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The SUPERHUMAN Project: Insights On An Ongoing Academic-Industry Alliance For Developing and Commercializing Passive Hip-Low Back Exoskeletons ⋆

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Abstract: Assistive robotics, especially passive exoskeletons, offer promising solutions for reducing musculoskeletal disorders (MSDs), particularly in the lower back—a key occupational health concern. The SUPERHUMAN project, uniting academic and industry partners, promotes the development and adoption of user-centered passive exoskeletons. This study presents early findings from the project, including feedback from partner companies and a pilot evaluation using NASA TLX to assess perceived workload. Results highlight the exoskeleton's ergonomic benefits and point to areas for improvement, such as weight and harness design, informing ongoing design refinements. More details are available at `https://superhuman-eitm.eu/`.

Keywords: Assistive robotics, wearable robotics, passive exoskeleton, musculoskeletal disorders, ergonomic evaluation, NASA TLX, industrial ergonomics.

1. INTRODUCTION

Assistive robotics holds significant promise in addressing the widespread challenge of musculoskeletal disorders (MSDs), including tendinopathies, tunnel syndromes, nerve compressions, and other conditions, which are among the most common and costly occupational illnesses. In the European Union (EU), MSDs are the most prevalent work-related health issue, with three in five workers reporting related complaints (European Agency for Safety and Health at Work, 2020). Annually, over 40 million EU workers suffer from work-related MSDs, which account for nearly 50% of absences exceeding three days and 60% of permanent work incapacity. Similarly, in the US, 30% of unwanted work absences are attributed to MSDs. The trunk is the body part most affected by work-related MSDs, accounting for 43% of cases in both the US and EU, often involving the spine and back. MSDs affecting the shoulders, neck, and upper limbs follow, comprising 36% and 41% of cases in the US and EU, respectively. Sociodemographic factors such as gender, age, and country of birth further influence MSD prevalence. Women face higher psychosocial risks due to workplace discrimination, impacting their physical and mental health. Age also plays a significant role: older workers are more likely to suffer from MSDs, while younger workers are exposed to greater physical risks. Migrant workers often take on high-risk jobs, including physically demanding roles, contributing to higher MSD incidences (Govaerts et al., 2021). The integration of assistive robotics, such as exoskeletons, offers an innovative approach to mitigate the physical strain associated with demanding occupational tasks.

Passive exoskeletons offer a promising solution for mitigating MSDs in industrial settings (De Looze et al., 2016; Madinei et al., 2020; Cardoso et al., 2021). These devices use passive mechanical systems like springs to redistribute loads, making them lightweight, cost-effective, and suitable for prolonged use (Roveda et al., 2022). Studies highlight their effectiveness in reducing lumbar strain during lifting tasks, although challenges such as discomfort and adaptability to complex movements remain (Ashta et al., 2023). Research underscores their utility in environments prioritizing cost-efficiency and ease of integration. The SUPERHUMAN project (SUPERHUMAN Project, 2025), a European initiative funded by EIT Manufacturing, exemplifies this focus by developing and commercializing passive exoskeletons optimized for diverse industrial applications (De Bock et al., 2018). It aims to reduce the prevalence of lumbar MSDs through user-centered designs, leveraging ergonomic analysis, rapid prototyping, and user feedback (Kermavnar et al., 2021). In this paper, a preliminary assessment to evaluate perceived comfort and ergonomics of a project's initial exoskeleton prototype is reported, with results guiding iterative improvements to align the design with industrial and user needs.

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2. THE SUPERHUMAN PROJECT

The project addresses these challenges by developing a low-back support exoskeleton prototype using kinematic analysis, finite element methods, and topological optimization. The device integrates two components: a back-support exoskeleton, developed by project's coordinator SUPSI [1], and a hip exoskeleton from project's partner GOGOA [2]. The back-support exoskeleton uses user-specific backbone-based kinematics for natural motion and passive elements to assist during lifting tasks. The hip exoskeleton incorporates gas cylinders as passive actuators to reduce lumbar stress while lifting loads up to 20 kg. Together, these systems will create a device optimized for lifting tasks requiring trunk inclination, common in agriculture, construction, and logistics. Inclusion and gender equality are central to the design, ensuring adaptability for diverse users. The exoskeleton enables women to perform traditionally male-dominated tasks, fostering workplace equity. Supported by EIC and EIT Manufacturing [3], the project is led by SUPSI in collaboration with the University of Bologna [4], ART-ER [5], CTAG [6], GOGOA, Bonfiglioli [7], and SONAE [8].

3. QUESTIONNAIRE ANALYSIS, PILOT EVALUATION AND RESULTS

3.1 The Survey: Understanding Company Perceptions And Expectations Regarding Exoskeleton Adoption

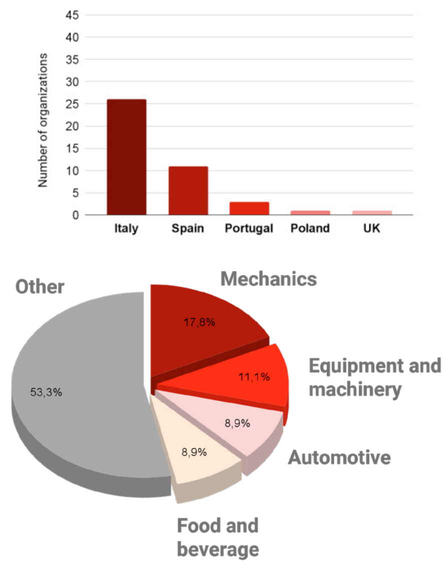
As part of the SUPERHUMAN project, a survey was conducted across a wide range of European companies to examine perceptions of passive exoskeleton adoption and to identify expected functionalities. Key industrial sectors were specifically targeted, including (i) mechanics, (ii) automotive, (iii) equipment and machinery, and (iv) food and beverage, to capture diverse requirements and preferences shaping exoskeleton adoption. The survey, distributed mostly via email, was designed as an online questionnaire targeting companies within the mentioned sectors. Fig. 1 illustrates an image that was part of the email invitation sent to all potential participants. The actual companies that responded to the invitation were a set of small, medium, and large enterprises, with near-equal distribution across these categories, including 17.8% in mechanics, 8.9% in automotive, 11.1% in equipment and machinery, and 8.9% in food and beverage (53.3% others industrial sectors), reflecting a wide spectrum of operational contexts. Importantly, 82.2% of respondents reported that their workers frequently handle loads exceeding 6 kg, highlighting how heavy lifting is very common, and the need for interventions based on exoskeleton technology to improve worker safety and productivity would be desirable.

Furthermore, the survey results revealed that the companies consider *ergonomic benefits* as a critical expectation from passive exoskeletons. Indeed, also looking at the results summarized in Fig. 2, weight optimization, freedom of movement, and reliability are reported as the most important features to be taken into account. Among the typology of assistive device, passive exoskeletons emerged as the preferred choice over active systems, because of their simplicity, cost-effectiveness, and ease of adoption for widespread industrial use. These insights provide a clear guidance for the development of exoskeleton system, which must be in the direction of ensuring a balance among functionality, practicality, and cost. Also, the emerged focus on lightweight and non-restrictive designs underscores the need for solutions that seamlessly integrate into existing workflows without hindering productivity.

Accordingly, the potential adoption of passive exoskeleton technology by companies resulted to be influenced by several factors, including perceived benefits and risks. The survey identified key barriers such as concerns over instability, potential fretting damage, and the risk of malfunction, which were among the most commonly cited fears by participants – see Fig. 3 – highlighting the need for careful engineering and thorough testing to ensure the product reliability level required for fostering real interest in from companies. Despite these concerns, 46.6% of respondents expressed willingness to adopt passive exoskeletons, indicating a significant level of interest and optimism. This means that addressing the identified risks through improved design and industry-specific customization can substantially enhance adoption rates.

Therefore, given the most relevant findings of the survey reported in this section, it is evident that the adoption of exoskeleton technology is seen as a valuable intervention to address ergonomic challenges, particularly in industries in-

(a)



(b)

Fig. 1. (a) Image included in the email for survey participation. (b) Companies actually involved in the survey (top: contries; bottom: industrial sectors).

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[3] www.eitdigital.eu
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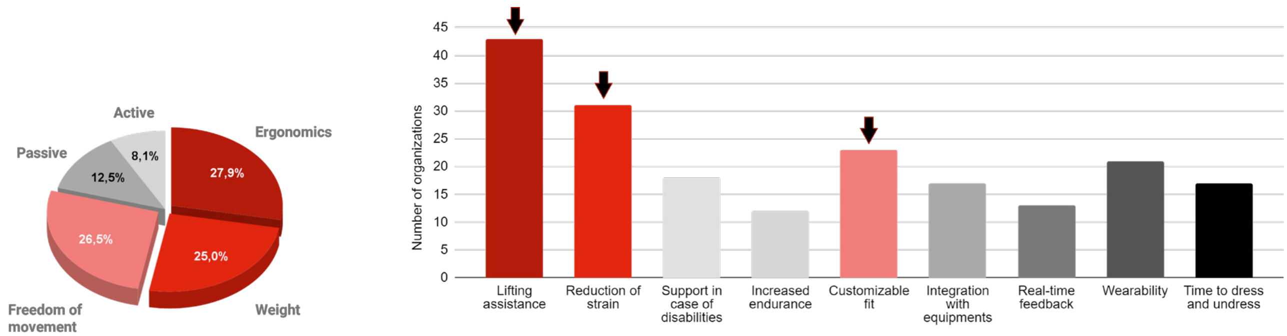

(a) (b)

Fig. 2. Survey results about expected (a) exoskeleton features and (b) functionalities. Arrows indicate the most important features reporeted in more than 50% of survey responses.

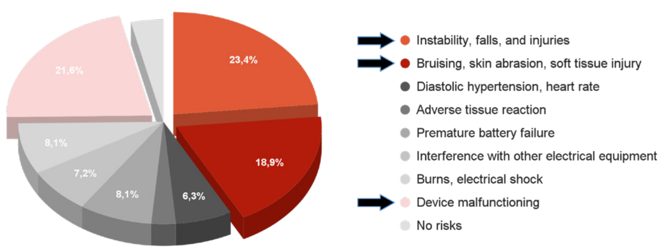

Fig. 3. Survey results on perceived risks of passive exoskeleton. Arrows indicates survey's resposnses provided by more than 50% of companies.

volving heavy lifting and repetitive tasks. A significant majority (88.8%) of companies acknowledged the importance of improving, in workplace, both safety and productivity by means of passive exoskeleton adoption. Now, having a look on the global trends in the exoskeleton market, we can observe that the data strongly supports these findings. The market has grown substantially, from $472.64 million in 2021 to $635 million in 2022, with a projected annual growth rate of 32% that could drive it beyond $2.5 billion by 2027 (Markets and Markets, 2023). This rapid growth is fueled by increasing recognition of musculoskeletal disorders, aging workforces, and a need to enhance workforce sustainability (Ashta et al., 2023), and passive exoskeleton technology represents a promising solution to address these current and future ergonomic challenges. By aligning with the global market trends and responding to industry expectations for reliability, affordability, and ease of use, the SUPERHUMAN project is well-positioned to make a meaningful impact. The integration of passive dorsal and hip-support exoskeletons not only meets these criteria but also contributes to advancing workplace safety and productivity in a rapidly evolving industrial landscape.

3.2 The Initial SUPERHUMAN Exoskeleton

The initial SUPERHUMAN exoskeleton is a passive back-support device designed to address the rising prevalence of lower back pain (LBP) in occupational settings by providing ergonomic support during lifting and other strenuous activities through a purely passive mechanical approach. This design choice reduces device cost and complexity while enhancing usability across various environments, making it suitable for real-world applications. The initial SUPERHUMAN exoskeleton (referred in the following as the *SH exoskeleton*) serves as the foundation for the SUPERHUMAN project, building upon previous work in user-centered back-support exoskeleton design and prototyping (Roveda et al., 2020, 2022; Pesenti et al., 2022).

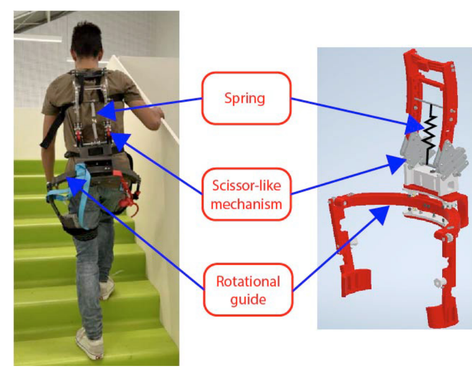

Fig. 4. The SH exoskeleton worn by a subject (left) and depicted in its CAD design (right) (Roveda et al., 2020, 2022; Pesenti et al., 2022).

The project focuses on refining and enhancing this design, with one targeted improvement being the lower part of the exoskeleton that attaches to the legs. This refinement will involve collaboration with partner companies to explore alternative attachment solutions for better lower-body integration. The immediate objective, however, is a preliminary evaluation of the SH exoskeleton to assess its ergonomic performance and identify areas for improvement. The design of the SH exoskeleton incorporated extensive biomechanical studies of the human spine, particularly its motion during lifting tasks. These studies highlighted the critical role of the T2 vertebra as a reference for creating a mechanism aligned with the spine's natural movement (Roveda et al., 2020). Real-world kinematic data, captured using a tailored vision system, informed the design of a scissor-like mechanism that mimics the body's dynamic motion (Roveda et al., 2022). The SH exoskeleton includes a spring-based mechanism that stores energy during spinal flexion and releases it during extension, reducing the physical effort needed to return to an upright position (Pesenti et al., 2022). Its operation is straightforward: during forward bending, the springs elongate to store elastic energy, which is then released during extension to assist the user. Adjustable harnesses and straps distribute weight evenly across the torso, hips, and shoulders, improving comfort and minimizing pressure points. A rotational guide at the hip allows for lateral and twisting movements. When not in use for lifting or bending, the exoskeleton remains in a zero-force configuration, exerting no pressure on the user. Fig. 4 shows the SH exoskeleton worn by one of the study participants during the experimental evaluation.

The next section presents the results of the pilot study's

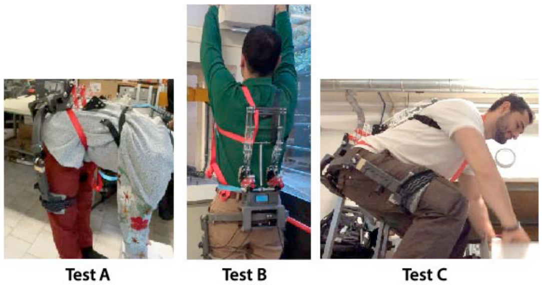

Fig. 5. Representative instants of the tasks in the experimental evaluation of the SH exoskeleton: Task A (load lifting task with back bending and straight legs); Task B (shelving a load on a elevated location); Task C (static squat configuration). See Sec. 3.3.

preliminary ergonomics tests, which aimed to gather user feedback and identify opportunities for improvement.

3.3 Pilot Ergonomics Evaluation

Experimental Protocol To evaluate the SH exoskeleton, the experimental protocol consisted of three tasks designed to replicate real-world applications. Participants were tasked with:

- **lifting and stacking boxes (Test A)**, a task performed both by bending their knees and using proper squat technique and by maintaining straight legs to assess stress levels under different conditions;
- **shelving activity (Test B)**, which involved lifting and placing packages at various heights, simulating a common industrial scenario;
- **maintaining a static squat hold (Test C)**, challenging their endurance while evaluating the exoskeleton's impact on load redistribution.

Fig. 5 depicts some representative instants of the three considered tasks. All tasks were conducted with participants wearing the exoskeleton, followed by subjective evaluations using the NASA TLX questionnaire (Hart and Staveland, 1988).

Group Of Subjects The experiment involved a total of 10 participants, with a balanced demographic profile to ensure a representative evaluation of the exoskeleton's performance. The participants, aged between 25 and 45 years, included six males and four females, all with varying levels of experience in physically demanding tasks. The average height of the participants was 1.72 m (range: 1.60–1.85 m), and their average body weight was 70 kg (range: 58–85 kg). All participants provided informed consent prior to their involvement in the study, ensuring they were fully aware of the experimental procedures, potential risks, and their right to withdraw at any time without penalty.

Results The analysis of the NASA TLX scores revealed insights into the perceived workload dimensions across the tasks performed with the SH exoskeleton.

Fig. 6 reports the NASA TLX scores obtained across all workload dimensions, averaged over the involved group of subjects. Starting with *mental demand* (see Fig. 6), participants consistently reported a moderate average value (< 4), suggesting that while the exoskeleton required some cognitive adjustment, particularly during tasks like shelving, the overall cognitive workload was manageable. On the other hand, *physical demand* emerged as a more critical factor, with scores notably higher during static and

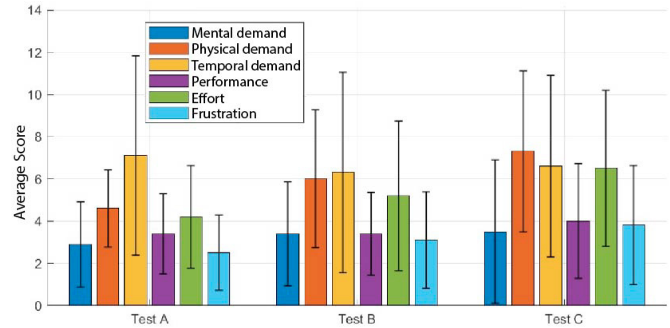

Fig. 6. NASA TLX's workload dimension factor scores, averaged over the subjects involved in the evaluation.

prolonged tasks such as the squat hold (Test C). Indeed, the exoskeleton effectively redistributed lower back strain but, however, the effort shifted to other muscle groups, particularly the lower limbs. This finding, essential for identifying ergonomic improvement areas, is observable in the data visualized in Fig. 6. *Temporal demand* showed less variation among tasks. Indeed, participants reported that the exoskeleton provided support, enabling more controlled actions and mitigating for some possible differences of urgency associated with the different tasks. *Performance* average ratings were positive overall (≤ 4), with participants expressing confidence in task execution while using the exoskeleton. *Effort* average ratings mirrored the trends in physical demand, with the squat hold task being identified as the most effort-intensive. In this regard, while the exoskeleton provided back strain relief, the need for better weight distribution and improved harness comfort became evident. Average *frustration* levels were generally low to moderate (< 4). Discomfort from straps and attachment points contributed to these ratings, although participants acknowledged the device's effectiveness in reducing physical strain for lifting tasks. The comprehensive view (also refer to visualization provided in Fig. 6) provided by these results reinforces the need for targeted design refinements.

Additionally, also a weighted analysis of the NASA TLX scores was carried out in order to provide a deeper insights. The total weighted mean score for each task (Test A, Test B, Test C), TLX_W, was calculated as:

$$TLX_W = \frac{\sum_i (R_i \cdot W_i)}{15} = \frac{\sum_i (TLX_i)}{15}, \quad (1)$$

where: R_i represents the raw scores for the six NASA TLX factors mental demand (R_M), physical demand (R_F), temporal demand (R_T), performance (P), effort (S), and frustration (F); W_i denotes the corresponding weights for each factor derived from the second section of the NASA TLX questionnaire; the denominator reports for the total sum of the weights. The weights, W_i, are obtained from a pairwise comparison process conducted during the second section of the NASA TLX questionnaire. Participants are presented with the 15 combinations of pairs of workload factors (e.g., mental demand vs. physical demand, etc.) and are asked to select the factor that contributes more significantly to their overall workload for each pair. For each factor, the weight corresponds to the number of times it is selected across these 15 comparisons. Thus, the weight for each factor ranges from 0 (if it is never selected) to 5 (if it is selected in every comparison involving

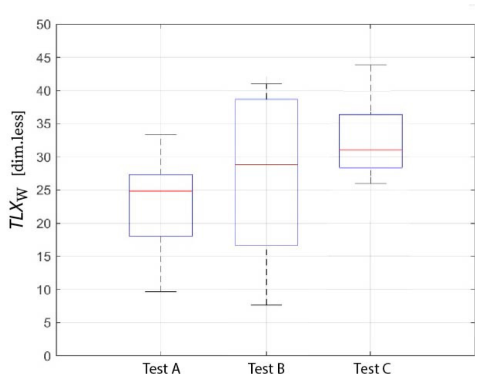

Fig. 7. Boxplot of the NASA TLX total weighted average scores for each experimental task.

that factor). By summing the weights for all factors, the total weight always equals 15. These weights reflect the relative importance of each factor to the participant's overall workload perception and are combined with the raw scores (R_i) to calculate the weighted TLX_W score for each task as in eq. (1). In relation to the NASA TLX weighted analysis, first of all, in Fig. 7, the boxplot of the total weighted average scores for each experimental task (Test A, Test B, and Test C) are reported. To evaluate whether the differences in TLX_W scores between the tasks were statistically significant, a one-way analysis of variance (ANOVA) was conducted. The results of the ANOVA indicated no statistically significant differences among the three tasks ($F(2, 27) = 1.56, p = 0.228$), suggesting that participants' perceived workloads across the tasks were comparable. While these findings do not establish statistical differences, they suggest that the exoskeleton may contribute to a normalization of effort among the different tasks, justifying further studies and improvement in this direction. This observation may be consistent with the exoskeleton's role in providing consistent ergonomic support, which could help balance the perceived workload across tasks with varying physical and cognitive demands. Furthermore, the Pearson correlation coefficient r was calculated to assess the linear relationship between pairs of weighted NASA TLX factors. The formula is given as:

$$r = \frac{\sum_{k=1}^{n}(x_k - \overline{x})(y_k - \overline{y})}{\sqrt{\sum_{k=1}^{n}(x_k - \overline{x})^2} \cdot \sqrt{\sum_{k=1}^{n}(y_k - \overline{y})^2}}, \qquad (2)$$

where x_k and y_k represent the weighted scores of two selected TLX workload factors (e.g., physical demand and effort) for participant k, and $\overline{x}$, $\overline{y}$ are the respective mean values of those factors across all n participants. The numerator reports the covariance between the two factors, while the denominator the product of the their standard deviations. This coefficient provides a measure of the strength and direction of the linear relationship between workload dimensions, with values ranging from -1 (strong negative correlation) to $+1$ (strong positive correlation). For instance, a strong positive r between physical demand and effort indicates that as one factor increases, the other tends to increase proportionally, offering valuable insights into the interplay between workload dimensions.

The analysis highlighted the following most relevant interdependencies. For the static squat task (Test C), there was a strong positive correlation ($r = 0.93$) between physical demand and effort, indicating that increased physical effort directly amplified perceived demand. A similarly high correlation was found between effort and frustration ($r = 0.7$), emphasizing how physical strain contributes to emotional discomfort. Conversely, the correlation between physical demand and temporal demand ($r = -0.4$) for shelving activities suggested that perceived time pressure decreased as physical effort increased, possibly due to the participants focusing more on the mechanical support offered by the exoskeleton. For shelving tasks (Test B), the analysis revealed moderate to strong correlations between physical demand, effort, and frustration, with values in the range from $r = 0.87$ to $r = 0.9$. These results suggest that as the physical and cognitive demands of repetitive tasks increase, user satisfaction tends to decrease, emphasizing the need for more adaptive design features that can alleviate both physical and psychological burdens. In lifting tasks, the correlation between mental demand and frustration was notably lower ($r = 0.3$), indicating that these tasks were less mentally intense but still required physical effort, which led to overall discomfort. The results suggest that refining even more the exoskeleton's alignment with natural movements can improve user experience by reducing mental effort and enhancing perceived performance. Additionally, subjective feedback further enriched these quantitative findings. Participants noted that discomfort from straps and attachment points amplified frustration during tasks requiring extensive mobility. Conversely, tasks that demanded stability, such as static squats, highlighted the exoskeleton's ability to redistribute load effectively, reducing back strain while increasing leg strain. Fig. 8 provides a color-coded full representations of the Pearson coefficients across the different tasks for the interplay of physical demand, effort, and frustration. These insights, derived from a detailed analysis of workload dimensions and interdependencies, offer valuable guidance for iterative improvements to the SUPERHUMAN exoskeleton, aiming to enhance both ergonomic functionality and user satisfaction in future iterations.

Table 1. Potential improvements for the SH exoskeleton.

Improvement Area	**Description**
Weight Distribution	Optimize load distribution to reduce strain on lower limbs during prolonged tasks.
Harness Comfort	Redesign straps to minimize discomfort and enhance mobility.
Adaptability and Fit	Enhance adjustability for diverse users, ensuring ergonomic alignment.
Material Optimization	Use lighter, durable materials to reduce weight and improve usability.

Finally, Table 1 summarizes the key areas for potential improvement identified during the pilot evaluation of the exoskeleton. These include optimizing weight distribution to reduce strain, enhancing harness comfort to minimize discomfort, improving adaptability to better fit diverse users, and exploring lighter materials for improved usability. These improvements, informed by both experimental results and user feedback from questionnaires, aim to enhance the exoskeleton's overall effectiveness and user experience, guiding the the SUPERHUMAN project's activities and developments.

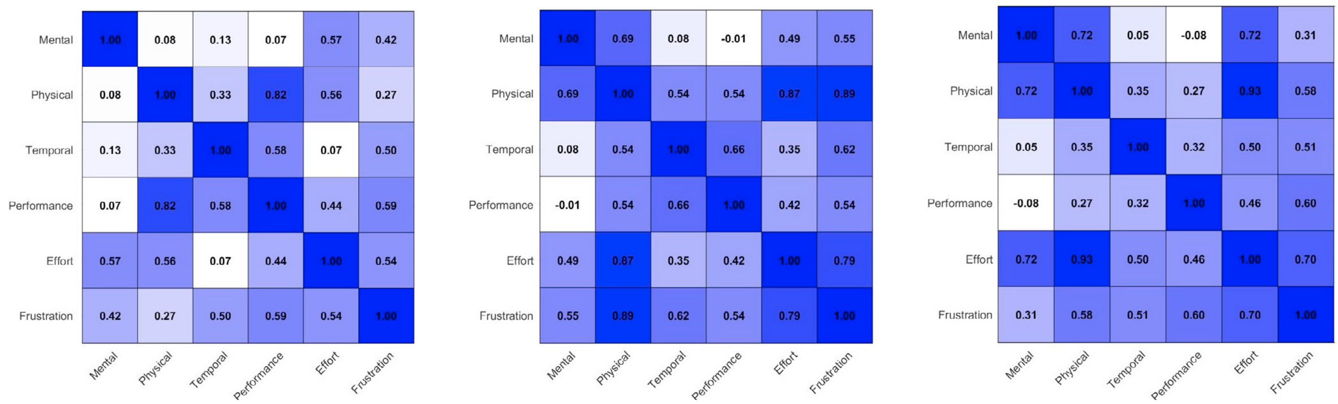

Fig. 8. Color-coded full representations of the Pearson coefficients across the Task A (left), Task B (center) and Task C (right). Refer to Sec. 3.3.

4. CONCLUSIONS

The SUPERHUMAN project advances efforts to mitigate musculoskeletal disorders (MSDs) in occupational settings by developing an optimized passive exoskeleton. Pilot evaluations confirm its potential to reduce lower back strain and improve ergonomic support, while feedback highlights areas for refinement, such as harness comfort and weight distribution. This initial study, though based on a limited sample size and subjective workload metrics, provides valuable insights into early design performance. Acknowledging these limitations, future phases will incorporate a control condition (i.e., task performance without the exoskeleton) to enable clearer comparative analysis. Additionally, the demographic profile of participants will be broadened, with a focus on increasing sample size and including older workers and more detailed sociodemographic data to better reflect real-world diversity and occupational needs. To strengthen validity, future evaluations will also integrate objective physiological and biomechanical measures (e.g., EMG, motion tracking) alongside subjective assessments. By addressing challenges related to usability, cost, inclusivity, and methodological robustness, the project continues to bridge research and industry, encouraging the broader adoption of passive exoskeletons in sectors such as logistics and manufacturing. Ultimately, SUPERHUMAN aims to contribute to safer, more sustainable, and more equitable industrial practices, with a strong commitment to gender equality and user-centered design in assistive robotics.

REFERENCES

Ashta, G. et al. (2023). Passive exoskeletons to enhance workforce sustainability: Literature review and future research agenda. *Sustainability*, 15(9), 7339. doi:10.3390/su15097339.

Cardoso, A., Colim, A., and Sousa, N. (2021). The effects of a passive exoskeleton on muscle activity and discomfort in industrial tasks. *Sustainability*, 13(4), 1931.

De Bock, S., Ampe, T., Rossini, M., Tassignon, B., Lefeber, D., and Meeusen, R. (2018). Passive shoulder exoskeleton support partially mitigates fatigue-induced effects in overhead work. *Applied Ergonomics*, 70, 32–38.

De Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., and O'Sullivan, L.W. (2016). Exoskeletons for industrial application and their potential effects on physical work load. *Ergonomics*, 59(5), 671–681.

European Agency for Safety and Health at Work (2020). Msds - facts and figures: Overview of prevalence, costs, and demographics of msds in europe. `https://osha.europa.eu`. Accessed: 2025-01-11.

Govaerts, R., Tassignon, B., Ghillebert, J., Serrien, B., De Bock, S., Ampe, T., El Makrini, I., Vanderborght, B., Meeusen, R., and De Pauw, K. (2021). Prevalence and incidence of work-related musculoskeletal disorders in secondary industries of 21st century europe: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders*, 22(1), 751.

Hart, S.G. and Staveland, L.E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. *Advances in Psychology*, 52, 139–183. doi:10.1016/S0166-4115(08)62386-9.

Kermavnar, T., de Vries, A.W., de Looze, M.P., and O'Sullivan, L.W. (2021). Effects of industrial back-support exoskeletons on body loading and user experience: An updated systematic review. *Ergonomics*, 64(6), 685–711.

Madinei, S., Alemi, M.M., Kim, S., Srinivasan, D., and Nussbaum, M.A. (2020). Effects of two passive back-support exoskeletons on muscle activity, energy expenditure, and subjective assessments during repetitive lifting. *Human Factors*, 62(3), 458–474.

Markets and Markets (2023). Exoskeleton market - global forecast to 2027. URL `https://www.marketsandmarkets.com`. Accessed: January 2025.

Pesenti, M., Gandolla, M., Pedrocchi, A., and Roveda, L. (2022). A backbone-tracking passive exoskeleton to reduce the stress on the low-back: proof of concept study. In *2022 International Conference on Rehabilitation Robotics (ICORR)*, 1–6. IEEE.

Roveda, L., Pesenti, M., Rossi, M., Rodriguez, M.C., Pedrocchi, A., Braghin, F., and Gandolla, M. (2022). User-centered back-support exoskeleton: design and prototyping. *Procedia CIRP*, 107, 522–527.

Roveda, L., Savani, L., Arlati, S., Dinon, T., Legnani, G., and Tosatti, L.M. (2020). Design methodology of an active back-support exoskeleton with adaptable backbone-based kinematics. *International Journal of Industrial Ergonomics*, 79, 102991.

SUPERHUMAN Project (2025). Superhuman project website. `https://superhuman-eitm.eu`. Accessed: 2025-01-11.