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Assessing the Subjective Effects of a Passive Low-Back Exosuit in Manual Urban Waste Collection: A Pilot Study

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ABSTRACT

Although occupational exoskeletons (OEXOs) are considered a viable solution to mitigate work-related musculoskeletal disorders (WMSDs), their real-world adoption remains limited and field evidence in operational contexts is scarce. Manual waste collection represents an especially relevant yet largely neglected setting for OEXO application and research. Concerning this domain, the presented pilot study evaluates the subjective effects of a commercial passive low-back exosuit during standard work tasks in manual urban waste collection, a sector characterized by high prevalence of WMSDs. Ten male waste collectors from an Italian waste management company wore a passive soft low-back exosuit (HeroWear Apex 2), for approximately two hours during standard work shifts. From the analytical standpoint, a mixed-methods approach was adopted: quantitative data were collected using the NASA-TLX scale, the Local Body Discomfort (LBD) scale, and an ad hoc five-point Likert-like questionnaire; qualitative data were gathered through post-trial semi-structured interviews. Descriptive statistics and thematic analysis were applied respectively. Concerning the main results, overall workload was comparable with and without the exosuit, with slight improvements in physical demand. The LBD scale indicated general comfort with slight discomfort across the body. Perceived usefulness was highly variable, as participants noted that the device did not address discomfort in the shoulders and knees. Consensus was specifically on social acceptability and ease of use, even though high operational pacing discouraged continuous manual activation. Thermal discomfort emerged as the primary adoption barrier, with unanimous concern about usability during summertime. A key functional trade-off was identified; in fact, the effort required to load the elastic element during trunk flexion may reduce the net perceived benefit under high-pacing conditions. These findings contribute field-level evidence on OEXO experience and highlight contextual factors critical for successful exosuit integration in physically demanding occupational settings.

Keywords: Occupational exoskeleton, Exosuit, Manual waste collection, Work-related musculoskeletal disorders, Field study, Usability, User experience

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INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are a prevalent issue in contemporary working settings. Particularly, low back pain (LBP) constitutes a primary contributor to disability worldwide (Hoy et al., 2014). While the underlying factors contributing to LBP are often multifaceted, crucial biomechanical risk factors include high peak forces and accumulated loads on the back during occupational activities related to manual material handling (Coenen et al., 2013; Norman et al., 1998). Among different working contexts, manual waste collection stands out due to its physically demanding nature that results in high prevalence of WMSDs (Kuijer et al., 2010; Poulsen et al., 1995). Urban waste collection involves the manual retrieval of refuse from kerbside bins, wheeled containers, and bags. This task requires workers to frequently alternate between operating collection vehicles and performing manual handling tasks under high operational pacing, driven by tight schedules and urban traffic. Repetitive bending and lifting, even from the ground, forces waste collectors into sustained, repetitive and excessive trunk flexion, axial rotation, and arm abduction, predisposing them to WMSDs (Ziaei et al., 2018). This risk profile is further modulated by crew organization. While two- and three-person crews allow for task specialization, where one individual drives and the remaining personnel handles waste retrieval, single-person operations demand a driver-collector who must continuously climb on and off the vehicle, introducing additional ergonomic stress.

Improving working conditions to reduce the risk of MSDs and physical workloads requires following general prevention guidelines. When collective solutions (e.g., organizational changes or mechanical tools) have proven ineffective, occupational exoskeletons (OEXOs) offer a viable alternative for individual physical assistance (Baldassarre et al., 2022). These wearable devices generate supportive force or torque around human joints to reduce physical workload (Schwartz et al., 2021). OEXOs are typically categorized by the body part supported (upper limb vs. back), actuation type (active/powered vs. passive/spring-based), and structural rigidity (rigid vs. soft exosuits) (de Looze et al., 2016; Crea et al., 2021). While rigid structures can be bulky and restrict mobility, soft exosuits lack a rigid kinematic frame, making them generally preferred for their comfort and unobtrusive design (Riemer and Wischniewski, 2023; Jakob et al., 2023; Siedl et al., 2021).

However, the actual adoption of OEXOs in real scenarios is limited compared to the expectations (Crea et al., 2021). While OEXOs can reduce physical strain and mitigate MSDs, they introduce new challenges that hinder their large-scale adoption. Empirical field data regarding the real-world use of OEXOs, particularly exosuits, is still scarce, necessitating more field studies to investigate real-world complexities and user experience variables. Furthermore, despite the high physical demands and awkward postures characteristic of manual waste collection, there is little knowledge about OEXOs use in this context (Ziaei et al., 2021).

In order to deepen the understanding, this study addressed these dual gaps by providing novel insights into subjective, contextual user experience of a passive low-back exosuit, while identifying potential barriers to the integration of these wearable assistive technologies into standard waste collection work procedures.

METHODS

The field trial was conducted in January 2026 following approval by the Ethical Committee of Politecnico di Milano (67/2025 – 22/09/2025). A total of ten male driver-collectors from an Italian waste management company voluntarily participated in the study and provided written informed consent. All participants operated as single-person crews, tasked with both driving the collection vehicle and manually retrieving waste along assigned routes. To capture variations across waste streams, the sample included workers collecting paper (n = 2), organic waste (n = 2), plastics (n = 2), and residual waste (n = 4).

Table 1: Waste collection methods and characteristics.

Waste Typology	Frequency	Main Activities
Plastic • 9kg bags • 240L bins	~ 430 bags/shift; ~ 80 bins/shift.	• Ground-level bag picking (single/multiple) • Overhead bag throwing into upper container • Moving and vehicle-assisted bin tipping
Organic • 35L bins • 120L bins • 240L bins	~75 bins/shift (35L) ~130 bins (120/240 L)	• Picking 35L bins/internal bags from ground • Lifting bins or throwing bags • Moving and vehicle-assisted bin tipping
Paper • 35L bins • 120L bins • 240 L bins	~ 145 bins/shift (120L/240L) ~ 190 bins /shift (35L)	• Ground-level 35L bin picking • Shoulder-height holding of 35L bins • Moving and vehicle-assisted bin tipping
Mixed waste • kg bags • 9kg bags	~ 960 bags/shift	• Ground-level bag picking (single/multiple) • Overhead bag throwing

Participants wore the HeroWear Apex 2, a passive, soft low-back exosuit, for approximately two hours during their standard work shifts. This specific device features a backpack-like module, thigh sleeves, and elastic bands that store energy during trunk flexion and return it during lifting to alleviate lower-back muscular strain. This exosuit was selected based on preliminary field observations and a market analysis, specifically for its low-profile architecture and its quick-engagement clutch mechanism, both of which are critical for compatibility with the high-intensity operational pacing of driver-collectors.

Figure 1: Participant using HeroWear Apex 2 during standard work.

One day prior to the field trial, participants gathered for a collective training session. During this session, researchers demonstrated the functioning of the exosuit, took anthropometric measurements to adjust the device components and elastic bands according to the manufacturer's guidelines, and briefed the participants on the experimental procedures. During the five-day trial (two participants per day), researchers accompanied operators on their routes to monitor safety, ensure proper usage, and assist as needed, while participants retained full autonomy over when and how to use the device during their shifts. All the participants were able to discontinue the use of the exoskeleton whenever they required to.

Table 2: Participants descriptive data.

Descriptive data	Average ± SD	Median	Range
Age (years)	45.4 ± 3.69	45.5	39 – 52
Height (cm)	178.2 ± 6.88	177.5	169 – 189
Weight (kg)	84.4 ± 9.86	87	70 – 100
BMI	26.6 ± 2.83	25.7	22.7 – 32.7
Work Experience (years)	5.9 ± 4.73	5	1 – 19

A mixed-method approach was used to collect subjective data at the conclusion of each trial. Quantitative data included the NASA-TLX scale to evaluate subjective workload differences between work with and without exosuit, a Local Body Discomfort (LBD) scale to evaluate physical comfort across different body regions and an ad hoc five-point Likert-like questionnaire evaluating user experience. The Likert-like questionnaire was composed of 15 items spanning multiple dimensions, including comfort, usability, cognitive demand, perceived usefulness and effectiveness, task compatibility and interference, social perception and overall exosuit acceptance.

Qualitative data consisted of spontaneous field comments, researchers' direct observations and a post-trial semi-structured interview designed to synthesize the user experience and deepen questionnaire items. Given the pilot sample size (n=10), descriptive statistical analysis was performed on quantitative data, while thematic analysis was used for qualitative data. Interview transcripts were systematically coded through an iterative process, and related codes were clustered into overarching themes representing recurring participant experiences.

RESULTS AND DISCUSSION

Perceived Physical Benefit and Workload

NASA-TLX results indicated that overall perceived workload was comparable with and without the exosuit, with slight improvements in physical demand when wearing the device (control: 5,4 ± 2,8, exosuit: 4,2 ± 2,3), a pattern consistent with findings from other occupational settings. In emergency medical services and construction work, NASA-TLX for physical demand, was similarly lower when the same exosuit was worn (Mukherjee et al., 2024; Bennett et al., 2023).

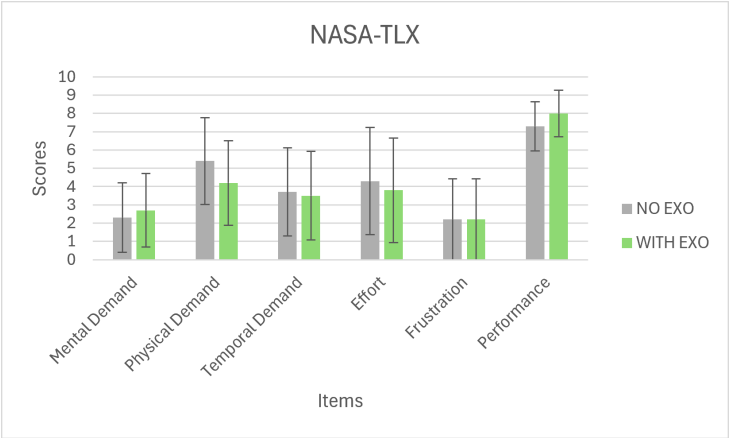

Figure 2: Perceived workload (NASA-TLX scale) with and without exosuit.

In the Likert questionnaire, most participants reported perceiving less back strain with the device (item 7) and believed it could reduce the risk of back injury (item 8), suggesting meaningful perceived ergonomic benefit at the lumbar level. Similar subjective benefits of passive back exoskeletons have been documented across multiple industrial sectors. Specifically, the device reduced perceived physical effort or muscle loading for warehouse workers and logistics personnel (Yandell et al., 2022; Cardoso et al., 2024). Furthermore, workers reported mitigated lower-back strain in construction tasks (Bennett et al., 2023), improved posture in healthcare settings (Saurio et al., 2023), and an average reduction of one effort level during waste management operations (Ziaei et al., 2021).

However, perceived usefulness was highly variable in our sample (item 6). While several participants reported immediate lumbar relief during the interviews, others maintained a neutral stance, perceiving the device as neither assistive nor restrictive. Participants noted that waste collection work is not just about back strain, pointing out that the areas also affected are the shoulders and knees. Consequently, while the exosuit effectively attenuated lower-back strain, its perceived systemic utility was mitigated by unaddressed physical demands on other joints.

Furthermore, a technically important observation emerging from the interviews concerns a functional trade-off. In fact, to receive assistive force during lifting, users had to actively load the elastic element during trunk flexion, effectively increasing the effort required to bend forward. This dynamic may reduce the net perceived benefit, particularly in high-frequency, time-pressured collection routes where the cost-benefit ratio of engaging the system is less favourable.

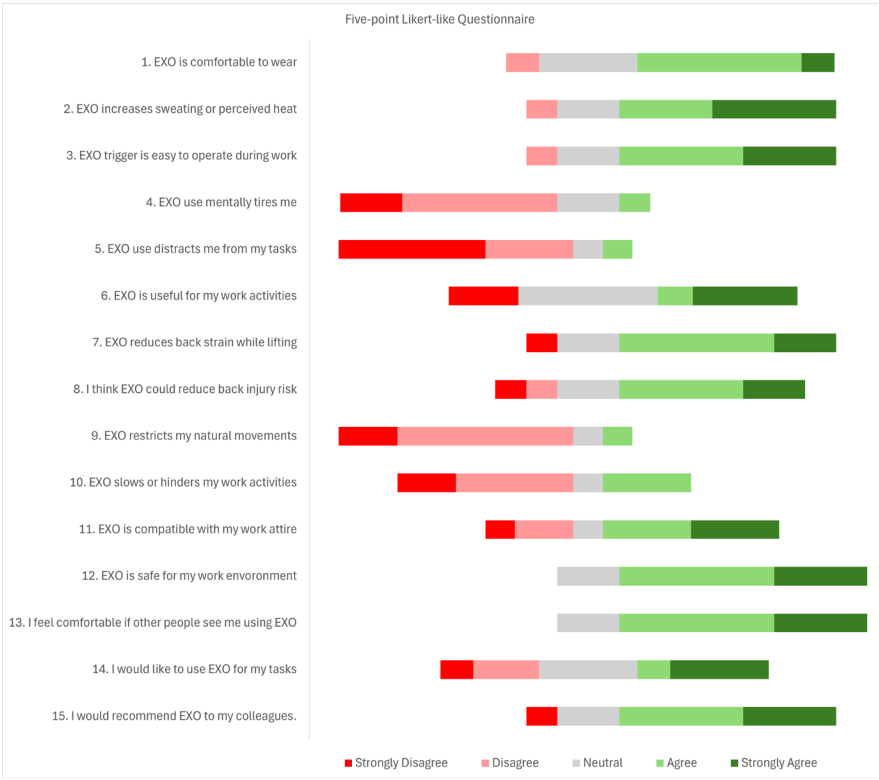

Figure 3: Likert-like questionnaire results.

Comfort and Thermal Load

The LBD scale indicated that participants found the exosuit generally comfortable, with slight discomfort concentrated in the body regions interfacing with the device (back, shoulders, chest, thighs, and glutes). The back was identified as the primary discomfort site, which the interviews

attributed to the semi-rigid backplate and augmented heat accumulation in that region.

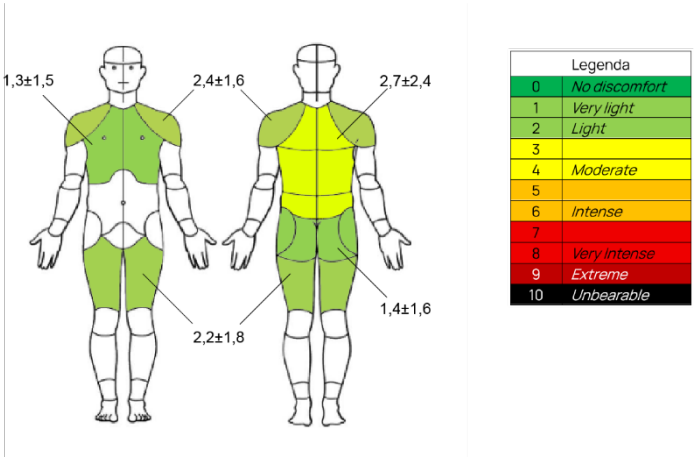

Figure 4: Local body discomfort map.

Thermal discomfort emerged as the most critical barrier in the qualitative data. Most of the participants expressed concern about summer usability, with unanimous agreement that sweat would make the device difficult to tolerate in hot conditions. This finding is consistent with the literature. Workers across multiple settings have reported that exoskeletons become uncomfortably hot during use, particularly when worn over uniforms that restrict airflow (Ziaei et al., 2021; Saurio et al., 2023). In agriculture, this high heat combined with poor device fit significantly increased both physical discomfort and the workers' perceived risk of use (Jakob et al., 2023). Thermal management therefore represents one of the most pressing design challenges for exosuit adoption in physically demanding outdoor occupations.

Ease of Use and Operational Integration

Participants broadly agreed on the simplicity of the clutch activation mechanism (item 3), and the interviews confirmed unanimous appreciation for its intuitiveness. However, a critical operational limitation emerged: the need for continuous manual and dynamic activation conflicted with the pace and traffic pressure of door-to-door waste collection. A similar learning curve was reported by healthcare workers using a comparable system, who identified remembering to activate and deactivate the support as the most challenging aspect of use (Saurio et al., 2023). During the interviews, it emerged that the device was perceived as better suited to repetitive, linear tasks, such as logistics operations, or for slower and more predictable routes within the work week, such as large bag accumulations, than to the dynamic, fragmented nature of standard door-to-door collection. This task-specificity nature of the exosuit could explain the mixed perceived usefulness and is coherent with literature findings: in logistic tasks exosuits showed

compatibility and low interference ratings (Hess et al., 2025; Cardoso et al., 2024), while in emergency medical services and care, benefit was confined to a specific task type (Mukherjee et al., 2024; Saurio et al., 2023).

Mobility and Range of Motion

Most of the participants did not feel their natural movements were restricted by the device (item 9), while responses regarding task slowdown and hindrance (item 10) were more mixed. The interviews reinforced this ambivalence: the flexion trade-off described above was identified as a hindering concern in high-pacing conditions.

The literature suggests that movement restriction is a context- and subject-dependent issue. In order-picking studies, range of motion ratings varied substantially between tasks and participants (Cardoso et al., 2024). In care settings, squatting positions were identified as particularly problematic, causing the suit to feel tight and compressive on the thighs and shoulders (Saurio et al., 2023).

Social Acceptability and Adoption Intention

The exosuit was perceived as safe for the work environment and socially acceptable, with no participants disagreeing on either dimension (items 12 and 13). Recommendation to colleagues was rated positively overall (item 15), indicating that despite reservations, participants recognised potential value in the device.

Acceptance of the device (item 14), however, showed high variability, even within the same collection route type (Fig. 5), reflecting the subjective nature of exosuit experience and the degree to which willingness to adopt depends on individual perception of need, subjective response to provided support, and environmental factors such as season and task characteristics.

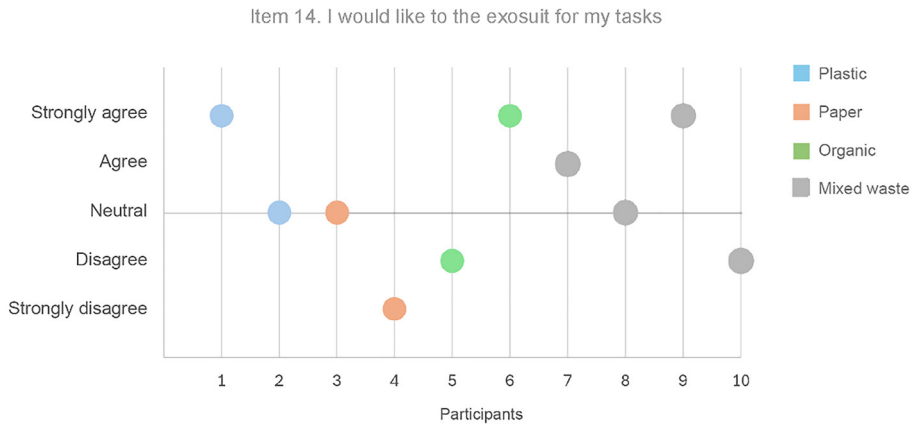

Figure 5: Exosuit acceptance per participant and waste type.

CONCLUSION

This pilot study provides field-level evidence on the subjective effects and adoption barriers of a passive low-back exosuit in manual urban waste collection, an operationally complex and understudied context. Results indicate that the device generally delivers perceived ergonomic benefit at the lumbar level, with most participants reporting reduced back strain, comparable overall workload, and high social acceptability and ease of use, findings consistent with evidence from other occupational settings.

However, the overall occupational utility of the exosuit is heavily mediated by the multi-joint, high-pacing dynamics characteristic of waste collection. Adoption is constrained by several contextual barriers: the device does not address physical demands on the shoulders and knees, thermal discomfort raises serious concerns about summer usability, and the need for continuous manual clutch activation conflicts with operational pacing on dynamic door-to-door routes. The inherent functional trade-off of the passive system, requiring users to overcome elastic resistance during trunk flexion in order to receive assistive force during lifting, may further reduce net perceived benefit under time-pressured conditions.

These findings underscore that successful exosuit integration in waste collection requires targeted design improvements in thermal management and activation mechanisms, as well as careful matching of device characteristics to specific task types and route profiles. Future research should involve larger and more diverse samples, longitudinal observation across seasons, and objective biomechanical measures to complement the subjective data presented here. Extending this work to multi-person collection crews and different waste streams would further clarify the conditions under which passive exosuits can deliver consistent and meaningful benefit in this occupational context.

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