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Research article

Field assessment of active BSE: Trends over test days of subjective indicators and self-reported fatigue for railway construction workers

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A R T I C L E I N F O

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A B S T R A C T

The research community has conducted several controlled “in -lab” assessments on the effectiveness of industrial exoskeletons, paving the way for their adoption. However, field testing, focusing on ergonomics and the user experience, could serve to enhance both end-users’ awareness and address open doubts concerning true effectiveness of industrial exoskeletons. This study presents an analysis of qualitative data regarding the use of back-support exoskeletons during field trials in harsh civil engineering environments. This work evaluates the StreamEXO’s (an active back-support exoskeleton) efficacy in reducing fatigue and the evolution of its perceived usefulness. This is achieved using qualitative data collection tools, during real scenarios testing over multiple-day trials. Collected data shows a positive correlation between self-reported fatigue, measured on a four verbal anchors-based Borg CR10 scale, and the use of the exoskeleton during physically demanding movements. Moreover, the evolution of scores throughout the testing sessions (90 minutes of exoskeleton use for three nonconsecutive days) suggests a trend due to the adaptation and learning curve of workers during the exoskeleton experience. The analysis of the open-ended answers highlights that the adaptation to physical interaction has a negative oscillation on day two to rise back during the third day, possibly correlated to a change in muscle pattern. The main critical factors affecting comfort during the exoskeleton experience are weight balance, body pressure, and thermal comfort, which can strongly affect device acceptance.

1. Introduction

In the last decade there has been a massive growth in research and development on industrial exoskeletons [1], [2] fueled by companies renewed awareness of workers’ well-being, workforce ageing and governmental awareness campaigns on workplace ergonomics. Exoskeletons are wearable robots that help workers by providing assistive forces and torque. The device is secured on the users’ body by means of straps or cuffs and the users’ body and the exoskeleton then move together.
Exoskeletons can be divided in categories, for instance, by their power source or the body district an exoskeleton assists. Therefore, exoskeletons can be *passive* if they rely on springs or elastics charged by the users’ body movements. In contrast, an *active* exoskeleton

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assists a body district by means of electric or pneumatic motors [3]. Finally, *semi-active* exoskeletons combines both active and passive actuation [4]. Industrial exoskeletons are focused on assisting body districts that are the most commonly impacted by Musculo-Skeletal Disorders (MSDs) due to prolonged exposure to unhealthy and poor ergonomic work conditions [5]. Industrial BSE acts on the back muscles, reducing their activation. Laboratory testing suggests that the BSE's action lowers the apparent load in Manual Material Handling (MMH) activities [6]. Over the years, efficacy of *passive* and *active* exoskeleton has been tested in laboratory setups, measuring beneficial effects in reducing ergonomic risks' exposure, such as: reduced muscular activation of lumbar muscles in MMH activities for back-support exoskeletons (BSE) or in deltoids, triceps or trapezius muscle in un-ergonomic overhead assembling work for upper body support exoskeletons. However, most of these studies have been undertaken in controlled laboratory environments and involved controlled movement tests [7]. In fact, only a 20% of the reviewed papers in [8] and [9] are set in-the-field scenarios. This results, usually, in a lack of data on user acceptance, and subjective experience evaluation on mid and long term (i.e. weeks and months apart) effects [10]. This, combined with a lack of truly validated and relevant in-the-field variability (scenarios, number of people, testing sample, time length) data, is hindering adoption in industry [11] and civil construction [10] scenarios. Golabchi et al. [12] stress that only a multi-factor analysis, where performance indicators are agreed with all the stakeholders (especially with workers' engagement and participation), would help in informing companies decisions on exoskeleton adoption. Standard industrial exoskeletons' performance indicators from literature [9] and [13] can be divided in *objective* and *subjective*. *Objective* indicators allow researchers and managers to quantify the beneficial effects on workers' health and benefits to the organization. On the other hand, *subjective* indicators typically show device acceptance rates, usability and comfort. Unfortunately, low scores on *subjective* indicators or a poor fit to the working activities can lead to rejection of the device, despite of the benefits shown by *objective* indicators [10] and [12]. Hence, it is of paramount importance to shape tests with all stakeholders by defining a suitable set of *subjective* and *objective* indicators, their metrics and the testing protocol that fit the companies' processes. The most commonly used *subjective* indicators are established scales such as System usability Scale (SUS), Rated of Perceived Exertion (RPE), Nasa Task Load Index (TLX) and Multiple-Choice and Open-ended feedback questionnaires [14], [15] and [1].

In this paper, we aim to provide a clearer focus for industry, that will help to guide and direct their understanding on exoskeletons. This will be achieved by providing testing and data recording in the workplace, using an iterative and participative process that is well suited to the needs of all the possible stakeholders. An operative setting will be developed that introduces all the variability in movements, task frequencies, and other unexpected events that could not be recreated in a laboratory setting. In this work, we will show qualitative data recorded during on-site tests with the StreamEXO BSE [16,17]. This will involve civil construction associated with a harsh environment involving railway construction and maintenance. The test subjects (rail workers) are assessed using multiple questionnaires to record multiple dimensions related to physical and mental load, comfort, acceptance, and self-reported experienced fatigue. In addition to value arising from this data being collected in uncontrolled and unconstrained scenarios [8], there is a secondary, but equally important benefit as testing was conducted during a span of 2 weeks on three equally time-spaced trial days. This facilitated extended measurement and testing of the self-reported fatigue, willingness of adoption and lead to a better understanding of mid-term effects such as adaptation trends and learning curves. This paper is structured as follows: Section 2 introduces in 2.1.1 the exoskeleton device, in 2.1 there is a description of the experimental protocol, in 2.2 the custom questionnaire and its administration is described, while in 2.3 the data analysis is presented. In Section 3 the results are presented divided in Self Reported Fatigue in 3.1, Local Perceived Discomfort in 3.2, Task Load Index in 3.3 and the Custom Questionnaire in 3.4. In Section 4 the results are commented and, finally Section 5 concludes with final remarks and future works.

2. Methodologies

This section is divided in subsection 2.1 that provides detailed information on the protocol and the activities addressed in the experiment while in 2.1.1 there is a brief description of the BSE device used in the test. The data analysis steps and algorithms are in subsection 2.3, while the subjective metric tools are presented in subsection 2.2.

2.1. Experimental protocol

Testing took place on a railway site located at the Rete Ferroviaria Italiana (RFI) facility close to the main train station in Asti, Italy. The assessment was organized withing STREAM project (streams2r.eu) in collaboration with the system integrator company MerMecSTE. The activities undertaken involved civil construction tasks to update the train station signaling system (maintenance and replacement of cable ducts), as a part of a bigger set of experiments in the framework defined by STREAM European project [17]. These cable ducting activities consist in: *(i)* removing old ducts or digging a new ditch, *(ii)* gross (rough) positioning of the concrete ducts, and *(iii)* and then fine positioning of ducts and cables [17]. All of those activities involve heavy MMH. Since these activities are highly dependent on the weather and higher priority railroad usage (such as traffic or failures on other lines), tests were held on a maintenance rail stub under an industrial canopy in the train station instead of a live line. This set-up allowed the research team, to work with real workers, in a harsh environment, planning ahead and working shifts to avoid the aforementioned organizational issues.

A total of 5 male workers were recruited as test subjects. The test cohort data is: age 49.8 ± 4.5 years old; height 175.7 ± 4.7 cm; weight 86.6 ± 17.6 kg.

The cable ducts are a 50 cm by 20 cm, 20 kg concrete prefabricated element, with a 10 kg lid. An analysis of the workers' maintenance activities divides the movements with higher impact on NIOSH Lifting Index (LI) into two groups: *gross* and *fine* positioning. The first set of movements involved lifting the ducts from a pallet and carrying them, with two hands, for a maximum

Fig. 1. The StreamEXO being used at the test.

distance of 5 meters before lowering them to the ground. The latter task consists in the workers positioning themselves in a symmetric wide-leg stance over the ditch, lifting, in a deep stoop, the ducts to interconnect each duct with its (in line) neighbor.

Each trial day was carried out for 90 minutes without the exoskeleton and 90 minutes with the exoskeleton. Each worker repeated the test over a two week period on three equally-spaced trial day. Workers were instructed to work at their natural pace and with their usual lifting and positioning techniques. Considering the lifting frequency (an average of 200 conduits per hour), postures, and handled loads, the activities have NIOSH Lifting Index of 3.36 (for workers younger than 45 years old) and 4.2 (for workers older than 45 years old).

The workers performed the activities in two different conditions:

1. *noExo*: working activities without any type of exoskeleton
2. *withExo*: working activities with the StreamEXO;

The two testing conditions make it possible to determine the perceived effectiveness of the exoskeleton. Although there are several studies (e.g., [18] [19]) that provide evidence of BSEs' objective effectiveness during MMH activities, there are numerous variables, work-related dependent and subjective, that could affect perceived effectiveness for each user.

The time span of this testing offers a unique perspective for active BSEs, in a set-up influenced by work-related dependent variables:

1. repetitions during the same trial day serve to highlight and record short term effects on fatigue. Any statistically relevant difference in perceived fatigue is recorded with a Borg CR10 scale. This methodology is not intrusive and does not rely on equipment that could interfere with the exoskeleton;
2. repetitions on a weekly basis test any mid term effects on different qualitative parameters related to perceived usefulness and willing to use. This structure can measure trends that would be impossible to notice in a shorter time span.

2.1.1. *Back support exoskeleton*

The StreamEXO is an industrial BSE that has been developed with requirements set by all the stakeholders of the STREAM consortium [17]. The StreamEXO, Fig. 1 is specialized for harsh construction environments and its control algorithms, geometries and motor power are tailored to the activities performed in rail construction and maintenance.

The experiment was approved by the Ethical Committee of Liguria (protocol reference number: CER Liguria 001/2019) and complies with the Helsinki Declaration. All the subjects signed a consent form prior to participating and for image publication, after a full explanation of the experimental procedure.

2.2. *Subjective data collection questionnaires*

In this field test, we used both standard and custom questionnaires. The rationale behind this choice is that there are no specific questionnaires for exoskeletons [20]. Standard questionnaires fail to effectively record all the subjective variables that can provide valuable insights for developers. However, standard questionnaires can be used to validate the custom ones, using results correlation between similar items or constructs [20]. They can also help to collect other parameters/dimensions (e.g., Frustration in executing the task) with a broader scope (i.e. with just one item in spite of multiple items) when researchers are interested only in the subjective dimensions as a whole.

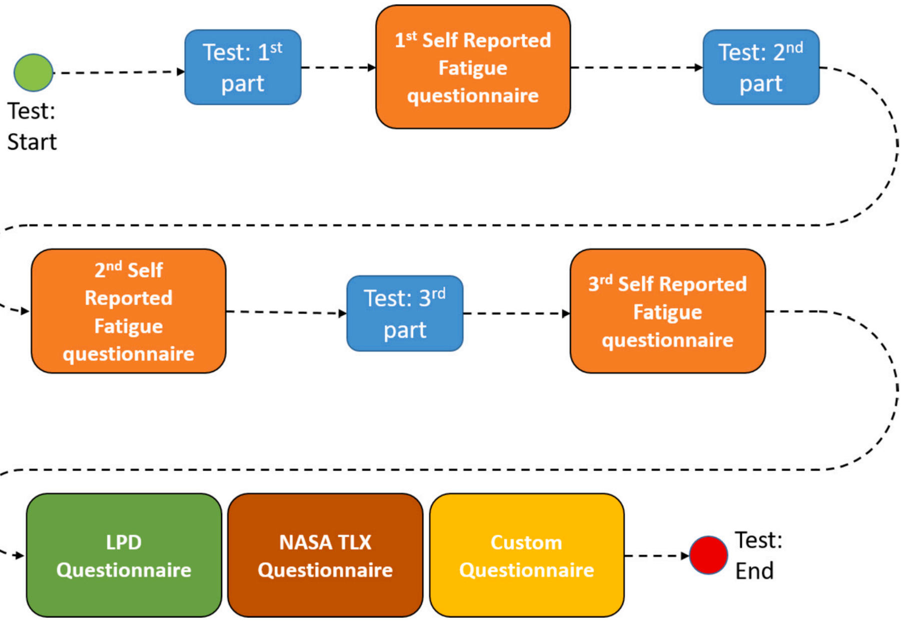

Fig. 2. Block representation of the timings of survey questions. This flow shows one day trial. Each of the parts in blue are repeated three time within each day test and referred as *Repetition-number*.

2.2.1. Standard questionnaires

The questionnaires were administered during different phases of the testing, as described below. In Fig. 2 there is a visual summary of the questionnaire administration timing.

1. *Self reported fatigue* for each body segment: to test the perceived fatigue during the tests. This part of the questionnaire is administered 3 times during the test day (every 30 minutes). This survey is a 4-point score on the CR-10 scale [21], as described in its revision [22], where 4 verbal anchors have been proposed as follows: “nothing”, “light”, “moderate”, and “somewhat hard”. This questionnaire is administered in both the *NoExo* and *withExo* conditions.
2. *Local Perceived Discomfort*: to track the discomfort in each body segment where the exoskeleton is attached. Data is collected using a full 10-points Borg CR10 scale. This questionnaire is administered only in *withExo* condition.
3. *NASA TLX*: to track the whole physical effort to correlate with the Borg CR10 scale and to evaluate the overall differences between with and without the exoskeleton this questionnaire is used to record overall physical, mental fatigue and self reported satisfaction of the activities when using the exoskeleton. This questionnaire is administered only in *withExo* condition.

2.2.2. Custom questionnaire

The customized questionnaire aims to collect structured qualitative data, specifically during the exoskeleton usage. It focuses on assessment of *Physical Comfort, Intention of Use and Usability* [20]. The custom questionnaire is composed of 7-point Likert-type scale items and open-end questions. In our previous work [23] and [24], the questionnaire was tested for wording and validity against standard questionnaires. Each *Construct* of the questionnaire is composed of multiple items (i.e. questions) regarding relevant physical feelings and impressions about the StreamEXO usage. This questionnaire is administered only in the *withExo* condition, at the end of the day test. Table 3 and 4, in Appendix A, report the full list of questions and constructs.

2.3. Data analysis

All data has been filtered for unanswered question that has been labeled as “N.A.” and then excluded from the calculation to build the analysis. The *Self Reported Fatigue* questionnaire has been translated from a fully-anchored 4-points Borg CR-10 scale in natural language to its corresponding numeric values (e.g. *Light* value becomes 2). Descriptive statistics are presented for the *Custom Questionnaire, LPD* and *Nasa TLX*. This consists of calculation of the median values for each item in the repetitions. Open end answers to items in the *Custom Questionnaire* are filtered for incomplete or unanswered items and then clustered for similarity. Each response is then counted for its occurrence, as in [15]. The *Self Reported Fatigue*, as it is administered for both the *Exo* and *NoExo* conditions, is reported in descriptive statistics and is also tested for statistical significance using the *Wilcoxon Signed rank* test.

Table 1
P-values data, median values with respective Inter-quartile range.

Movements	Median *NoExo*	Median *withExo*	*p-values*		
			Rep.1	*Rep.2*	*Rep.3*
picking	2.30 *1.55*	1.60 *(1.38)*	0.136	**0.002**	**0.001**
moving	1.91 *1.34*	1.55 *(1.25)*	0.148	**0.0156**	0.879
lowering	1.94 *1.37*	1.27 *(0.75)*	0.148	**0.003**	**0.004**
positioning	2.16 *1.53*	1.55 *1.30*	0.0615	**0.008**	0.0712

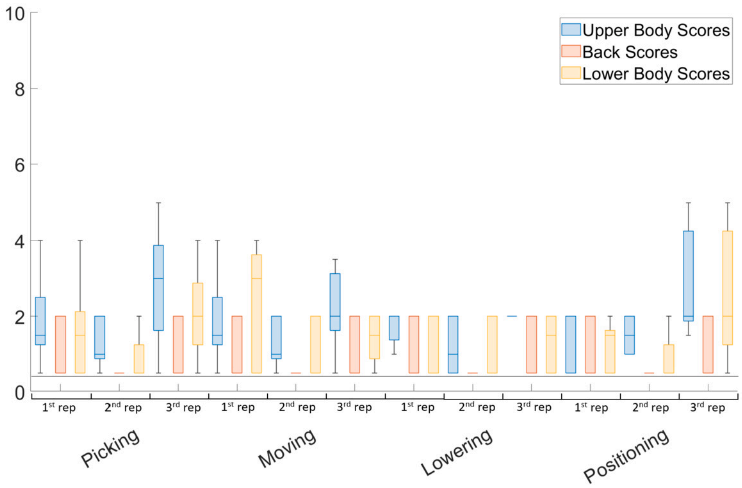

Fig. 3. Bar plot representing Self Reported Fatigue in the *WithExo* condition. Plots are grouped by repetitions and movements. The color of each bar represents a different body region.

3. Results

In this section the results are divided as follows: 3.1 shows figures and tables regarding results for the statistical analysis and descriptive statistics of the *Self Reported Fatigue*; 3.2 and 3.3 show aggregated data in figures showing the median, upper and lower quartiles and highest and lowest values. 3.4 shows median, upper and lower quartiles and highest lowest values plots and table reporting the most occurrences of each keyword in the *Custom Questionnaire's* open ended items.

3.1. *Self reported fatigue*

Table 1 reports average and deviation values for each movement performed during the tasks on each row versus each of the two experimental conditions on the second and third row, respectively. The statistical significance shows that *picking* and *lowering* movements are those that are the most statistically relevant among all the movements. In addition, the second repetition shows statistical relevance to all the movements.

Fig. 3 shows changes in the average values of *Self Reported Fatigue*, in the different repetitions, in the *withExo* condition. Low scores means that the user reports low fatigue, while an unchanged score means that the user always gave the same score in different repetitions (i.e. hours apart, with resting time). The highest scores with respect to *Self Reported Fatigue* arose in the Upper Body and Lower Body, respectively, with a score of 5 for positioning during the last repetition. The most stable score is for the Back area, that is unchanging with an average value of 2.

Fig. 4 shows the percentage reduction of each score divided for repetitions and body areas. A zero value on the bar plots means that there is no difference between the average scores given in the two experimental conditions, while a 100 value means that the average scores are completely at the opposite sides of the Borg CR10 scale. Fig. 4 shows that in Repetition 2 there is the greatest difference of scores given to fatigue, for all the body areas and movements. The Back body area registered a score of 15% difference in all the movements, with a maximum difference of 45%. The highest average difference is in picking for the Lower Body during the Second repetition: an average difference of 40%.

3.2. *Local perceived discomfort*

In this section, Fig. 5 shows the subjective scores collected with the LPD questionnaire. The bar plots show the repetitions in different colors. The bars are grouped by body area to highlight changes in the perception of discomfort.

Fig. 5 shows that the Thighs are the body district that most suffer from discomfort when wearing the exoskeleton. This area has an

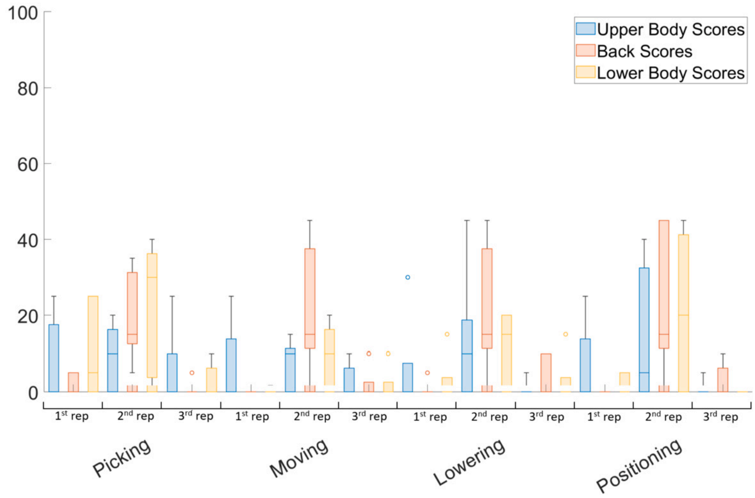

Fig. 4. Bar plot representing percentage differences on Self Reported Fatigue in the two experimental condition. Plots are grouped by repetitions and movements. The color of each bar represent a different body region.

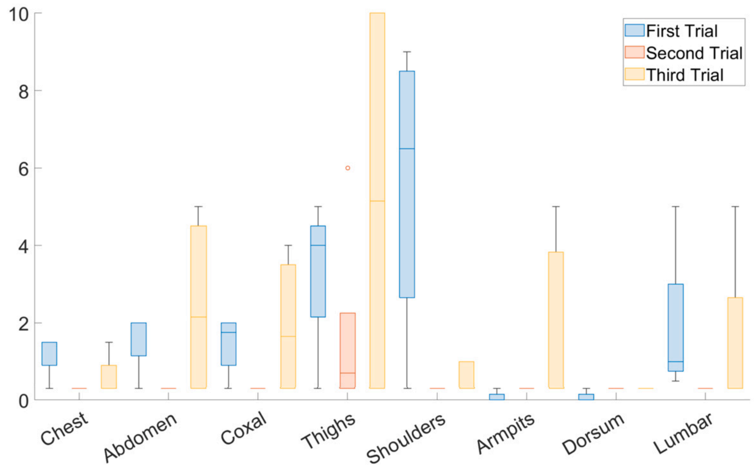

Fig. 5. Bar plot representing LPD scores for different body regions. Each color represent a different trial day.

average value of discomfort of 5, with high variability between operators, and shows an abrupt increase on day 3.
Regarding the other body segments, the only discomfort in the Shoulder and Coxal areas have an average value of 4, with a high discomfort in the Shoulder area on the First trial day and then a fast reduction in the following trials.

3.3. Nasa TLX

Fig. 6 shows, for each different Trial Day, the average values that each construct was given. All the constructs share a trend where the second trial shows better performance with a reduction of score for Mental Demand (MD, median value 2), Physical Demand (PD, median value 1), Temporal Demand (TD, median value 8), Effort (EF, median value 2.5) and highest Performance (PE, median value 20). Frustration (FR), instead, shows a completely different trend where the score increases over time from a median of 4.5 for the first trial to a median of 9 for the last trial.

3.4. Custom questionnaire

In this section, Fig. 7 reports aggregated scores for constructs (Acceptability, Assistance, Comfort, Stability, and Usability) grouped by single-day trial, while Fig. 8 shows the scores for every single question belonging to each construct for each day's trial.

The aggregated scores over the different trial days (Fig. 7) show that the highest variation is in Acceptability (with a median of 6 on day one, a median of 3.5 on day 2, and a median of 5 with maximum variability). The most consistent score is for Comfort, with a median value of 5. The highest-scoring construct is Usability, which always scores over a median 6 in all three trials. In the second trial, all the constructs shows an average high variability of scores (i.e. the difference between the 25^{th} and 75^{th} quartile).

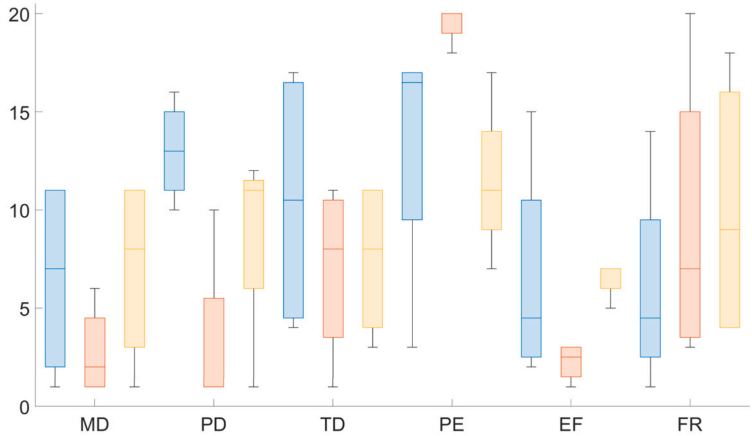

Fig. 6. Bar plot representing Nasa TLX scores for different body regions. Each color represent a different trial day.

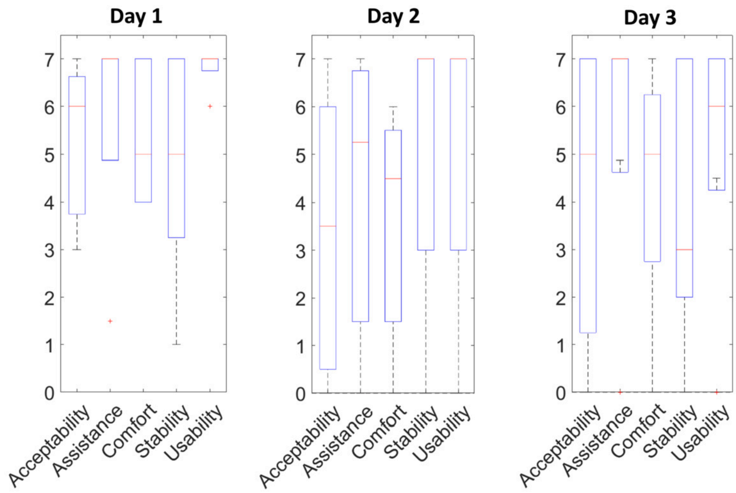

Fig. 7. Box plots presenting the median values of the constructs, as a whole. In the left plot, there is data from the first trial. In the central plot, data from the second trial. In the rightmost plot, data from the third trial.

Fig. 8 allows an in-depth analysis of which part of the exoskeleton mostly influences the aggregated scores for each construct. The highest scoring for the *Acceptability* construct is the AC1 with a median value of 7 throughout the three trials. The lowest scoring is recorded in AC7 (median value of 2), indicating that the users preferred to use the exoskeleton only in MMH and not in other working tasks. Regarding *Comfort*, the lowest score is recorded in the CM1 regarding the weight of the exoskeleton, with a median value of approx. 3 out of 7. The best scoring is CM4 with a consistent median value of 7 that suggests the pressure arising from the shoulder straps on the chest is comfortable. The *Assistance* construct shows an optimum result on the perception of fatigue and strain on the back (median value of 7). On the other hand, the hindering of the lower body score reduces with the trials (with a minimum of 2). The *Stability* of leg wraps (ST3) shows the greatest variability and lowest scores (median value of 4). The overall effect of exoskeleton stability (ST1) performs well (median over 5). Finally, *Usability* has all its items scoring over a median value of 4 with minimal variability. The lowest scoring aspect relates to the ease with which the exoskeleton can be turned on and off (median 4). At the same time, all users agreed on the highest score in US3 about the confidence of using the machine autonomously without any support from the researchers.

In conclusion, Table 2 reports answers to the open-ended items. Up to 94% of all the answers given to the construct are positive for *Stability*, over 50% for *Physical Assistance* and *Comfort*. 26% of responses on *Acceptability* are positive while this drops to 15% when considering *Stability*. For negative impacts they key findings relate to the soreness on the thigh's muscles, hindering the legs movement when the exoskeleton is delivering assistance, and pressure over lumbar and coxal areas (e.g. statements such as "*I feel the legs more sore than usual*" or "*when bending, the belt bothers me*").

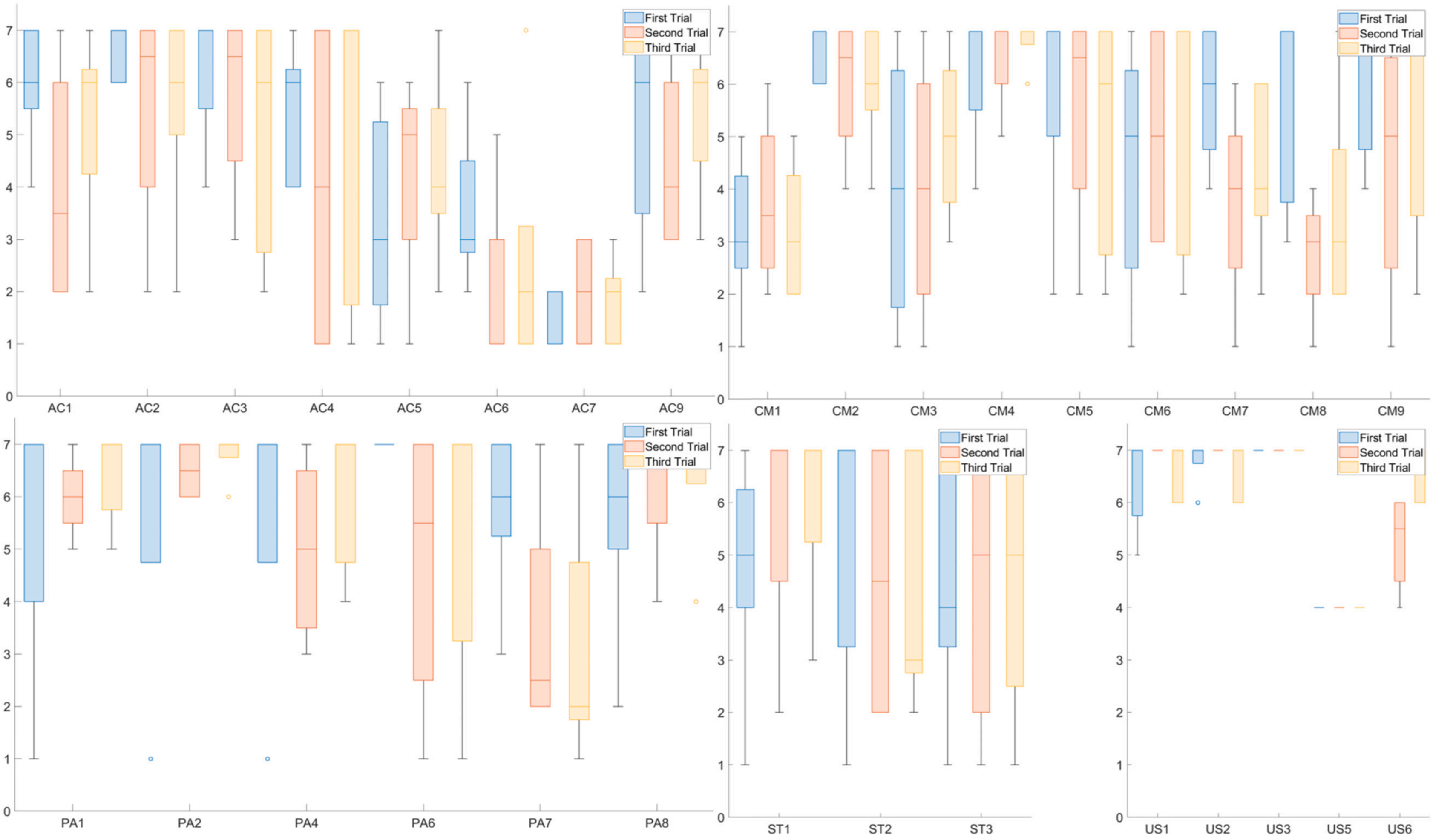

Fig. 8. Bar plots showing data relative to each item in the *Custom questionnaire*. Each color represent a different trial day.

Table 2
Custom questionnaire open end question items' results.

Constructs	# of Answers	Labels	Answers
Physical Assistance	57	**PA3**	The assistance suits me(12) ;I feel the legs more sore than usual(3); Legs are more sore after carrying(1); Legs are more sore after bending(1); Legs aremore sore after static stoop(2)
		PA5	No movement in particular (10); Full squat and stoop bending are hindered(2); motors and belt hinder(1); exoskeleton seldom oscillates(1); back bending and straigthening is hindered(1); the assistance is too high when bending and straightening(1); torso lateral bending is hindered(1)
		PA9	No part in particular(8); the UI should be more accessible, maybe on the arm(3); the control algorithm should not be customized on each ones' preferences(1); I should get going and learn to use it(1); the exoskeleton should not oscillate(2); the assistance is too high during lifting(1); the exoskeleton is too cumbersome in several movements(1)
Comfort	19	**CM10**	It is fine(1); when bending the belt bother me(1); I feel discomfort on chest and armpits(3); pressure is high on the lumbar area(9); leg wraps are too tight(3); Motors covers bother me while carrying(1)
Stability	19	**ST4**	The exoskeleton is fixed(17); the whole exoskeleton structure is too big, but it is ok(1); the leg wrap are moving down(1)
Usability	19	**US4**	I would prefer to put on only when needed (16); I would keep the whole shift (3)
Acceptability	38	**AC8**	only for laying the cable conducts(18); I don't know(1)
		AC10	No other activities except for laying ducts(15); it would suit also for laying cables in conducts(1); during MMH for loads over 10 kg and over 5 repetitions(1); maintenance tools for the construction site or the intelocking and signaling apparatus building(1).

4. Discussion

4.1. Self reported fatigue

Overall, the results show a general consensus among the users about the aid given by the exoskeleton to their assist their back muscles. Indeed, the self reported fatigue, TLX and Assistance custom questionnaire all show a trend that supports the conclusion that:

- the users experienced less fatigue on their back during the same trial in different repetitions (days) and
- the users noted valuable assistance on their back throughout the 3 trials

Indeed, the results from the descriptive statistics in Fig. 4 and 8 show that users particularly feel the assistive force on their back. This is perhaps not surprising as the Picking, Lowering and Positioning as shown in Fig. 4 are the activities where the back muscles are the most activated to balance the steep trunk inclination (especially in Positioning as described in [17]). These findings are also supported by PA1, PA2 and PA8 median values in Fig. 8, that are the highest scores in the *Assistance* construct.

4.2. Evolution of subjective score

While fatigue data clearly suggests that users may benefit from the BSE use, the other subjective perceptions may create a different impression. However, these evaluations are often influenced by several parameters that cannot be controlled by researchers. The simultaneous consideration of multiple indices allows for a multidimensional analysis, offering a comprehensive qualitative evaluation. Moreover, this approach also enables a cross-validation of measurements using diverse instruments, which helps minimize uncertainty in the obtained results.
For instance, *Frustration* rises test after test (Fig. 6), especially in the second trial. Here is an inverse correlation with the other dimensions recorded by the Nasa TLX. However, the *Custom Questionnaire* also confirms this with a similar trend of decreasing scores. Further analysis of single items suggests that a drop at day 2 in *Comfort* and, consequently, *Acceptability* could be the cause of the rise in the Frustration score as trial days progress.

Literature underlines that Exoskeletons induce changes in postural strategies [25]. Even if the change is not important in terms of absolute variation of joint angles, this can lead to the generation of different muscle patterns [26]. When this is associated with strenuous activities, it can lead to the manifestation of localized muscle fatigue [27]. This phenomenon can rapidly appear and can be recovered soon in trained subjects [28]. This could be the reason behind the results drop in *Comfort* and *Acceptability*, experienced in averaged by the workers during the second day of the test. Moreover, this is further supported by the increased fatigue in the legs reported at the end of the second and third days of tests.

Comfort drops mainly due to CM7 and CM8, which measure perceived thermal comfort. Unfortunately, air temperature changes are not predictable and directly affect sweating, which can be mistakenly interpreted as an alteration of pressure. The positive results for CM2 to CM6 that report the score concerning the weight distribution and the pressure felt on the chest, waist, and thighs, do not follow the pattern observed in CM7-8, as increased usage of the exoskeleton with days involved in the trial shows a growing level of adaptability (and acceptance) of the worker to the device. A similar correlation could be found in AC1 and AC4 ("the exoskeleton meets my expectation", and "I would use it on a regular basis"), which drop down at day 2. This result could be biased by the negative sensations of sweating and *Frustration*, which are completely compensated on the third day with a median of 6 for AC1 and 7 for AC4.

The LPD data, in Fig. 5, reveals the impact of the device on leg constriction. Even on certain *Custom Questionnaire* open-ended questions, participants consistently describe this sensation as unfamiliar and, probably, confusing. They use terminology more closely associated with leg fatigue rather than actual pressure. Interestingly, it has been observed that the same muscle soreness can be experienced even when exerting the same effort, but with the addition of pressure on the active muscles [29]. This finding may explain the reduction observed on day three for *Stability* (from 7 to 3) and *Usability* (from 7 to 6), as shown in Fig. 7. In conclusion, we can with good confidence state that for certain parameters/constructs, e.g., *Comfort*, *Assistance*, and *Acceptability* the adaptation of the workers is reached after three days of use when at least 90 minutes of continuous usage is performed. The score on the third day increases again after the second-day drop, confirming that workers, on average, require this amount of time to get used to the exoskeleton. For other constructs, e.g., *Stability* and *Usability*, it seems that more than three days are required to complete the learning curve. This will require further study in the future to determine the exact nature and limit to this learning/adaptation. The analysis of *Frustration* further supports this consideration that the trend increases during the three test days (Fig. 6) even if scores are always below eight on a scale of 20. In conclusion, three days of tests are required to understand functionalities and benefits and get used while adapting motion patterns to the usage modality of an active exoskeleton by the workers in their tasks. However, completing the learning curve requires, on average, more than three days.

4.3. Open-ended answers

Acceptability is influenced from drop scores in AC6 and AC7 over time, but the median values remain around a mean score of 5 on a 7-point scale. This is explained by the fact that users during trial days provide positive and negative responses to the experience based on the exoskeleton experience. However, in average the overall consideration of their exoskeleton experience is positive. In particular, considering the question AC8 *"Would you suggest the exoskeleton to your colleagues in other departments? If yes, for which tasks?"*, most users responded *"Only for laying the cable conducts"*, that means that the users would not reject the exoskeleton but only used in the activities that were tested.

Similarly, concerning *Usability*, most users prefer to put on the device only when needed. This kind of response highly depends on the work organization and the type of activities that each operator carries out. Without the possibility to test the device in an operational environment, allowing to deal with the standard work organization (e.g., shifts or single activity vs. multiple activities for each operator), it would not be possible to collect this valuable information that impacts so high on the final *Acceptability* and *Usability* of the device to understand when and how it could be used accordingly with tasks schedule.

4.4. Future work

Two main issues were revealed during the data analysis. The first issue concerns the unpredictable effects of real-world conditions on the users' responses. Measuring thermal comfort on a rainy or hot summer could bias the study outcomes, thus requiring further studies to prove this assumption. Longer trials, equally divided into different seasons, could affect the impact.

The second issue concerns the bias introduced by the work organization: Usability, Performance and Acceptability are highly dependent on this aspect. Researchers should challenge BSEs to work in unconstrained and harsh environments and test their usability in highly activity-variable work pattern shifts. This is particularly important as the ergonomic risks in developing a work related Musculo-skeletal disorder are higher when there is a prolonged exposure to MMH activities. To this end, an update of the *Custom Questionnaire* is needed to include scores that are dependent also on the different activities within the shift. Finally, to evaluate the quality of our specific exoskeleton concerning other, not specific solutions, a dedicated experiment should be performed to compare the StreamEXO against other exoskeletons as in [30].

5. Conclusion

In conclusion, this study provides valuable insights into the qualitative/subjective dimensions of back-support exoskeletons' use during field trials in a challenging civil engineering environment. By leveraging real-world scenarios and taking advantage of the work organization in construction sites, we assessed the effectiveness and perceived usefulness of an active back support exoskeleton in reducing fatigue.

Our findings reveal a positive correlation between self-reported fatigue, as measured on the Borg CR10 scale, and the use of the exoskeleton during demanding movements. This indicates that the exoskeleton successfully alleviated fatigue, offering support to users engaged in manual material handling tasks.

Furthermore, the evolution of scores throughout an extended testing sequence suggests a trend of adaptation/familiarization and a learning curve associated with the use of the exoskeleton. As users became more familiar with the exoskeleton over time, they experienced increased comfort and efficiency, suggesting even greater potential for long-term adoption and integration into industrial work practices. In addition, this work underlines the need to test the exoskeleton for at least three days before showing good adaptability/acceptance to the device in terms of Assistance and Comfort.

Analysis of the open-ended responses shed light on a specific issue related to discomfort in the lower limbs, which appeared to be unrelated to weight distribution or compensatory movements. Instead, it was primarily attributed to the pressure and mechanical strain exerted by the exoskeleton attachments on the limbs, which could be misinterpreted as muscle soreness. This emphasizes the importance of carefully designing and optimizing attachment mechanisms to minimize such discomfort and enhance user comfort.

In summary, our subjective data analysis conducted during field trials addresses the doubts surrounding active BSE by providing insights into the practical utilization and testing in an operational environment. The subjective analysis confirms the potential benefits of exoskeletons in reducing fatigue in a rail based civil engineering environment. Further research and development should focus on addressing issues about trials in-the-field and how to maximize their impact on BSE adoption.

Declarations

Ethics statement

The experiment was approved by the Ethical Committee of Liguria (protocol reference number: CER Liguria 001/2019) and complies with the Helsinki Declaration. All the subjects signed a consent form prior to participating and for image publication, after a full explanation of the experimental procedure.

CRediT authorship contribution statement

Matteo Sposito: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vasco Fanti:** Writing – review & editing, Methodology, Investigation, Data curation. **Tommaso Poliero:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Darwin Gordon Caldwell:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Christian Di Natali:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This work was supported by the STREAM project funded by Shift2Rail Joint Undertaking, established under the European Unions Horizon 2020 Framework Programme for research and innovation, under grant agreement No. 101015418.

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Appendix A. Custom questionnaire

This custom questionnaire, in order to be administered to workers at the italian partner working site, is written both in English and Italian. Following there is only the english version. Each item is either a *close-ended* or *open-ended* question. A *close-ended* question has a fully anchored, 7-point Likert-like scale The anchors are the following: *1 - Completely Disagree*, *2 - Disagree*, *3 - Slightly Disagree*, *4 - Neutral*, *5 - Slightly Agree*, *6 - Agree*, *7 - Totally Agree*.

Table 3
Custom questionnaire items regarding *Physical Assistance* and *Comfort* constructs.

Constructs	Labels		Closed ended	Open ended
Physical Assistance	**PA1**	I feel less fatigue while using the exoskeleton	X	
	PA2	I feel less strain on my back muscles	X	
	PA3	Do you feel that any body area is more sore with respect to normal? If yes, which one?		X
	PA4	I feel that the exoskeleton follows my movements	X	
	PA5	Which movements do you feel hindered by the exoskeleton?		X
	PA6	I feel my trunk movement's constrained	X	
	PA7	I feel my legs movement's constrained	X	
	PA8	I feel the assistance level fit my needs	X	
	PA9	Describe which exoskeleton's characteristics you would like to change		X

(*continued on next page*)

Table 3 (*continued*)

Constructs	Labels		Closed ended	Open ended
Comfort	**CM1**	I feel that the exoskeleton's weight is fine	X	
	CM2	I feel that the exoskeleton's weight distribution suits me well	X	
	CM3	I feel that the harness is too tight	X	
	CM4	I don't feel pressure on my chest	X	
	CM5	I don't feel pressure on my waist	X	
	CM6	I don't feel pressure on my thighs	X	
	CM7	I feel that thermal dissipation is adequate	X	
	CM8	I don't feel sweating on my back more than usual	X	
	CM9	I don't feel sweating on my thighs more than usual	X	
	CM10	Describe any other exoskeleton's parts that may bother you		X

Table 4
Custom questionnaire items regarding *Stability*, *Usability* and *Acceptability* constructs.

Constructs	Labels		Closed ended	Open ended
Stability	**ST1**	I feel the exoskeleton firmly attached to my body	X	
	ST2	I feel the belt thightly attached to my waist	X	
	ST3	I feel the leg wraps firmly attached to my thighs	X	
	ST4	Do you feel any part of the exoskeleton that is not firmly attached to you rbody? If any, which one?		X
Usability	**US1**	The harness is easy an intuitive to don	X	
	US2	The harness is easy to regulate and open to doff	X	
	US3	I feel confident to wear the exoskeleton on my own	X	
	US4	Would you prefer to wear the exoskeleton continuously or to remove and put on it more quickly?		X
	US5	The exoskeleton is easy to turn on and off	X	
	US6	The exoskeleton is easy and intuitive to operate	X	
Acceptability	**AC1**	The exoskeleton meets my expectation	X	
	AC2	I think that the exoskeleton is suited for my tasks	X	
	AC3	I don't feel hindered by the exoskeleton during my tasks	X	
	AC4	I would use on a regular basis if it was available on the market	X	
	AC5	I feel that the exoskeleton is robust and suited for the work environment	X	
	AC6	I think that I would use the exoskeleton the whole working day	X	
	AC7	I think that I would use the exoskeleton for all my working tasks	X	
	AC8	Would you suggest the exoskeleton to your colleagues in other departments? If yes, for which tasks?		X
	AC9	Please, give a total score to the exoskeleton' s performance	X	
	AC10	If you think that the exoskeleton helps you only in few tasks, in what other tasks would you use it?		X

Appendix B. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33055.

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