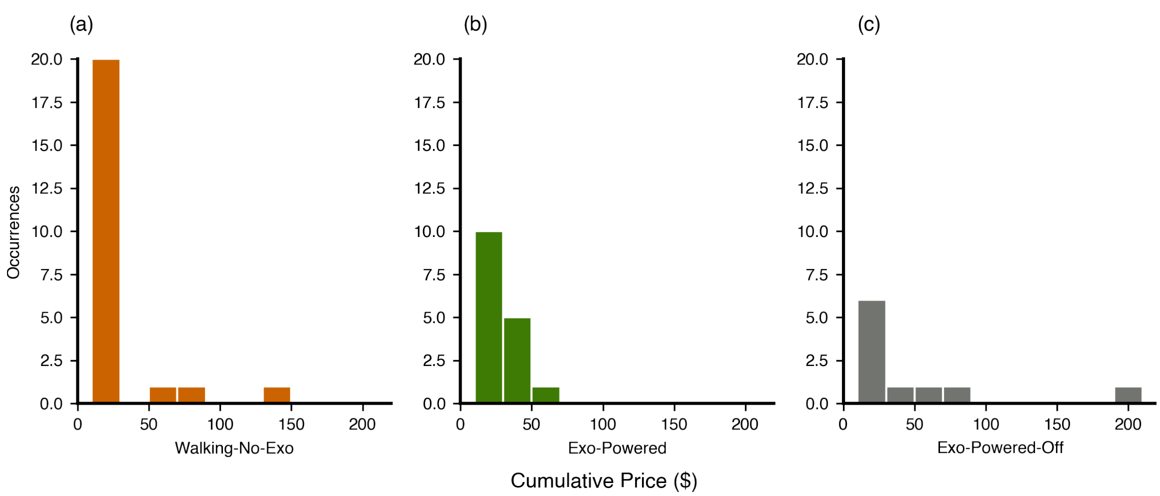

Figure 10: Histograms of the cumulative costs for (a) the walking-no-exo condition, (b) the exo-powered condition, and (c) the exo-powered off condition.

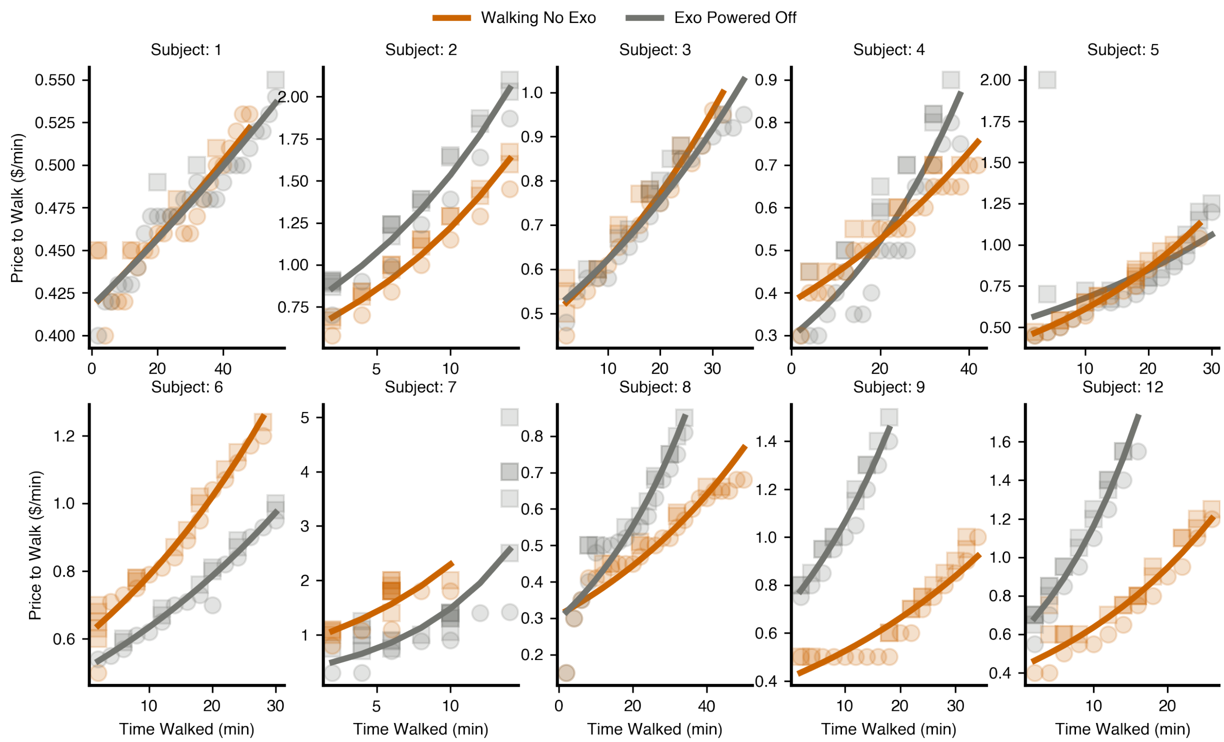

Figure 11: The price to walk curves for the exo-powered-off (gray) and walking-no-exo (teal) for the ten subjects who completed the former condition. Circles denote winning bids, while squares denote losing bids.

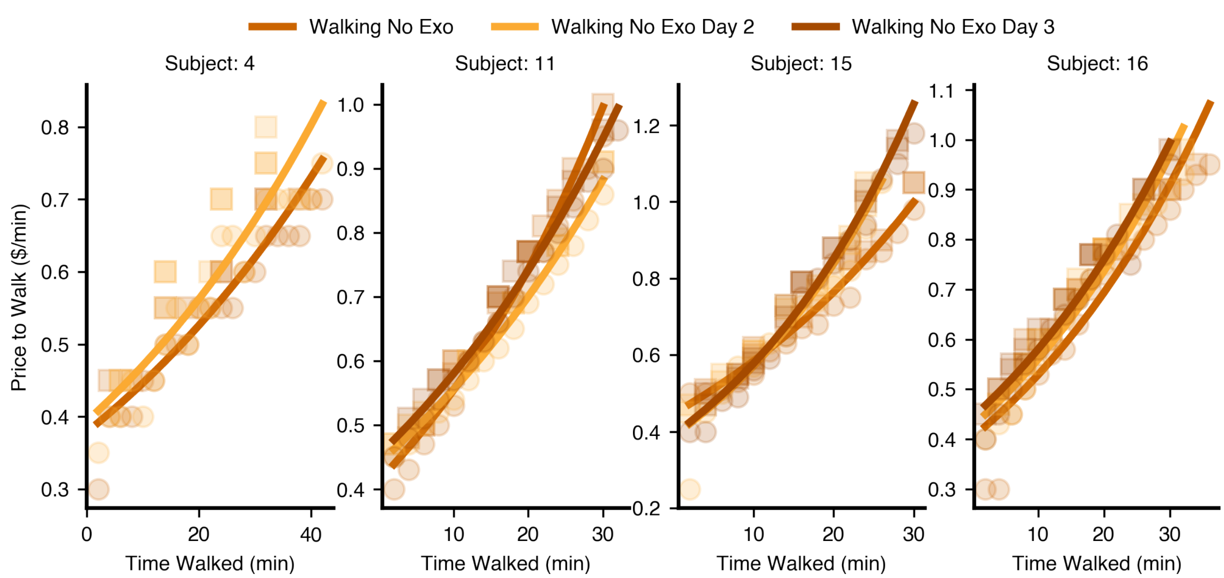

Figure 12: The price to walk curves for the walking-no-exo conditions across different days for the four subjects who repeated the walking-no-exo condition. Circles denote winning bids, while squares denote losing bids. Subject 4 only repeated the walking-no-exo condition once, while the rest of the participants repeated it twice.

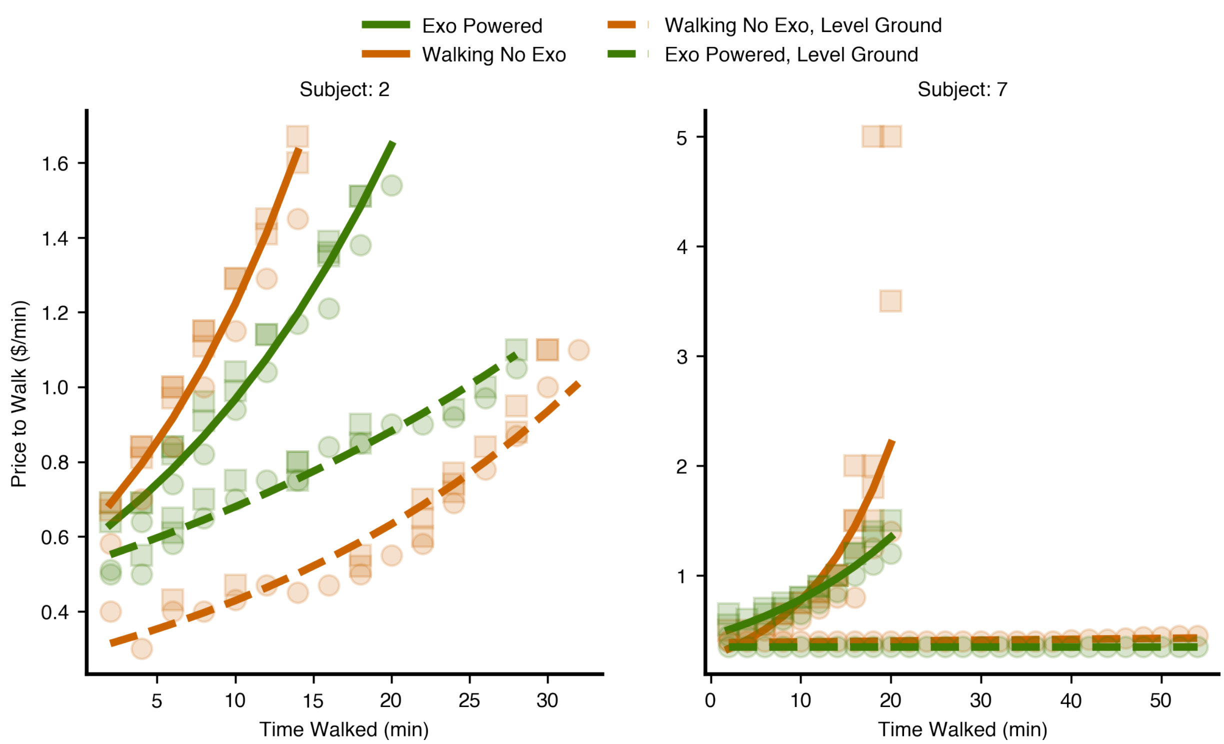

Figure 13: The price to walk curves for two subjects (2 and 7) that repeated the walking-no-exo and exo-powered conditions on a level ground condition. The solid lines denote the standard 10° incline task featured in this work; the dashed lines are the level ground condition. Both participants' MEVs decreased during the level ground condition.