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Back Exoskeletons For Construction Workers: Investigation Of Human-Exoskeleton Interaction Forces

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Abstract

Low back pain (LBP) is a prevalent issue among construction workers, with prevalence rates ranging from 27% to 52%. This significant burden not only affects worker health but also incurs substantial economic costs, exemplified by Brazil's annual expenditure of approximately USD $500 million and Spain's EUR €8945.6 million in related costs. To mitigate LBP, back exoskeletons have emerged as promising solutions, designed to reduce low back load during repetitive lifting tasks. This study compares the human-exoskeleton interaction forces in three back exoskeletons - SV Exosuit (a soft active exosuit integrated with a safety vest), Laevo V2 (a rigid passive exoskeleton), and MATE-XB (also rigid and passive) - through experimental tasks involving bending and squatting. Three healthy male participants performed these tasks while wearing each exoskeleton, during which human-exoskeleton interaction forces at the thigh and shoulder/chest were measured. Results demonstrated that SV Exosuit produced higher contact forces at both body regions, attributed to its smaller contact area and less cushioning material. Conversely, Laevo V2 exhibited two peaks in contact forces during a motion cycle due to its torque generation mechanism, highlighting the influence of supporting torque design on user comfort. This research underscores the critical need for optimizing exoskeleton designs to enhance comfort and usability in construction settings. Future studies should investigate a larger sample size and additional body regions to comprehensively assess the relationship between supportive torque, contact forces, joint angle, and user comfort.

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1 Introduction

1.1 Prevalence Of Low Back Pain

Construction workers usually perform long period and high physical demanding tasks, causing a high incidence of low back pain (LBP) (Adhikari et al., 2021; Vasiwala et al., 2021). Safety records indicate that the prevalence of low back injuries, LBP, and low back disorders among construction workers ranges from 27% to 52% (Adhikari et al., 2021; Kashif et al., 2022; Wang et al., 2017). The financial burden on both workers and managers is significant, encompassing medical expenses and losses due to early retirement and absenteeism. For instance, Brazil spends approximately USD $500 million annually on LBP treatment (Carregaro et al., 2020), while Spain incurs EUR €8945.6 million in annual costs (Alonso-García & Sarría-Santamera, 2020).

Research highlights a strong association between LBP and heavy workloads (Burdorf & Jansen, 2006; Miranda et al., 2008; Serranheira et al., 2020). Therefore, reducing low back load is crucial for decreasing LBP incidence. However, replacing workers with automated machines poses challenges due to the complexity of construction tasks, which require a high degree of physical dexterity in dynamic and confined environments (Wu et al., 2022). Consequently, physical demands remain unavoidable for construction workers.

1.2 Back Exoskeletons To Reduce Low Back Load

Back-support exoskeletons, or known as back exoskeletons, are wearable devices designed to reduce low back load during repetitive lifting tasks (Koopman et al., 2020). These devices support industrial workers by compensating for the voluntary efforts of low back muscles through providing external support (Kranenborg et al., 2023). Back exoskeletons can be classified as active (utilizing electric motors or pneumatic actuators) or passive (using springs and elastic straps) based on their actuation mechanism (Matthew et al., 2015). They can also be categorized as rigid (made from metal or carbon) or soft (constructed from fabrics and textiles) according to their structural materials (Schwartz et al., 2021). In general, back exoskeletons can provide assistive force of up to 500 N or assistive torque of up to 60 Nm (Koopman et al., 2020; Luger et al., 2021). Previous studies confirm that back exoskeletons can reduce back muscle load by 10% – 40% (Poliero et al., 2020; Walter et al., 2023), potentially lowering the risk of low back disorders by approximately 20% (Zelik et al., 2022). Some studies also indicate that back exoskeletons may enhance productivity. For example, Bennett et al. (2023) found that when performing construction tasks (specifically, pushing and emptying a construction gondola and installing and removing wooden blocks between metal studs), the workers completed 5.3% faster on average with Herowear Apex (HeroWear, Nashville, USA).

Despite the potential benefits, limitations such as discomfort and motion impediment can hinder the broader application of back exoskeletons (Golabchi et al., 2023; Luger et al., 2021). For example, subjects in the study of Golabchi et al. (2023) reported increased discomfort in the chest, arms, knees, and upper legs when using a passive exoskeleton. Similarly, Kim et al. (2020) noted moderate discomfort in the chest, waist, and thighs with two passive exoskeletons. Discomfort levels can become unacceptable after two hours of use (Hensel & Keil, 2019). Therefore, mitigating discomfort is essential for increasing the adoption of back exoskeletons in construction. Research on human-exoskeleton interaction forces is crucial for improving user comfort and effectiveness. While some studies have explored interaction forces in lower limb exoskeletons (Serrancolí et al., 2019; Shushtari & Arami, 2023; Wang et al., 2020), discomfort in back exoskeletons has primarily been assessed through subjective feedback (Hensel & Keil, 2019; Kim et al., 2020; Luger et al., 2021). Thus, investigating the interaction forces between users and back exoskeletons is necessary for wider application in construction. This study aims to preliminarily investigate interaction forces at the thighs and shoulders/chest of three representative back exoskeletons, comparing the relationships between these forces, supportive torque, and contact materials.

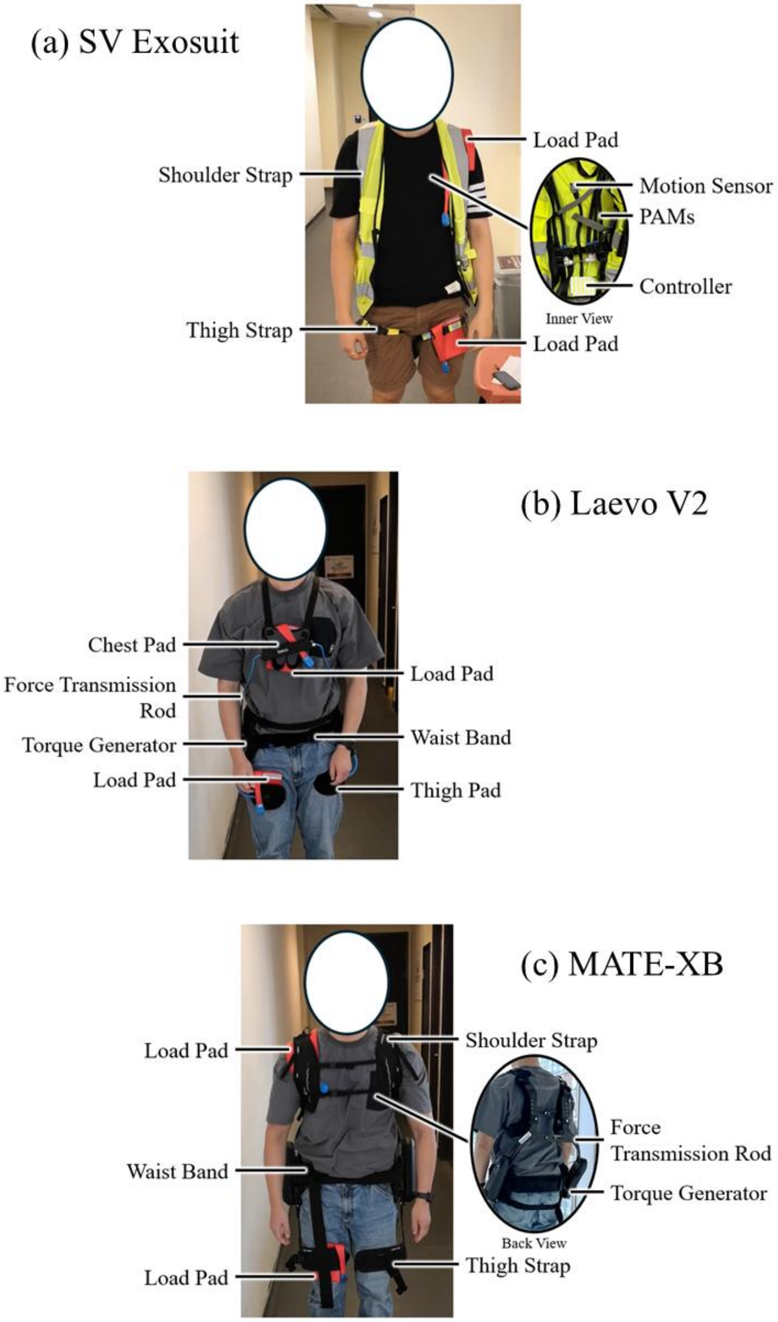

Figure 1: Main structures of the three compared exoskeletons and the installation positions of the load pads.

2 Method

2.1 Subjects And Exoskeletons

A convenience sample of three healthy young male participants was recruited from university students, with a mean (standard deviation, SD) age, body mass, and height of 27 (0.8) years, 79.7 (9.8) kg, and 177.3 (6.0) cm. Participants were not trained for labor-intensive work and were unfamiliar with back-support devices. Selection criteria included: (a) no history of pathological low back pain, and (b) no injuries or disorders affecting trunk lifting tasks. These criteria were set as the compared devices aim to prevent low back injury rather than assist with rehabilitation, and the injuries or medical histories might affect the task performance. The participants provided written informed consent prior to experiments.

Three representative back exoskeletons were compared in this study. Exoskeleton 1, referred to as the SV Exosuit [Fig 1(a)], is a soft active back exosuit that is integrated with a safety vest. It is based on the design previously proposed by our team (Lei et al., 2024) and provides supportive force through eight pneumatic artificial muscles (PAMs) located in the back region. Upon detecting trunk bending, the integrated motion sensor triggers the system to provide compressed gas to the PAMs, causing them to contract. The contraction force is transmitted through shoulder and thigh straps to the wearer. Exoskeleton 2, Laevo V2 (Laevo, Rijswijk, the Netherlands) [Fig 1(b)], is a rigid passive back exoskeleton that generates supportive force through two spring-based torque generators positioned next to the hips. When the wearer bends the trunk, these torque generators are compressed, producing elastic forces that are transferred via a chest pad and two thigh pads to the wearer. Exoskeleton 3, MATE-XB (Comau, Turin, Italy) [Fig 1(c)], is also a rigid passive back exoskeleton that operates similarly to Laevo V2 but transfers the load through shoulder straps and thigh pads. These three exoskeletons were selected for their different designs: SV Exosuit is a soft and active exosuit that transfers load with shoulder straps and thigh straps, MATE-XB is a rigid and passive exoskeleton that transfers load with shoulder straps and thigh pads, while Laevo V2 is a rigid and passive that transfers load with chest pad and thigh pads. The variety allows for a thorough examination of the relationships between the human-exoskeleton interaction forces and the exoskeleton design.

2.2 Experimental Design

The experiment includes two tasks: bending task and squatting task. In the bending task, as shown in Fig 2(a), participants held a weight while standing, then bent to place the weight on the floor without bending their knees and finally lifted the weight back to a standing position. In the squatting task, as shown in Fig 2(b), participants held a weight while standing, squatted to place the weight on the floor, and then performed a squat-lift with the weight to return to a standing position. Each exoskeleton condition was tested with both tasks, repeated five times with a 5 kg weight and five times with a 15 kg weight. The sequence of these four sessions within one exoskeleton condition was randomized. The order of these sessions was randomized. Each of the three exoskeletons was tested in a randomized sequence, and participants were allowed three to five minutes to acclimate to each exoskeleton before performing the tasks.

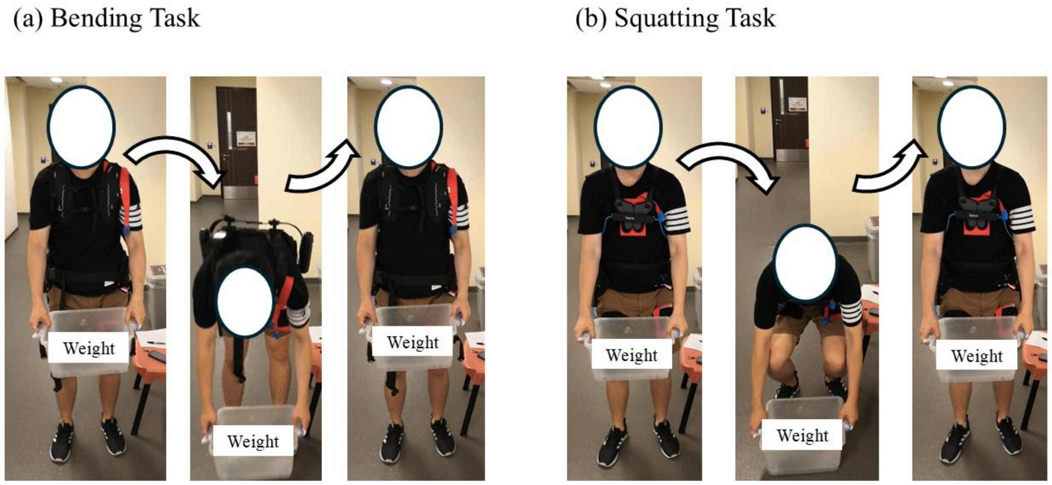

Figure 2: Illustrative graphs of (a) bending task and (b) squatting task.

2.3 Data Collection And Analysis

The human-exoskeleton interaction forces were measured at two body parts, the thigh and the shoulder (for SV Exosuit and MATE-XB) or the chest (for Laevo V2), as these areas are commonly reported to experience the highest discomfort when using back exoskeletons (Alemi et al., 2020; Kim et al., 2020; Poliero et al., 2022). Interaction forces were collected using flexible and stretchable load pads (novel GmbH, Munich, Germany) at a sampling rate of 100 Hz. The load pads were positioned between the target body regions (i.e. shoulder/chest and thigh) and the corresponding parts of the exoskeleton (Fig 1). Given that both bending and squatting tasks were symmetrically performed, and no significant differences were observed in muscle loads during symmetric tasks with back exoskeletons (Alemi et al., 2019), load pads were placed on only one side of each participant in this study. The collected contact force data were normalized from time frame to motion cycle frame for comparison, with one motion cycle representing one bending or squatting task. Outliers were removed from the analysis.

3 Results

The compared contact forces are presented in Fig 3. Generally, the contact forces at both the thigh and shoulder/chest regions were higher with SV Exosuit compared to the other two devices, likely due to its contact design. The shoulder straps of SV Exosuit are approximately 7 cm wide, narrower than the 10 cm width of the MATE-XB shoulder straps and the 12 cm width of the Laevo V2 chest pad. Also, the thigh straps of SV Exosuit (about 3 cm width) have smaller contact areas than the thigh pads of the other two devices (about 12 cm width). A smaller contact area and less cushioning material can significantly increase the human-exoskeleton interaction force (Kozinc et al., 2021), indicating that adequate contact area and cushioning is essential in exoskeleton design. Further research is needed to explore the relationship between user comfort and the contact materials used in exoskeletons for the optimal material selection. The design of the clothing components also influences the contact force. Compared to SV exosuit, the shoulder straps of MATE-XB are connected with two straps across the chest region, allowing the load partly distributed to the chest. Also, there is no waist band in the design of SV Exosuit, while both MATE-XB and Laevo V2 incorporate a waist band. The waist band potentially distributes part of the load at the shoulders/chest and the thighs to the waist region. This suggests that effective load distribution through design may be beneficial. Moreover, the contact force is related to the supportive force provided by the exoskeleton. For instance, it is estimated that SV Exosuit can generate about 54 Nm assistive torque (Lei et al., 2024), surpassing the 30 Nm maximum of Laevo V2 (Van Harmelen et al., 2022), resulting in greater applied forces on the body. Further investigation is necessary to analyze the relationship between the human-exoskeleton interaction forces and the assistive torque provided by the back exoskeleton. Further, in most fractions of the motion cycle, the contact force at the thigh exceeded that at the shoulder/chest, likely due to the moment arm from the waist to the shoulder/chest being nearly twice as long as that to the thigh. In Laevo V2, the shorter moment arm from the chest pad to the waist resulted in a smaller difference in contact forces between the chest and thigh.

In the bending task, the contact forces at the thigh remained consistent regardless of whether participants held 5 kg or 15 kg, while shoulder/chest forces slightly increased with heavier weight. This indicates that in the bending task, as load increases, the supportive forces of these three back exoskeletons tend to exert more influence on the upper body rather than the lower limbs. Notably, both SV Exosuit and MATE-XB displayed a single peak in contact forces during the task, whereas Laevo V2 exhibited two peaks. This discrepancy arises because the supportive torques of SV Exosuit and MATE-XB correlate positively with the bending angle, while Laevo V2 reaches maximum torque at a bending angle of 40° – 50° (Van Harmelen et al., 2022). Distributing peak contact forces throughout the motion cycle may impact perceived discomfort, although further study is required to understand the extent and nature of these effects. Comparing the contact force curves of SV Exosuit and MATE-XB, the peak force for SV Exosuit (60% – 70% of motion cycle) occurred later than that for MATE-XB (40% – 60 % of motion cycle). This difference is attributed to how each device supports torque: MATE-XB generates torque based on spring compression in direct response to bending angles, while SV Exosuit provides torque by actively injecting compressed gas following a specific bending angle, resulting in a delayed peak contact force. The contact force variation of these three back exoskeletons suggest that the design of the supporting torque affects the human-exoskeleton interaction forces, which may also have an impact on user comfort.

In the squatting task, as in the bending task, contact forces at the shoulder/chest region increased with heavier weights for all three exoskeletons. However, unlike the bending task, contact forces at the thigh increased with heavier weights for the SV Exosuit and Laevo V2. This variation is primarily due to differences in joint angles during these activities. The waist joint angle varies minimally during both tasks (0° – 70° for the bending task and 0° – 60° for the squatting task), while the hip joint angle varies significantly (-5° – 50° for the bending task and -5° – 90° for the squatting task) (Hwang et al., 2009). This explains the relatively higher contact forces at the thigh in the squatting task compared to in the bending task. Further study is needed to confirm the relationship between joint angles and contact forces. Notably, with MATE-XB, contact forces at the thigh decreased when participants held heavier weights during the squatting task. This reduction is likely due to the displacement of the thigh pads. As MATE-XB's force transmission components are rigid and the thigh pads are not fixed, increased pressure may lead to the pads shifting toward the knees, resulting in reduced contact forces at the thigh pad due to an increased moment arm. Previous studies have also observed displacement of back exoskeletons during activities, attributed to relative motion and misalignment between the exoskeleton and human anatomy (Näf et al., 2018; Park et al., 2022; Sarkisian et al., 2021).

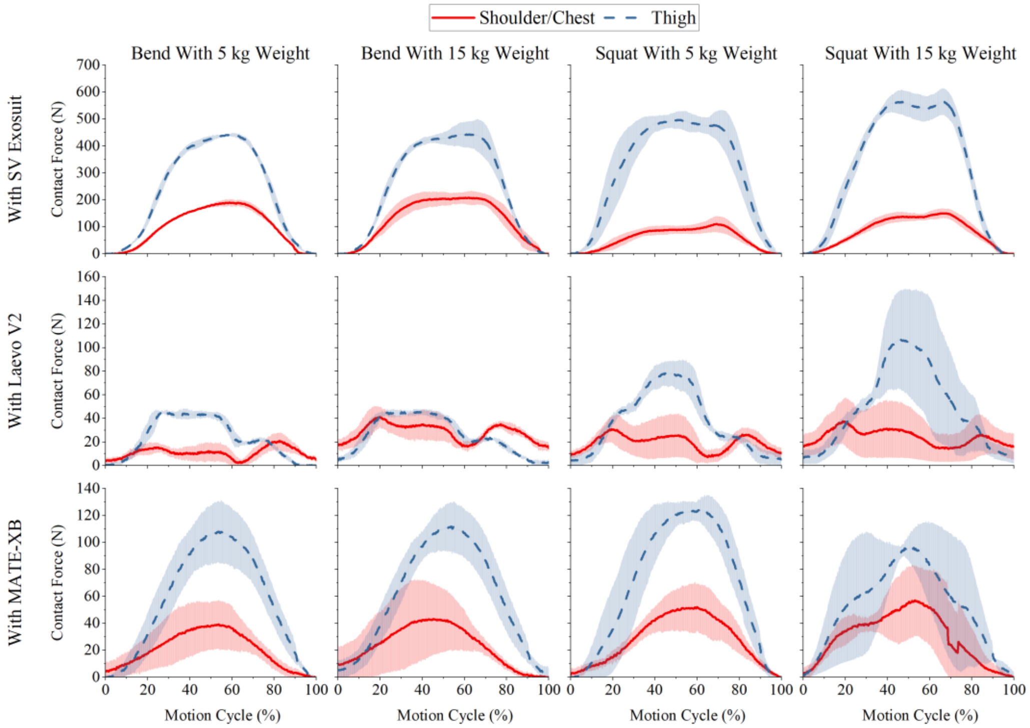

Figure 3: Contact forces in bending and squatting tasks with 5 and 15 kg weight under three back exoskeleton conditions.

4 Discussion

Back exoskeletons are engineered to alleviate the low back load on wearers and reduce the risk of low back pain (LBP). However, the human-exoskeleton interaction force remains a significant source of discomfort, contributing to the low acceptance of these devices in the construction industry (Hensel & Keil, 2019; Levesque et al., 2017). Consequently, investigating the human-exoskeleton interaction force during the activities is needed for improving the exoskeleton design. This study addresses the pressing need to investigate these interaction forces to improve back exoskeleton design.

The analysis revealed that contact forces at the shoulder/chest and thigh regions were notably higher with the SV Exosuit compared to the other two exoskeletons. This difference may be attributed to the smaller contact area and the use of less cushioning materials (Kozinc et al., 2021). This finding underscores the importance of considering both the shape and material of contact areas in exoskeleton designs, suggesting that improved cushioning could reduce pressure on the wearer. Moreover, design elements such as connecting shoulder straps across the chest might help distribute loads more effectively, although further research is needed to validate these strategies. Optimizing the lengths of the moment arms from the waist to the shoulder/chest and thigh is also crucial. Short moment arms can increase contact forces, while longer moment arms might hinder natural movements like walking and squatting (Park et al., 2022). Thus, achieving a balance in moment arm lengths is essential for effective exoskeleton functionality.

The contact forces exhibited by Laevo V2 varied from the other two devices, primarily due to differences in the relationship between supportive torque and bending angle. Variations in torque strategies between SV Exosuit and MATE-XB also resulted in different peak contact force moments. Results suggest that the variation of supporting torque affects the contact forces. This highlights the need to consider how the distribution of contact forces and peak moments across the motion cycle relate to wearer comfort, a topic that warrants further exploration.

Additionally, the study observed displacement of the thigh pad in the MATE-XB during squatting tasks, indicating potential misalignment between the wearer and the exoskeleton. Previous studies have noted that the relative motion and misalignment between the wearer and the exoskeleton can cause undesirable interaction forces and torques (Jarrasse & Morel, 2012; Sarkisian et al., 2021), yet these factors are inevitable (Sarkisian et al., 2020). Consequently, it is necessary to optimize the exoskeleton design to minimize these side effects. The results also suggest that the joint angle can affect the contact force at the corresponding region, and further study is needed to confirm the relationship. This relationship might depend not only on the supporting extent but also the impediment of natural movement, reinforcing the necessity for design optimization to mitigate these effects.

Several limitations of this study should be acknowledged. The small sample size of three participants limits statistical power. Furthermore, the investigation focused on only two body regions (shoulder/chest and thigh), leaving out other important areas like the waist and hip that could influence overall comfort. The absence of empirical data on supporting torques also restricted the analysis of their relationship with contact forces. Additionally, as relating user comfort with human-exoskeleton interaction force is a further topic, current study did not well investigate user comfort for now. Future studies should aim for a larger, statistically robust sample size and include additional body regions. Investigating the relationship between supportive torque curves and contact forces would enhance understanding of how support is distributed across the body and inform better load distribution designs. Moreover, exploring the link between user comfort and contact forces will shed light on pressure tolerance and improve the design of pressure distribution features in back exoskeletons. Lastly, further examination of how joint angles affect contact forces is crucial for optimizing exoskeleton functionality and user comfort.

5 Conclusions

The investigation into the interaction forces between users and back exoskeletons revealed significant insights into their design and functionality for reducing low back load in construction workers. SV Exosuit, characterized by its active support through pneumatic artificial muscles, demonstrated notably higher interaction forces at both the thigh and shoulder/chest regions compared to Laevo V2 and MATE-XB. This increase can be largely attributed to the smaller contact area and lack of sufficient cushioning in the SV Exosuit, suggesting that while its supportive capabilities are advanced, user comfort remains a critical challenge. Laevo V2's design, which employed a rigid passive mechanism, exhibited distinct contact force behaviour, including two peaks across the motion cycle, influenced by its torque generation strategy that reaches its maximum supportive torque at the bending angle between 40° – 50°. This indicates a need for careful consideration of how torque is distributed throughout the motion cycle to minimize discomfort. Furthermore, the MATE-XB's observed displacement of the thigh pad during squatting tasks points to potential misalignment issues that could affect user experience and exoskeleton effectiveness. These findings highlight the necessity for further research focused on optimizing exoskeleton designs, particularly in terms of cushioning materials and load distribution strategies, to enhance user comfort and promote wider adoption in the construction industry. Future studies should also aim to include a diverse participant pool and investigate additional anatomical regions, ultimately informing better design practices and improving the efficacy of back exoskeletons in preventing LBP among construction workers.

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