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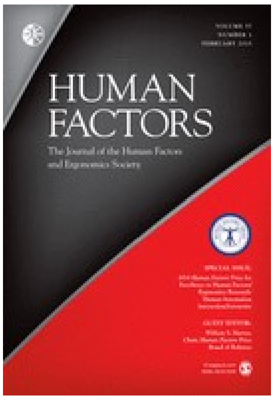
Special Issue: User Centered Design for Exoskeleton & Exosuit Usage



SPECIAL SECTION: USER CENTERED DESIGN FOR EXOSKELETON & EXOSUIT USAGE

Kermit G. Davis, Christopher R. Reid, David D. Rempel, Delia Treaster. *Introduction to the Human Factors Special Issue on User-Centered Design for Exoskeleton*. pp. 333–336.

Wearable technologies, such as smart watches, head-mounted displays, wearable sensors, electronic textiles, exoskeletons, and exosuits, are examples of an emergence of disruptive technology. These technologies are iteratively pushing our society through a paradigm shift—one that is closer toward the bionic human interfaces that until now were the stuff of Hollywood movies and comic books.

Shirley A. Elprama, Jorre T. A. Vannieuwenhuyze, Sander De Bock, Bram Vanderborght, Kevin De Pauw, Romain Meeusen, An Jacobs. *Social Processes: What Determines Industrial Workers' Intention to Use Exoskeletons?* pp. 337–350.

Objective: The aim of this study is to test the unified theory of acceptance and use of technology (UTAUT) model for explaining the intention to use exoskeletons among industrial workers. **Background:** Exoskeletons could help reduce physical workload and risk for injuries among industrial workers. Therefore, it is crucial to understand which factors play a role in workers' intention to use such exoskeletons. **Method:** Industrial workers (*N* = 124) completed a survey on their attitudes regarding the use of exoskeletons at their workplace. Using partial least squares (PLS) path modeling, the UTAUT model and a revised version of the UTAUT model were fitted to these data. **Results:** The adapted UTAUT model of Dwivedi et al. (2017) was able to explain up to 75.6% of the variance in intention to use exoskeletons, suggesting a reasonable model fit. **Conclusion:** The model fit suggests that effort expectancy (how easy it seems to use an exoskeleton) plays an important role in predicting the intention to use exoskeletons. Social influence (whether others think workers should use exoskeletons) and performance expectancy (how useful exoskeletons seem to be for work) play a smaller role in predicting the intention to use. **Applications:** This research informs companies about the optimal implementation of exoskeletons by improving the determinants of acceptance among their workers.

Anna L. Ármannsdóttir, Philipp Beckerle, Juan C. Moreno, Edwin H. F. van Asseldonk, Maria-Teresa Manrique-Sancho, Antonio J. del-Ama, Jan F. Veneman, Kristín Briem. *Assessing the Involvement of Users During Development of Lower Limb Wearable Robotic Exoskeletons: A Survey Study*. pp. 351–364.

Objective: To explore user-centered design methods currently implemented during development of lower limb wearable robots and how they are utilized during different stages of product development. **Background:** Currently, there appears to be a lack of standardized frameworks for evaluation methods and design requirements to implement effective user-centered design for safe and effective clinical or ergonomic system application. **Method:** Responses from a total of 191 experts working in the field of lower limb exoskeletons were analyzed in this exploratory survey. Descriptive statistics were used to present responses and measures of frequency, and chi-square tests were used to contrast the answers of respondents who identified as clinicians versus engineers. **Results:** A vast majority of respondents involve users in their development, in particular at the initial and iterative stages, although some differences were found between disciplines. A variety of methods and metrics are used to capture feedback from users and test devices, and although valuable, some methods used may not be based on validated measures. Guidelines regarding tests on safety of exoskeletons also lack standardization. **Conclusion:** There seems to be a consensus among experts regarding the importance of a user-centered approach in exoskeleton development; however, standardized frameworks with regard to appropriate testing methods and design approaches are lacking. Such frameworks should consider an interdisciplinary focus on the needs and safety of the intended user during each iteration of the process. **Application:** This exploratory study provides an overview of current practice among engineers and clinicians regarding the user-centered design of exoskeletons. Limitations and recommendations for future directions are identified.

Saskia J. Baltrusch, Han Houdijk, Jaap H. van Dieën, Coen A. M. van Bennekom, Anja J. T. C. M. de Kruif. *Perspectives of End Users on the Potential Use of Trunk Exoskeletons for People With Low-Back Pain: A Focus Group Study*. pp. 365–376.

Objective: The objective of this study was to identify criteria to be considered when developing an exoskeleton for low-back pain patients by exploring the perceptions and expectations of potential end users. **Background:** Psychosocial, psychological, physical load, and personality influence incidence of low-back pain. Body-worn assistive devices that passively support the user's trunk, that is exoskeletons, can decrease mechanical loading and potentially reduce low-back pain. A user-centered approach improves patient safety and health outcomes, increases user satisfaction, and ensures usability. Still, previous studies have not taken psychological factors and the early involvement of end users into account. **Method:** We conducted focus group studies with low-back pain patients (n = 4) and health care professionals (n = 8). Focus group sessions were audio-recorded, transcribed, and analyzed, using the general inductive approach. The focus group discussions included trying out an available exoskeleton. Questions were designed to elicit opinions about exoskeletons, desired design specifications, and usability. **Results:** Important design characteristics were comfort, individual adjustability, independency in taking it on and off, and gradual adjustment of support. Patients raised concerns over loss of muscle strength. Health care professionals mentioned the risk of confirming disability of the user and increasing guarded movement in patients. **Conclusion:** The focus groups showed that implementation of a trunk exoskeleton to reduce low-back pain requires an adequate implementation strategy, including supervision and behavioral coaching. **Application:** For health care professionals, the optimal field of application, prevention or rehabilitation, is still under debate. Patients see potential in an exoskeleton to overcome their limitations and expect it to improve their quality of life.

Jackie S. Cha, Sara Monfared, Dimitrios Stefanidis, Maury A. Nussbaum, Denny Yu. ***Supporting Surgical Teams: Identifying Needs and Barriers for Exoskeleton Implementation in the Operating Room*****. pp. 377–390.**

Objective: The objective of this study was to identify potential needs and barriers related to using exoskeletons to decrease musculoskeletal (MS) symptoms for workers in the operating room (OR). **Background:** MS symptoms and injuries adversely impact worker health and performance in surgical environments. Half of the surgical team members (e.g., surgeons, nurses, trainees) report MS symptoms during and after surgery. Although the ergonomic risks in surgery are well recognized, little has been done to develop and sustain effective interventions. **Method:** Surgical team members (n = 14) participated in focus groups, performed a 10-min simulated surgical task with a commercial upper-body exoskeleton, and then completed a usability questionnaire. Content analysis was conducted to determine relevant themes. **Results:** Four themes were identified: (1) characteristics of individuals, (2) perceived benefits, (3) environmental/societal factors, and (4) intervention characteristics. Participants noted that exoskeletons would benefit workers who stand in prolonged, static postures (e.g., holding instruments for visualization) and indicated that they could foresee a long-term decrease in MS symptoms with the intervention. Specifically, raising awareness of exoskeletons for early-career workers and obtaining buy-in from team members may increase future adoption of this technology. Mean participant responses from the System Usability Scale was 81.3 out of 100 (SD = 8.1), which was in the acceptable range of usability. **Conclusion:** Adoption factors were identified to implement exoskeletons in the OR, such as the indicated need for exoskeletons and usability. Exoskeletons may be beneficial in the OR, but barriers such as maintenance and safety to adoption will need to be addressed. **Application:** Findings from this work identify facilitators and barriers for sustained implementation of exoskeletons by surgical teams.

Linda Shore, Valerie Power, Bernard Hartigan, Samuel Schülein, Eveline Graf, Adam de Eyto, Leonard O'Sullivan. ***Exoscore: A Design Tool to Evaluate Factors Associated With Technology Acceptance of Soft Lower Limb Exosuits by Older Adults*****. pp. 391–410.**

Objective: This pilot study proposed and performs initial testing with Exoscore, a design evaluation tool to assess factors related to acceptance of exoskeleton by older adults, during the technology development and testing phases. **Background:** As longevity increases and our aging population continues to grow, assistive technologies such as exosuits and exoskeletons can provide enhanced quality of life and independence. Exoscore is a design and prototype stage evaluation method to assess factors related to perceptions of the technology, the aim being to optimize technology acceptance. **Method:** In this pilot study, we applied the three-phase Exoscore tool during testing with 11 older adults. The aims were to explore the feasibility and face validity of applying the design evaluation tool during user testing of a prototype soft lower limb exoskeleton. **Results:** The Exoscore method is presented as part of an iterative design evaluation process. The method was applied during an exoskeleton research and development project. The data revealed the aspects of the concept design that rated favorably with the users and the aspects of the design that required more attention to improve their potential acceptance when deployed as finished products. **Conclusion:** Exoscore was effectively applied to three phases of evaluation during a testing session of a soft exoskeleton. Future exoskeleton development can benefit from the application of this design evaluation tool. **Application:** This study reveals how the introduction of Exoscore to exoskeleton development will be advantageous when assessing technology acceptance of exoskeletons by older adults.

Blake Bequette, Adam Norton, Eric Jones, Leia Stirling. *Physical and Cognitive Load Effects Due to a Powered Lower-Body Exoskeleton*. pp. 411–423.

Objective: The aim of this study is to determine the effects of a powered exoskeleton on measures of physical and cognitive performance. **Background:** US warfighters carry heavy equipment into battle, and exoskeletons may reduce that burden. While exoskeletons are currently evaluated for their effects on physical performance, their cognitive effects are not currently considered. **Method:** Twelve military members participated in a simulated patrol task under three conditions: wearing a powered exoskeleton (PWR), an unpowered exoskeleton (UNP), and without wearing an exoskeleton (OFF). While following a confederate over obstacles at a constant pace, participants performed additional audio and visual tasks. Dependent measures included visual misses, visual reaction time, audio misses, audio reaction time, incremental lag time, and NASA-TLX scores. **Results:** The variability in the follow-task lag time was lowest with OFF and highest with UNP, highlighting reduced ability to maintain pace with the exoskeleton. Visual reaction time was significantly slower with PWR compared to OFF for 5 of 12 subjects. The NASA-TLX overall workload scores were lower for OFF compared to PWR and UNP. **Conclusion:** Efforts to understand individual variability are warranted such that exoskeleton designs can be used for a wider set of the population. While not all subjects had measurable differences in the selected performance tasks, the perception of increased workload was present across subjects. It remains to be determined what difference in reaction time would be operationally relevant for task-specific settings. **Application:** Findings draw attention to the need to consider "cognitive fit" and subject differences in the design and implementation of exoskeletons.

Leia Stirling, Damian Kelty-Stephen, Richard Fineman, Monica L. H. Jones, Byoung-Keon Daniel Park, Matthew P. Reed, Joseph Parham, Hyeg Joo Choi. *Static, Dynamic, and Cognitive Fit of Exosystems for the Human Operator*. pp. 424–440.

Objective: To define static, dynamic, and cognitive fit and their interactions as they pertain to exosystems and to document open research needs in using these fit characteristics to inform exosystem design. **Background:** Initial exosystem sizing and fit evaluations are currently based on scalar anthropometric dimensions and subjective assessments. As fit depends on ongoing interactions related to task setting and user, attempts to tailor equipment have limitations when optimizing for this limited fit definition. **Method:** A targeted literature review was conducted to inform a conceptual framework defining three characteristics of exosystem fit: static, dynamic, and cognitive. Details are provided on the importance of differentiating fit characteristics for developing exosystems. **Results:** Static fit considers alignment between human and equipment and requires understanding anthropometric characteristics of target users and geometric equipment features. Dynamic fit assesses how the human and equipment move and interact with each other, with a focus on the relative alignment between the two systems. Cognitive fit considers the stages of human-information processing, including somatosensation, executive function, and motor selection. Human cognitive capabilities should remain available to process task- and stimulus-related information in the presence of an exosystem. Dynamic and cognitive fit are operationalized in a task-specific manner, while static fit can be considered for predefined postures. **Conclusion:** A deeper understanding of how an exosystem fits an individual is needed to ensure good human–system performance. Development of methods for evaluating different fit characteristics is necessary. **Application:** Methods are presented to inform exosystem evaluation across physical and cognitive characteristics.

Saman Madinei, Mohammad Mehdi Alemi, Sunwook Kim, Divya Srinivasan, Maury A. Nussbaum. *Biomechanical Evaluation of Passive Back-Support Exoskeletons in a Precision Manual Assembly Task: "Expected" Effects on Trunk Muscle Activity, Perceived Exertion, and Task Performance*. pp. 441–457.

Objective: To assess the efficacy of two different passive back-support exoskeleton (BSE) designs, in terms of trunk muscle activity, perceived low-back exertion, and task performance. **Background:** BSEs have the potential to be an effective intervention for reducing low-back physical demands, yet little is known about the impacts of different designs in work scenarios requiring varying degrees of symmetric and asymmetric trunk bending during manual assembly tasks. **Method:** Eighteen participants (gender balanced) completed lab-based simulations of a precision manual assembly task using a "grooved pegboard." This was done in 26 different conditions (20 unsupported; 6 supported, via a chair), which differed in vertical height, horizontal distance, and orientation. **Results:** Using both BSEs reduced metrics of trunk muscle activity in many task conditions (≤47% reductions when using BackX™ and ≤24% reductions when using Laevo™). Such reductions, though, were more pronounced in the conditions closer to the mid-sagittal plane and differed between the two BSEs tested. Minimal effects on task completion times or ratings of perceived exertion were found for both BSEs. **Conclusion:** Our findings suggest that using passive BSEs can be beneficial for quasi-static manual assembly tasks, yet their beneficial effects can be task specific and specific to BSE design approaches. Further work is needed, though, to better characterize this task specificity and to assess the generalizability of different BSE design approaches in terms of physical demands, perceived exertion, and task performance. **Application:** These results can help guide the choice and application of passive BSE designs for diverse work scenarios involving nonneutral trunk postures.

Mohammad Mehdi Alemi, Saman Madinei, Sunwook Kim, Divya Srinivasan, Maury A. Nussbaum. *Effects of Two Passive Back-Support Exoskeletons on Muscle Activity, Energy Expenditure, and Subjective Assessments During Repetitive Lifting*. pp. 458–474.

Objective: The aim of this study was to explore the efficacy of two different passive back-support exoskeleton (BSE) designs during repetitive lifting in different postures. **Background:** Although BSEs have been proposed as a potential intervention for reducing physical demands, limited information is available about the impacts of different exoskeleton designs in diverse work scenarios. **Method:** Eighteen participants (gender-balanced) performed lab-based simulations of repetitive lifting tasks. These tasks were performed in 12 different conditions, involving two BSEs and a control condition, two levels of lifting symmetry (symmetric and asymmetric), and two postures (standing and kneeling). Outcome measures described muscle activity and energy expenditure, along with perceived discomfort, balance, and usability. **Results:** Using both BSEs significantly reduced peak activity of the trunk extensor muscles (by ~10%–28%) and energy expenditure (by ~4%–13%) in all conditions tested. Such reductions, though, were task dependent and differed between the two BSEs. In most of the tested conditions, using BSEs positively affected subjective responses regarding perceived exertion and usability. **Conclusion:** Our results suggest that the beneficial effects of a BSE are task specific and depend on the specific BSE design approach. More work is needed, though, to better characterize this task specificity and to determine the generalizability of BSE effects on objective and subjective outcomes for a wider range of conditions and users. **Application:** Our results provide new evidence to guide the selection and application of passive BSE designs in diverse lifting tasks.

Tjasa Kermavnar, Kevin J. O'Sullivan, Adam de Eyto, Leonard W. O'Sullivan. *Discomfort/Pain and Tissue Oxygenation at the Lower Limb During Circumferential Compression: Application to Soft Exoskeleton Design*. pp. 475–488.

Objective: To establish the relationship between circumferential compression on the lower limb during simulated ramp and staircase profile loading, and the resultant relationship with discomfort/pain and tissue oxygenation. **Background:** Excessive mechanical loading by exoskeletons on the body can lead to pressure-related soft tissue injury. Potential tissue damage is associated with objective oxygen deprivation and accompanied by subjective perception of pain and discomfort. **Method:** Three widths of pneumatic cuffs were inflated at the dominant thigh and calf of healthy participants using two inflation patterns (ramp and staircase), using a computer-controlled pneumatic rig. Participants rated discomfort on an electronic visual analog scale and deep tissue oxygenation was monitored using near infrared spectroscopy. **Results:** Circumferential compression with pneumatic cuffs triggered discomfort and pain at lower pressures at the thigh, with wider cuffs, and with a ramp inflation pattern. Staircase profile compression caused an increase in deep tissue oxygenation, whereas the ramp profile compression decreased it. **Conclusion:** Discomfort and pain during circumferential compression at the lower limb is related to the width of pneumatic cuffs, the inflation pattern, and the volume of soft tissue at the assessment site. The occurrence of pain is also possibly related to the decrease in deep tissue oxygenation during compression. **Application:** Our findings can be used to inform safe and comfortable design of soft exoskeletons to avoid discomfort and possible soft tissue injury.

Minerva V. Pillai, Logan Van Engelhoven, Homayoon Kazerooni. *Evaluation of a Lower Leg Support Exoskeleton on Floor and Below Hip Height Panel Work*. pp. 489–500.

Objective: The aim of this study is to determine the effectiveness of using a leg support exoskeleton (legX) in different modes on simulated work tasks which emulate real-world job tasks. **Background:** Prolonged kneeling and squatting tasks increase the risk of work-related musculoskeletal disorders at the knee in industrial occupations. **Methods:** We evaluated legX capable of spring assistance throughout one's range of motion and/or locking support at a fixed angular position. Participants performed a dynamic panel task, alternating between hip and knee height, and a sustained floor level task with and without the exoskeleton. The exoskeleton was evaluated in spring mode, locking mode, and spring + locking mode for the panel task and only in locking mode for the floor task. The participants' (N = 15) muscle activity was recorded for the right lumbar erector spinae, thoracic erector spinae, tibialis anterior, rectus femoris, semitendinosus, and lateral gastrocnemius. **Results:** Significant reduction of the rectus femoris activity was observed with the exoskeleton (median reduction: 22%–56% and peak reduction: 12%–48% for the panel task and median reduction: 57% and peak reduction:34% during the floor task). **Conclusion:** legX significantly reduces rectus femoris activity during squatted static (floor) and dynamic (panel) work and may reduce pain and discomfort associated with squatting and potentially reduce the risk of developing knee disorders. Dynamic tasks benefit from both locking modes and spring assistance, the greatest benefit occurring with a combination of the two. **Application:** These results show that the legX can be beneficial to activities such as electrical panel work, grinding, sanding of larger surfaces, and concrete laying.