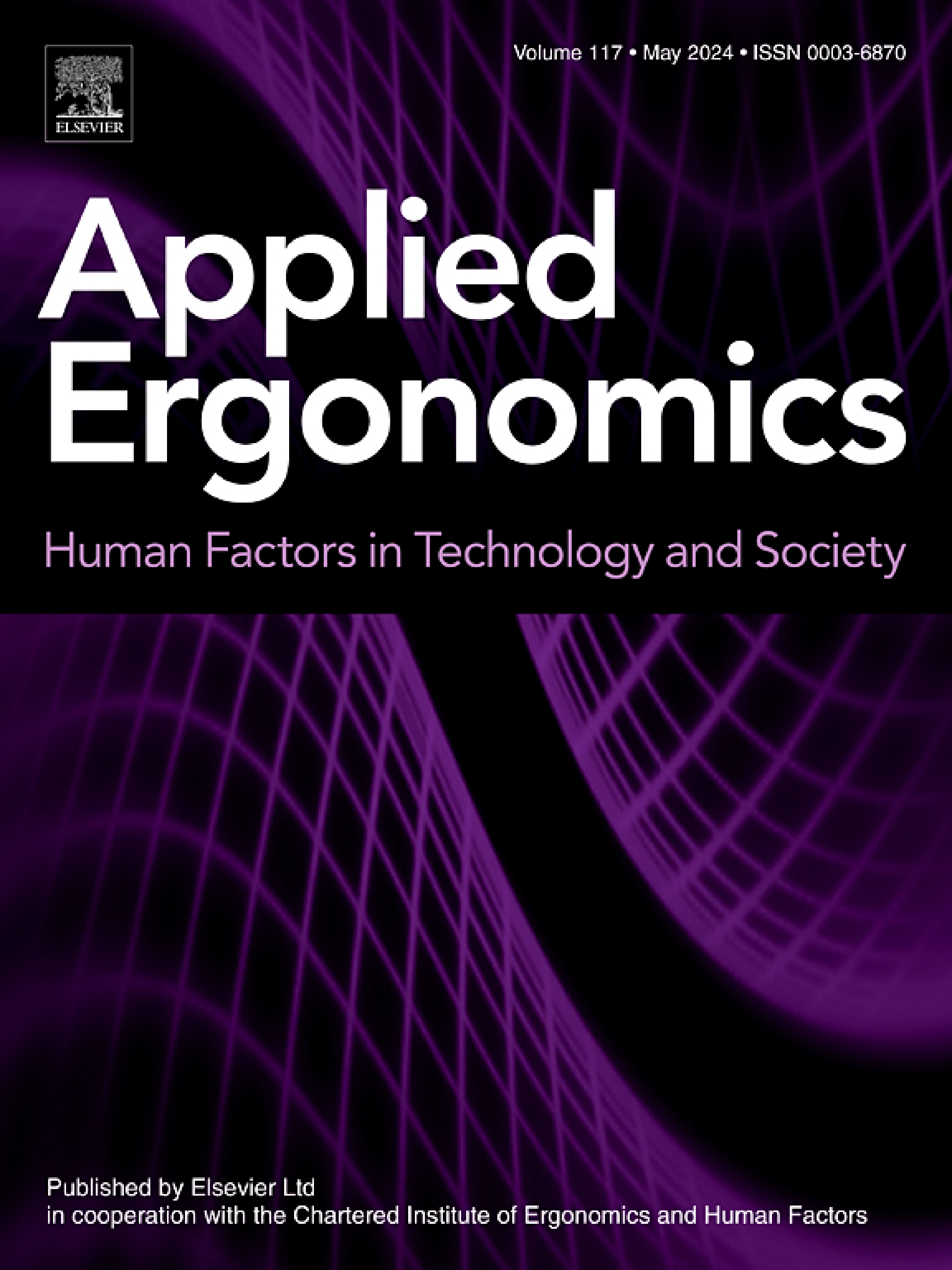

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Equivalent weight: Application of the assessment method on real task conducted by railway workers wearing a back support exoskeleton ☆

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ABSTRACT

Commonly used risk indexes, such as the NIOSH Lifting Index, do not capture the effect of exoskeletons. This makes it difficult for Health and Safety professionals to rigorously assess the benefit of such devices. The community requires a simple method to assess the effectiveness of back-support exoskeleton's (BSE) in possibly reducing ergonomic risk. The method introduced in this work is termed "Equivalent Weight" (EqW) and it proposes an interpretation of the effect built on the benefit delivered through reduced activation of the erector spinae (ES). This manifests itself as an apparent reduction of the lifted load perceived by the wearer. This work presents a pilot study where a practical application of the EqW method is used to assess the ergonomic risk in manual material handling (MMH) when using a back support exoskeleton (StreamEXO). The results are assessed by combining observational measurements from on-site testing with five different workers and quantitative measures of the muscle activity reduction achieved during laboratory evaluation with ten workers. These results will show that when lifting, lowering, and carrying a 19 kg load the StreamEXO can reduce risk by up to two levels (from "high" to "low") in the target sub-tasks. The Lifting index (LI) was reduced up to 64% when examining specific sub-tasks and the worker's movement conduction.

1. Introduction

Occupational exoskeletons (OEs) are wearable devices that aim to reduce exposure to risk factors associated with work-related musculoskeletal disorders (WMSDs) (Crea et al., 2021). Back-Support Exoskeletons (BSE) are made specifically for Manual Material Handling (MMH) (Kermavnar et al., 2021), to reduce the muscular activity in the lumbar spine, where there is particular risk of injury. When a worker is lifting a load, a BSE provides a part of the required torques usually generate by the back muscles to accomplish the task (De Looze et al., 2016). A reduction in the required torque can be correlated with reduced compressive load on the lumbar spine. This loading on the lumbar spine is one of the main risk factors for musculoskeletal injury (Schneider and Irastoeza, 2010).

Several groups have recently conducted assessments of the effectiveness of such exoskeletons (Pesenti et al., 2021; McFarland and Fischer, 2019). These studies have provided valuable results in short and focused laboratory investigations (Kuber et al., 2022), however across these studies, different categories of metrics have been used in the evaluations of exoskeletons and their impact on the workers (Grazi et al., 2019). This often happens as existing ergonomic evaluation frameworks (such as the NIOSH lifting equation (NIOSH, 1981) or the OCRA checklist (Colombini and Occhipinti, 2018)) do not yet incorporate OEs within their guidelines. This omission presents a challenge for Health and Safety professionals when they are asked to assess the use of OE for possible workplace use. Hence in a few recent works, researchers have attempted to connect potential OE benefits with standard ergonomic evaluation guidelines (Di Natali et al., 2021; Spada et al., 2018; Zelik et al., 2022).

The work presented in Di Natali et al. (2021) lays down a methodology to indirectly measure a BSE's effectiveness in terms of the apparent reduction of the lifted weight. The method proposes an interpretation

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Fig. 1. StreamEXO: BSE developed within the EU project STREAM.

of the benefits of OE use based the reduction activation of the erector spinae (ES) muscles. This manifests itself as an apparent reduction of the lifted load perceived by the wearer and is termed "equivalent weight" (Di Natali et al., 2021). This analytical method defines a coefficient that considers the exoskeleton's usage benefit, enabling the use of traditional evaluation tools (e.g. the Lifting Index (LI) (Waters et al., 1999)) for ergonomic risk assessment.

This pilot study aims to evaluate the reduction in the ergonomic risk for MMH activities carried out by specialized workers when wearing the StreamEXO BSE. A standard ergonomic assessment based on an evaluation of the NIOSH Lifting Index (LI) will be carried out and integrated with our method called "Equivalent Weight (EqW)" (Di Natali et al., 2021). This will evaluate the benefit produced when using a generic BSE that provides an assistive force orthogonal to the scapular plane. To achieve this, we will show how to combine specific calculation tables that implement the guidelines of UNI ISO 11228-1:2022 (Fox, 2019) and our concept of EqW (Di Natali et al., 2021). A twofold methodology of onsite tests with contextual measurements, and lab testing collecting kinematics and muscular activation is presented. In addition, a demonstration of how the EqW method can be practically used in a real-world context is presented. Finally, the results obtained by workers when performing a typical task (electric line renewal), while wearing the StreamEXO are presented and analyzed. This study focuses on validating the EqW-based methodology in a case study centered on a non-repetitive task.

2. Materials and methods

2.1. StreamEXO

The StreamEXO exoskeleton (ADVR-IIT) has been designed to maximize safety, comfort, ergonomics, and acceptance for workers in general construction and particularly the railway sector, while carrying out renewal and maintenance operations. The StreamEXO features proprioceptive sensors, electric actuation, and a bioinspired controller to dynamically modulate the worker's physical assistance (Fig. 1). The exoskeleton's weight is 7.2 kg, and the workers wear and control it independently (without supervision by the investigators). Two electric actuators generate assistive forces on-demand, transmitting these to the shoulders and legs of the workers during MMH. The software combined with the sensors is able to understand the workers' intentions and can modulate the activity and assistance accordingly. There are three main control modalities: dynamic task assistance (Toxiri et al., 2018), static task assistance (Di Natali et al., 2024a), and transparent mode. This third mode that corresponds to a neutral gear modality, is engaged to ensure the worker experience no hindrance during walking or other activities that do not require lumbar assistance (Di Natali et al., 2020). The workers can perform typical operations while the exoskeleton applies specific forces synchronized with the musculoskeletal system (Sochopoulos et al., 2023). The final aim of the exoskeleton is to reduce the risk of accumulating overload in the lower back, in particular in the spinal segment L3-L4, while reducing the carried load.

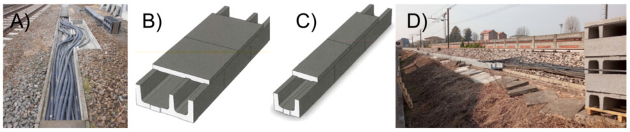

Fig. 2. A) Electric line renewal conducted along the railway. B-C) Two models of cable ducts are displayed. D) A typical setup scenario with pallet collecting all the conducts is shown.

This evaluation method is design dependent. Indeed, it is important to underline that this method is applicable only on exoskeletons that generate assistive forces applied normal to the wearer's spine, thus, devices that do not contribute to compression of the spine itself (Toxiri et al., 2015). This method may not be applicable to exoskeletons with different force application directions, such as (Goršič et al., 2021; Zhang et al., 2016). For exoskeletons that generate assistive forces parallel to the spine, the EqW method and the biomechanical model must be modified.

2.2. Task description

This experimental study aims to assess the exoskeleton's performance during a real workplace operation, i.e., the electric line renewal. This activity requires the laying down, within capped conduits, of optical fiber or copper cables for telecommunication, signaling, and supply systems. The installation of the conduits system to host the cablings consists of laying down heavy concrete conduits that form a containment trench running alongside the track (Fig. 2). Depending on the purpose, the ducts that are manually manipulated can weigh from 10 kg to 50 kg. The placement is performed individually for lighter parts and by a team of 2 workers for the heavier ones. Clamps weighing 7 kg are suggested for handling the heavier cable ducts, but often they are not used. Generally, the trench laying activity lasts several days. On average, a team of 3-4 workers can complete 100-200 meters daily. When the ducts and cables are installed, they are covered with concrete covers that weigh 10 kg to 30 kg. Workers must work in awkward positions during these activities, e.g. with back and knee bending. This can cause back, shoulder, and neck pain. A typical working routine involves (1) Walking; (2) Carrying heavy loads; (3) Transporting loads, (4) Positioning loads; (5) Maintaining awkward postures; and (6) Use of often heavy tools such as hammers, blades and rakes to settle the ducts and prepare the trench for an even placement. Within this work schedule, we identified two main distinctive tasks: "Gross positioning" and "Fine positioning". The "Gross positioning" sub-task involves lifting, transporting, and laying down concrete cable ducts. For the "Fine positioning," the sub-task consists of precisely manipulating each conduit a few centimeters above the ground to align the ducts and settle them in the trench.

Due to the high complexity and variability of the tasks, the typical working day is analyzed to select all those tasks that primarily generated a high load on the workers' backs. Since assessing and quantifying the advantages of an exoskeleton when performing these tasks in a real work scenario is extremely problematic, it is also important to supplement these tests with laboratory evaluation (De Bock et al., 2020). To achieve this, we designed a combined test that evaluates the exoskeleton performances in both Laboratory and onsite.

2.3. EqW method

This work extends and tests in the field, the experimental hypothesis around the concept of "Equivalent Weight" (Di Natali et al., 2021), which suggests that the assistance provided by an exoskeleton reduces the load experienced by the muscles in the lower back. The concept of

EqW correlates with the apparent (user perceived) reduction of effort needed to perform a task when assisted by an exoskeleton. This correlation is used in biomechanical equations to explore such load reduction with a coefficient σ usable in ergonomic assessment.

Di Natali et al. (2021) introduced this analytical method in two approaches to quantify the ergonomic benefit: an analytical technique based on a Bio-mechanical model, and a second method based on the muscle activity data interpolation. The method used in this work uses the second of these techniques relying on the data interpolation of the ES muscle measurements (evaluated during the lab testing) to quantify the benefit of the exoskeleton in terms of perceived load reduction. The results are then used to evaluate the ergonomic risk reduction of a specific task. The data interpolation method presented in Di Natali et al. (2021) is based on recording the overall trunk extensor muscles activities, with and without the exoskeleton, and subsequently computing the selected activity index (90^th percentile).

Each task is characterized by a maximum muscle activity generated without the use of the exoskeleton. The maximum activity is evaluated at the 90^th percentile to prevent the possible selection of spikes arising from signal errors. The muscle activity is reported as a normalized EMG value, with respect to the MVC. These values are associated with the max load being lifted. This procedure is repeated for each test subject to establish a statistical value for the population, and also to ensure that the same experimental conditions were replicated for the workers when using the exoskeleton. The resulting discrete values can be interpolated with linear functions, to obtain two equations that relate the muscle activity to the weight lifted:

$$g(x_L) = EMG^{noe} = a_{noe}x_L + b_{noe} \tag{1}$$

$$f(x_L) = EMG^{exo} = a_{exo}x_L + b_{exo} \tag{2}$$

where a_{noe} is the first-order coefficient of the without exoskeleton condition (the index "exo" is used for the modality with the exoskeleton), b_{noe} is the intercept for the same test condition. x_L is the independent variable of the function, which corresponds to the weight lifted. To derive the EqW as a function of both trends, i.e., the muscular activation in the normal condition and the muscular activation while using the exoskeleton, we apply the inverse of a composite function. The composite function is $g^{-1}(f(x_L))$. The inverse of the function $g(x_L)$ returns the lifted load, taking as its input function the normalized muscular activity:

$$g^{-1}(EMG^{noe}) = (EMG^{noe} - b_{noe})/a_{noe} = x_L \tag{3}$$

The function returns the corresponding rated value of the lifted weight which corresponds with the specific muscular activity. Thus, the EqW can be calculated by feeding the equation g^{-1} with the rated value of muscular activity while wearing the exoskeleton:

$$\begin{aligned} g^{-1}(EMG^{exo}) &= (EMG^{exo} - b_{noe})/a_{noe} = \\ &a_{exo}/a_{noe} + (b_{exo} - b_{noe})/a_{noe} = x_L^* \end{aligned} \tag{4}$$

Where x_L^* is the perceived load thanks to the assistance provided by the exoskeleton as determined by the EqW method. This function has a null intercept to retain its physical meaning, thus b_{exo} and b_{noe} are similar. Therefore, the equivalence can be simplified as follows:

$$x_L^* = \sigma x_L = a_{exo}/a_{noe}x_L \tag{5}$$

2.4. Experimental protocol

This study aimed to assess the performance of the StreamEXO in a railway sector (Di Natali et al., 2023) test scenario that extended over several sessions over several days (Di Natali et al., 2024b). The experimental protocol had two aspects: combining tests in both a real environment and laboratory setting. The dual assessment approach is driven by the form of the investigation, the nature of the data, and the goals of the experimental campaign. When using a BSE, with the EqW method, the ergonomic assessment for an MMH task requires and combines observational and quantitative measurements.

The onsite experimental testing aims to evaluate the workers' performance in their real working environment. This test was conducted mainly to assess the presence of common behaviors between workers, postural trends, and how, for each individual subject, the exoskeleton impacts the geometry of the movement. Safety requirements mean that access to a rail worksite is limited to a maximum of 4-6 workers in any work area. This creates an important constraint on the data collection as there is a limit to the extent of external interaction with the worker and observational measurements form the primary assessment modality

In contrast, the controlled environment offered by the laboratory setting enables accurate, repeatable and verifiable data gathering, where the equipment can be screened from external impacts or interference. Further benefits of the lab testing include: expanding the test population, simplifying the task routine, and subsequent full statistical analysis.

The observational measurements, which form the basis of the ergonomic assessment, require the completion of a calculation table, following the guidelines in UNI ISO 11228-1:2022 (Fox, 2019). This process identifies the main movements (sub-tasks) that contribute to the ergonomic risk. This ergonomic assessment was repeated twice for each test modality (NOE and EXO). Note that NOE is the baseline configuration for normal working without the exoskeleton, and EXO is when the worker wears the exoskeleton to perform target tasks.

The main sub-tasks are analyzed in the laboratory to determine the associated muscle activity. This lab testing quantifies the muscular activity as primitive movements. The EqW formulation is applied to this data to identify the reduction provided by the BSE.

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, after a full explanation of the experimental procedure. The study did not have any exclusion criteria since the workers were all fir and able to accomplish the heavy tasks that form this assessment. Concerning gender balance, this sector (rail) has limited gender balance because of the heavy nature of these tasks (European Railway et al., 2010). Hence it is unusual to find a female in these teams.

2.4.1. On-site simulation

Testing was conducted in a relevant work-like environment. This allowed assessment of the workers approach to their daily activities when wearing the exoskeleton. It also provided a first observation of the influence of various environmental parameters (temperature, humidity, different weather conditions) on the human-exoskeleton system. The index that this work evaluates is the variation and possible reduction of ergonomic risk. The assessment is based on a comparison of the workers performance in two states: with and without the use of the exoskeleton (EXO and NOE) respectively. The activity requires that the worker carries out normal work activities for 90 minutes without the use of the exoskeleton (NOE modality). At the end of this test period there is thirty minutes rest. Subsequently, the worker dons the exoskeleton and completes the same activity for another 90 minutes (EXO modality). Five workers (height 175.4±4.5 cm, weight 86.6±17.1 kg, age 49.8±4.4 years, 80% of workers > 45y) were tested three times over three different days. The order of the tests modality (with or without exoskeleton) is chosen at the beginning of the experiment and every time alternated in accordance with the analysis objectives and availability of the tester.

The in-field evaluation of an electric line renewal was performed in an rail worksite operated by Trenitalia. The system integrator company (MerMec STE) hosted the evaluation team at a dedicated space close to Asti train station (Italy).

The experimental protocol in Fig. 3.A, is designed to test the two main activities "Gross" and "Fine" positioning of the cable duct as this is the most relevant task from an ergonomic risk prospective. During

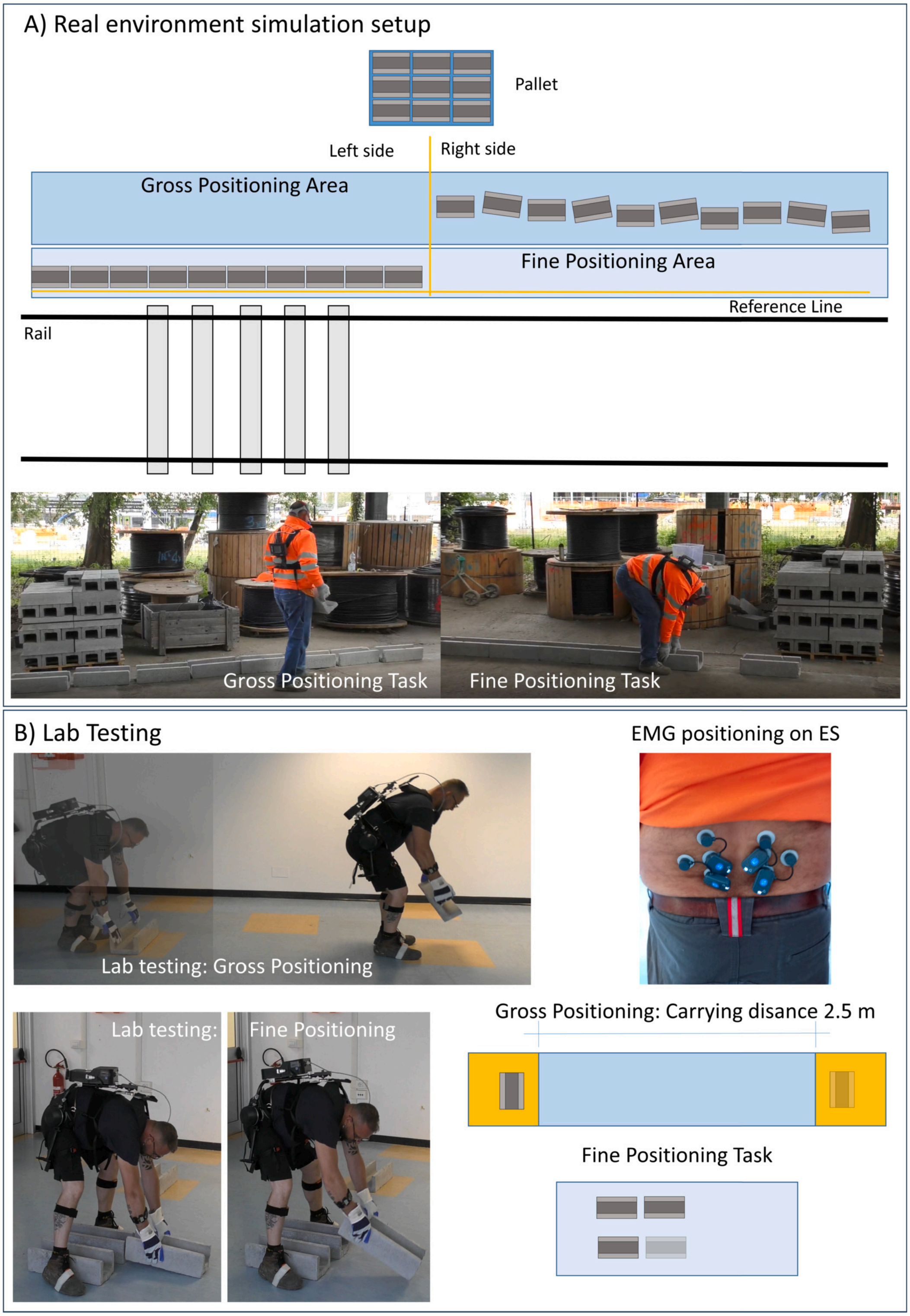

Fig. 3. A) Schematic representation of the real environment simulation and pictures of workers performing "gross" and "fine" positioning. B) Lab test setup with workers performing fine and gross positioning, EMG positioning on the workers ESs and schematic representation of both tasks.

the test, the worker was required to pick and carry a cable duct from the top of a pallet, and then to deploy it near the starting point of the duct placement line (shown in Fig. 3.A as the reference line). The positioning of the ducts during "gross" positioning was at about 50-60 cm from the reference line. The workers repeated this "Gross" positioning of the cable ducts ten times to create a line approx. 5 m long. Then the "Fine" positioning phase starts. Each worker positions themselves with their legs spread apart and their back bent forward. They then place all ten cable ducts in a precise manner along the reference line (shown in Fig. 3.A). Once the worker completes both phases, he repeats the test with "Gross" positioning of the same ten cable ducts. Therefore, the worker lifts the first cable duct closer to the vertical line (between the right and left part of the testing scenario) and moves it 1 m to cross the vertical line. Then, the worker lifts the second duct for 2 meters lowering it close to the first cable duct. This is repeated ten times until all the ducts are moved from the right side to the left side of the test area. The last cable duct is carried a distance of 10 m. Then the cable duct "Fine" positioning phase is repeated on the left side of the testing area. Each cycle of the test that includes both "Gross" and "Fine" positioning is repeated for 90 min for each modality (NOE and EXO) at the worker's natural speed:

- Gross positioning: Lifting, transport and "Gross" placement of 10 concrete cable ducts of 20 kg carried for an average distance of 5 m.
- "Fine" positioning: lifting, lowering and settling in a precise position of the same 10 blocks (20 kg).

During the final cycles of the task execution (the last 15 minutes of the test), the ergonomic risk was assessed using observational techniques (NIOSH Fox (2019)).

2.4.2. *Lab testing*

The in-the-field evaluation was then conducted in a controlled environment where the movements performed by workers and their associated muscle activities can be analyzed in detail during the cable ducts' "gross" and "fine" positioning. Ten experienced rail workers (height 177±7 cm, weight 84±14, age 45.4±9.1 years, 50.0% of workers > 45y) were engaged for the lab test. The workers performed 10 repetitions of the "gross positioning" subtasks (i.e. lifting, transportation, and lowering) and 10 repetitions of the "fine positioning" subtasks (bending, duct settling, and standing). Motion capture of the working task, synchronized with the specific measurement of the muscle activations, was recorded. As before the workers repeated each task 10 times for each testing modality (NOE and EXO).

The "gross positioning" was reproduced in the lab in a format that is easily cyclically reproducible, as shown in Fig. 3.B. It consisted of lifting a cable duct from the ground level and carrying it with two hands for approx. 2 meters before lowering it to the ground (Fig. 3.B). The task was repeated ten times. The "fine" positioning of the cable duct is shown in Fig. 3.B. During this phase the worker positions themselves with their legs spread apart and their back bent as shown in Fig. 3.B. The workers lift the cable duct a few centimeters, moving it from the area close to the left leg to the right leg and then vice versa. Finally, the worker stays bent over about 8 seconds before standing up. This permitted evaluation of the effect of the static posture with and without handling a load. This motion is repeated ten times, and for each repetition the cable duct is positioned close to the left leg or to the right alternately. The objective is to repeat the typical motion that the worker performs while placing the cable ducts in a precise manner along the reference line.

Before the start of the test, each subject underwent theoretical and practical training to learn the experimental procedure, including how to use the exoskeleton and become familiar with the device. In the setup phase, the motion tracking relies on measurements from an inertial-based wearable system, and the muscular activation was measured using a wireless surface electromyography multiple channel system. The Xsens wearable motion tracking system was used to record full-body kinematics (MTw Awinda 3D Wireless Motion Tracker, Xsens Technologies B.V. Enschede, the Netherlands) at a sampling rate of 100 Hz. An 8-channel Wi-Fi transmission surface electromyography (FreeEMG 300 System, BTS, Milan, Italy) was used to acquire the surface myoelectric signals (sEMG) at a sampling rate of 1000 Hz. After skin preparation, bipolar Ag/AgCl surface electrodes (diameter 2 cm) prepared with electroconductive gel were placed over the muscle belly in the direction of the muscle fibers (2 cm between the center of the electrodes) according to the European recommendation for surface electromyography (Hermens et al., 2000) and the atlas of muscle innervation zones (Barbero et al., 2012). The electrodes were bilaterally placed, as shown in Fig. 3.B, on two trunk extensors. After the electrode placements, subjects performed (three times) a series of specific exercises to record the isometric maximum voluntary contractions (MVC) for each of the investigated muscles (Merletti et al., 2009; Vera-Garcia et al., 2010). These exercises followed SENIAM recommendations (Hermens et al., 2000). The recommended Xsens calibration procedure was followed before the start of the recording of the motion tracking.

The ES 90^{th} percentile of the signal distribution was computed by averaging the right and left side activation levels of the Erector Spinae Longissimus (ESL) and the Erector Spinae Iliocostalis (ESI). These signals are, firstly, band-pass filtered (35–350 Hz), smoothed, rectified, and subsequently normalized with respect to MVC values. For each of the test modalities (NOE and EXO) we applied a paired-sample t-test to all normally distributed. The post-hoc test was used to evaluate the significance of the different test modalities for the selected metrics (p-value < 0.05). Matlab 2021b (The Mathworks, Natick, MA) software was used to perform the statistical analysis and data processing.

3. Results

This section presents the ergonomic evaluation conducted onsite and the results of the muscle activity analysis collected in the laboratory. Then, the observational and quantitative studies are combined to evaluate the overall ergonomic risk reduction based on the EqW method as assessed for the target task.

3.1. *Ergonomic evaluation*

Ergonomic evaluation of a task conducted by a worker while wearing an exoskeleton combines results collected during the relevant environment simulation (Section 2.4.1) and the lab testing (Section 2.4.2). The measurements apply observational techniques and specific calculation tables that implement the NIOSH method for the Mono Task, Composite Task, Variable Task and the Sequential Task:

- Mono Task: This modality involves lifting only one type of object (with the same weight), using the same body posture (body geometry) between the origin and the destination. The "Lifting Index" (LI) is derived in this case.
- Composite Task: This modality involves lifting objects of one type but on different geometries (taking or placing from/on shelves at different vertical heights and/or horizontal distances). The "Composite Lifting Index (CLI)" is derived in this case.
- Variable Task: This modality involves lifting or lowering many objects with different weights at different heights and/or depths. The "Variable Lifting Index" (VLI) is derived in this case.
- Sequential Task: with this modality, the daily shift of the work, is characterized. Each different task (each lasting at least 1 hour continuously) is analyzed by considering the specific characteristics of the task (MONO, COMPOSITE, VARIABLE). The "Sequential Lifting Index" (SLI) is obtained in this case.

Table 1

NIOSH risk classification. (*) To be used in conjunction with the general considerations outlined in the table, the ergonomic principles and approaches that should be used in all workplaces. For any level of Risk it is required to: (i) Identify all workers who may have special needs or vulnerabilities in lifting tasks and assign or plan the work accordingly; (ii) Train workers to recognize and eliminate the risk of handling materials; (iii) Limit the weights to be lifted, even if lower than the reference mass.

LIFTING INDEX (LI) Value	Exposure level	Recommended actions (*)
$LI \leq 1$	VERY LOW	None in general for the healthy working population.
$1 < LI \leq 1,5$	LOW	Pay particular attention to low frequency / high load conditions and extreme or static postures. Include all task or location redesign factors and redesign tasks or work stations and consider efforts to lower the $LI < 1$ values.
$1,5 < LI \leq 2$	MODERATE	Redesign tasks and workstations based on priorities to reduce the LI, and then analyze the results to confirm effectiveness.
$2 < LI \leq 3$	HIGH	The high priority Change the tasks to reduce the LI (high priority)
$LI > 3$	VERY HIGH	Change the tasks to reduce the LI (immediately)

Table 2

Cumulative masses lifted and transported: Recommended limits for cumulative mass for manual transport.

Transportation distance (for each task)	Kg for min.	Kg for 1 h	Kg for 2 h	Kg for 3 h	Kg for 4 h	Kg for 5 h	Kg for 6 h
$> 1mand < 2m$	75	2500	3400	4200	5000	5600	6000
$> 5mand < 10m$	-	-	-	-	-	-	3600
$> 10mand < 20m$	-	-	-	-	-	-	1200

Table 3

LI and transportation Index calculated for the NOE modality for the four classified working scenarios for the “gross” positioning task (A) Ideal, (B) “expert worker”, (C) “tired worker” and (D) the “fine” positioning task.

	Male	Index LI	Cumulative Mass (lifted and transported) [kg]	Cumulative Mass (only transported) [kg]	Transp. Index
A) Ideal scenario	20-45y	1.47 LOW	5850	2925	2.44
	$> 45y$	1.84 MODERATE	5850	2925	2.44
B) Expert worker	20-45y	2.45 HIGH	5850	2925	4.06
	$> 45y$	3.06 VERY HIGH	5850	2925	4.06
C) Tired worker	20-45y	3.02 HIGH	8775	2925	4.06
	$> 45y$	3.77 VERY HIGH	8775	2925	4.06
D) Fine positioning	$20 - 45y$	1.32 LOW	2275	0	-
	$> 45y$	1.65 MODERATE	2275	0	-

The adopted risk classification identifies the following areas of exposure level (Table 1):

The limits for the cumulative masses lifted and transported are always indicated by the technical standard ISO 11228-1 as shown in Table 2. The limit for the cumulative mass transported in a work shift is 6,000 Kg. The standard also indicates that when movements are in “Not Optimal” geometries, the value must be decreased by inserting a coefficient.

The evaluation of the ergonomic risk associated with both working tasks (i.e. “Gross” positioning and “Fine” positioning) have been carried out. The simulated real-world working cycle is designed to repeat the following two main working steps for 90 minutes at the workers’ natural speed; completing lifting, transport and placement of 10 concrete cable ducts of 20 kg carried an average of 5 m (“gross” positioning task), and lifting, lowering and settling in a precise position of 10 blocks (“fine” positioning).

Based on this, evaluations can be made for the “Gross” positioning and “Fine” positioning actions. From observational measurements three conditions were analyzed for the “gross” positioning (**A**, **B** and **C**) when not wearing the exoskeleton (NOE). These were identified as: The ideal postural condition (category **A**) requires that all the sub-tasks for the “gross” positioning (lifting, carrying and lowering) performed using two limbs. Fig. 4 and Fig. 5 show the characteristic movements of the other two categories of workers respectively, which are classified as “real scenario expert worker” (B) and “real scenario tired worker” (C). Case 2A reports and details the “Fine” positioning (D). Table 3 reports the results of the ergonomic evaluation on the task “gross” positioning for the three postural conditions and for the “fine” positioning task which all the workers are performing with no substantial postural changes between the ideal case and the real situation.

The measurements for all the NIOSH multipliers and the corresponding coefficients for the NOE and the EXO conditions for each of the two main tasks are reported in Table 4. The main observed changes in the NIOSH coefficients between the expert and the tired workers (we have classified workers as expert and tired based on the quality of their movements) wearing and not wearing the exoskeleton consist of the lifting action performed with a single or two hands and the frequency. In particular, we considered a higher frequency for the tired worker performing multiple semi-lifts before starting the transportation (about one more every two lifting). Such behavior is no longer present when the exoskeleton is worn and extra forces are available to the worker.

3.2. *Muscular activity results*

The tests performed in the laboratory on 10 workers each performing 10 repetitions of each sub-task are presented in Section 2.4.2. This shows the methodology to extract the data needed to derive the EqW coefficients that are used in the ergonomic analysis in Section 2.3. This

Fig. 4. Real scenario with an expert worker carrying out the sequence of sub-tasks analyzed.

test modality evaluates the reduction in the ES muscle activation during the sub-tasks (lifting/lowering and carrying) of the "gross" positioning, for both modalities (NOE and EXO). A similar approach is taken for the "fine" positioning task.

For the muscle analysis, the 90^{th} percentile was selected, as it gives relevant information on the peak loads, with a probability level $p = 0.9$. Fig. 6 shows the muscle activation comparing both the experimental modalities (NOE and EXO), for each of the sub-tasks. The 90^{th} percentile of the muscle activity was measured for three main sub-tasks as shown in Fig. 6. This shows the statistical significance of the data gathered wearing the exoskeleton using an (*). Significance was found for lifting & lowering, carrying, and "fine" positioning, with P-value of 0.0028, 0.0042, 0.000034 respectively. The results were averaged over the ten repetitions of each tasks for each subject. This gave the following mean muscle activities and standard deviations: lifting/lowering activities: 50.01 ± 13.43 for the NOE and 37.29 ± 9.39 for the EXO, carrying activities: 45.84 ± 8.95 for the NOE and 35.96 ± 10.57 for the EXO, and "fine" positioning activity: 38.60 ± 16.62 for the NOE and 27.85 ± 10.89 for the EXO.

Fig. 5. Real scenario with an older, tired or less experienced worker when completing the sequence of sub-tasks.

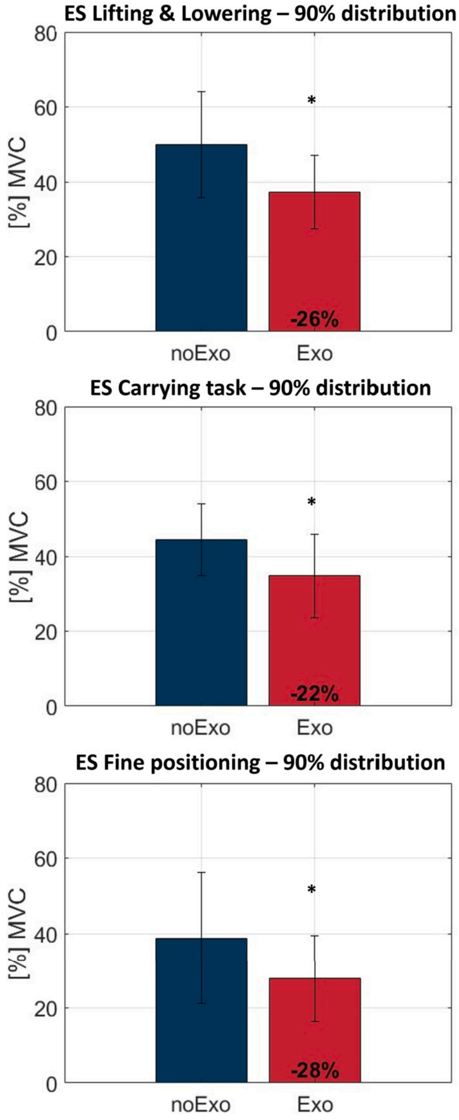

Fig. 6. Muscle activation of baseline (blue) and exoskeleton modality (red) during (top) lifting and lowering task, (center) carrying task and (bottom) "fine" positioning task. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

The interpolation method introduced in the EqW concept and also reported in Section 2.3, shows that the reduction in ES muscle activity is associated with an EqW coefficient σ that determines the "perceived" reduction in the weight of the supported load. Table 5 reports for each sub-task the measured values of muscle activation for both modalities (NOE and EXO), and the subsequently derived EqW coefficients (σ). Thanks to the assistance provided by the exoskeleton, the activation of the back muscles is reduced. This can be related to an apparent reduction in the load that the weight exerts on the vertebral column.

3.3. Ergonomic analysis and EqW combined results

To fully assess the ergonomic risk, the observational evaluation and the experimental theory are combined in the "Equivalent Weight" concept (Di Natali et al., 2021), with the EqW assigning an ergonomic risk based on the derived reduction in the ES muscles activation. The concept of EqW correlates the apparent reduced effort needed when assisted by the exoskeleton with the reduction of the load weight held by the exoskeleton wearer.

Fig. 7. Real scenario with a worker wearing the StreamEXO that carry out the sequence of sub-tasks analyzed.

The ergonomic risks for the workers performing both the "Gross" positioning and "Fine" positioning were assessed. Standard methodologies, as mentioned in Section 3.1, were applied on the onsite in-field simulation with the exoskeleton modality.

Fig. 7 shows the movements of the workers wearing the StreamEXO when performing the sub-tasks. For the three "gross" positioning (A, B and C) cases, the postural geometry observed across all the workers when wearing the exoskeleton was not dissimilar to those in 3.1.

Table 4
NIOSH multipliers and coefficients for each sub-task and condition for a worker <45y.

Multipliers	“Gross” B NOE	“Gross” B EXO	“Gross” C NOE	“Gross” C EXO	“Fine” NOE	“Fine” EXO
Hands ground height at the beginning of the lift	0.84	0.84	0.84	0.84	0.84	0.84
Vertical distance covered from the start and end of the lifting	0.9	0.9	0.9	0.9	0.9	0.9
Distance of the weight from the body	1.0	1.0	1.0	1.0	1.0	1.0
trunk torsion	0.95	0.95	0.95	0.95	0.95	0.95
Type of grasp	0.9	0.9	0.9	0.9	0.9	0.9
Frequency	0.8	0.8	0.65	0.8	0.89	0.89
Two limbs	0.6	1.0	0.6	1.0	1.0	1.0
Recommended weight limit (RWL)	7.76	12.93	6.3	12.93	14.38	14.38

Table 5
Muscle activity and EqW coefficients for each sub-task.

Sub-task	NOE [%MVC]	EXO [%MVC]	ES reduction [%]	EqW σ [%]
Lifting/Lowering	50	37	26	74
Carrying	46	36	22	78
“Fine” positioning	39	28	28	72

Suggesting the wearing of the exoskeleton does not impacts the natural work process/movements. In addition the workers’ movements when wearing the exoskeleton can be referenced to the ideal condition and classified as A_X. For the “fine” positioning sub-task, the movements are conducted with no substantial postural changes as in the NOE condition and in the EXO condition, thus the results are reported in Table 6 at the D_X line.

In conclusion, Table 7 shows the results of the ergonomic assessment conducted with the combined methodology presented in this work. The results are presented for the sub-tasks: “gross”, carrying, and “fine” positioning, and considering the real scenario observed for the B and C modalities of motion conduction for the “gross” positioning task due to awkward postures.

4. Discussions

This pilot test, conducted onsite using real work tasks aims to provide a tool for the ergonomic assessment of MMH tasks conducted with the support of an exoskeleton. It is essential to underline that these results are related to the specific tasks analyzed and the specific exoskeleton model (StreamEXO). From the results, and particularly for the NOE condition, it was evident to see that workers used to approach tasks not always in an ideal condition but incongruous postures or movements could be performed as shown in Fig. 5, where an “expert worker” style prefers to lift the load with a single hand, or a “tired worker” style prefer to conduct two consecutive semi-lifting before standing up and start the transportation. These two not ideal behaviors have been observed to be the most probable ones even if the workers participated singularly in the experiment to avoid possible conditioning between colleagues. These behaviors exacerbate the ergonomic condition of the tasks, particularly the “gross” positioning as shown in Table 3 for the **B** and **C** conditions, when compared to the ideal scenario **A**. Thus allowing the exoskeleton also perform the function of an orthosis. Moreover, the inappropriate behaviors are not manifest in the EXO condition, where workers cannot lift and carry out the load with a single hand due to the lateral volume of the motor on the worker’s sides. In addition, thanks to the extra force and reduction of effort required to complete these tasks (Di Natali et al., 2024b), workers were able to lift the load in a single action without the need to accomplish two semi-lifting as in the “tired worker” condition. Because of such consideration, it has been observed that the workers could accomplish the task thanks to the exoskeleton, performing the movements in an ideal manner.

In conclusion, when applying the σ coefficient to the weight of the load handled (i.e. 20 kg of the block is considered 14 kg for the lifting task, where $\sigma = 0.74$) and processing it in the LI equation, the evaluation of the risk reduces significantly. In particular, it is evident that the reduction in the “gross” positioning is reduced in averaged between **B** and **C** scenarios of about 59.7% when compared with the A_X scenario. The carrying task, which is the same for all the scenarios, is reduced by 54%. These two sub-tasks are improved of at least two classes of exposure level of risk, modifying the condition from “very high” to “moderate” or from “high” to “low”. Concerning the sub-task “fine” positioning, the evaluated risk is reduced by 28% because of the benefit introduced only by the exoskeleton and highlighted by the EqW coefficient, but also, in this case, the exposure level drops one level down from “low” to “very low” or from “moderate” to “low”.

It is worth underlining that the exoskeleton is worn by an expert worker in scenario B and a tired worker in scenario C. However, in both instances the worker’s behavior and the geometry of the task execution are the same as for the idea case (A scenario). This means that even if a tired worker is performing multiple intermediate liftings and is using only a single limb, when they use the exoskeleton, this “wrong” behavioral motion is eliminated thanks to the extra forces that allow the user to accomplish a single movement. This is also coupled to spatial constraining of the side of the worker preventing this undesirable single limb lifting. As a result a tired worker is subjected to the same risk as an expert worker. This could be a valuable training tool.

Finally, this work shows how to implement the EqW method to estimate the benefit that the use of a back support exoskeleton can introduce in a work task. Although this work did not initially aim to formally prove the method’s validity through ergonomic risk analysis, we were able to investigate the usability and impact that such a tool can introduce for the specific case study. Therefore, although this work is not conclusive and exhaustive with respect to assessing exoskeletons within the NIOSH process, it has shown some valuable insights, but much further investigation will be required.

5. Conclusions

This work presents the practical application of the EqW method for assessing the ergonomic risk in MMH when using a back support exoskeleton. The results are assessed by combining on-site observational measurements, conducted in tests with five different workers, and quantitative measures of muscle activity reduction recorded during laboratory evaluation with ten workers. These results show that the StreamEXO can reduce exposure risk by up to two levels (from “high” to “low”) in targeted sub-tasks involving lifting, lowering and carrying a 20 kg load. The reduction in LI for these tasks was between 54% and 64%. These results combined the benefit directly generated in the muscle activity and improved task execution, which enabled such a high-risk reduction. For the “fine” positioning, no significant changes in the motion pattern were noted. Thus, the reduction in the ergonomic risk is only due to the benefit introduced by the exoskeleton and quantified by the EqW, which underlines a 28% reduction in the ergonomic risk. Thanks to the use of the exoskeleton, in this task, at least a level of exposure risk was reduced.

This work underlines the importance of conducting OE assessments in two separate phases; the onsite phase is essential to observe how the worker approaches the task and to form a comparative basis ensuring that there is zero/minimal posture modification resulting from the use

Table 6
LI and transportation Index calculated on the EXO modality for the “gross” positioning task (A_X) and the “fine” positioning task (D_X).

	Male	Index LI	Cumulative Mass (lifted and transported) [kg]	Cumulative Mass (only transported) [kg]	Transp. Index
A_X) EXO **“gross”**	$20-45y$	1.09 LOW	5850	2925	1.9
	$>45y$	1.36 MODERATE	5850	2925	1.9
D_X) EXO **“fine”**	$20-45y$	0.95 VERY LOW	2275	0	-
	$>45y$	1.15 LOW	2275	0	-

Table 7
Combination of observation and the EqW method to evaluate the ergonomic risk for MMH tasks wearing the StreamEXO.

Sub-task	Initial condition (LI or Transp. I)	Final condition (LI or Transp. I)	Reduction [%]
“Gross” B	2.45 ($<45y$); 3.06 ($>45y$)	1.09 ($<45y$); 1.36 ($>45y$)	55.5
“Gross” C	3.02 ($<45y$); 3.77 ($>45y$)	1.09 ($<45y$); 1.36 ($>45y$)	63.9
“Carrying” B or C	4.6	1.9	54
“Fine” positioning	1.32 ($<45y$); 1.65 ($>45y$)	0.95 ($<45y$); 1.15 ($>45y$)	28

of the exoskeleton. This phase can be conducted with minimal interaction and interference with the workers’ normal routine. The second phase in the laboratory allows for dedicated and focused data acquisition that aims to extract the key indexes, e.g., muscle activity reduction and EqW coefficients, etc. Then, these can be combined with the previously collected assessment information.

Clearly this study cannot cover all health and safety aspects of all work processes. Here the focus was around some specific rail sector case studies rather than on a comprehensive analysis and proof of the universal applicability of this method. Hence, although we have been able to show that several important NIOSH coefficients can be positively impacted (reduced risk) for these target tasks, the consistency of this method has yet to be proven across the whole parameters range. This will form a very substantial body of work for the future.

Even if it is still premature for the EqW method to be used on-site for the ergonomic risk assessment, we strongly encourage expert ergonomists to use the proposed method in combination with laboratories able to conduct motion capture and muscle activity analysis.

In future work, we would like to extend the pool of subjects to be tested for this method to verify the anthropocentric bio-mechanical model presented in Di Natali et al. (2021) and to determine if other indexes that evaluate the impact of the exoskeleton on muscle activity might form even better candidates. We believe this would allow possible generalization of the methodology. In addition, to assess the feasibility of using the EqW for the ergonomic risk assessment, it should be tested and verified against the NIOSH method for extreme postures or when approaching NIOSH evaluation boundaries.

Finally, a greater sample size and variability is always valuable in increasing the confidence and formal validation of any new method.

CRediT authorship contribution statement

Christian Di Natali: Conceptualization of this study, Methodology, Experimental campaign, data analysis, manuscript writing, supervision, project administration, and funding acquisition.

Giorgio Buratti: Writing contribution and revision.

Luca Dellera: Experimental campaign, data analysis, and writing contribution.

Darwin Caldwell: Writing revision and supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

An author (**Christian Di Natali**) is cofounder of a startup that aims to commercialize occupational exoskeletons.

The other coauthors have not conflict of interest.

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