The Relationship Between User Perceptions of Exoskeletons and Changes in Muscle Activity and Range of Motion

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***Abstract*—While through the literature different objective metrics, such as kinematics and muscle activity, have been used for the evaluation of exoskeletons performance, there is less research on how these metrics represent users' perceptions. This study aimed to find the relationships between muscle activity and joint kinematics with user perception. Muscle activity was measured using electromyography sensors, focusing on the Latissimus and Thoracolumbar muscles. Body joint kinematics measurements were taken for the knee and trunk joints. The study also investigated how users' overall selections of exoskeletons, considering all aspects, align with their choices based on comfort and biomechanical support. A similarity index and point biserial correlation coefficient were used for finding the relationships. Four individuals performed trunk bending and weight lifting while wearing different exoskeleton configurations. Both perceived comfort (similarity index: 57%) and biomechanical support (similarity index: 62.5%) played a role in users' overall preferences, and users prioritized one of them depending on the exoskeleton setting. Comparing the objective and subjective results revealed that muscle activity represented human perception of support to some extent (average similarity index and correlation coefficient of 49% and 0.27 across static and dynamic tasks), while trunk range of motion had a high similarity and correlation with users' perceived comfort (similarity index: 74.2% and correlation coefficient: 0.53). In summary, this study contributed to understanding the rationale behind users' perception across different aspects. The results highlight the necessity of future research on finding more sensitive objective metrics, leading us toward obtaining the objective function underlying users' preferences.**

Keywords— Exoskeleton, Comfort, Biomechanical Support, Muscle activity, Range of motion, User perception

I. Introduction

Despite significant automation in many industries, the manual workforce is still one of the main parts of the industry [1]. Due to the physically demanding nature of their tasks, manual material handling workers face musculoskeletal disorders, leading to high rates of injuries among them and consequently increasing healthcare costs [2], [3]. Lower back disorders continue as the leading cause of work-related disability, accounting for the majority of work-related musculoskeletal disorders and lost workday cases [4]. Earlier research has explored diverse interventions to prevent occupational lower back disorders, including workspace redesign and the use of mechanical aids [5], [6], [7], [8]. However, evidence of their efficacy, sustainability, and usability remains limited in practice [9]. Industrial back-support exoskeletons, designed to augment the back and hip muscles, have been introduced as an alternative intervention to reduce the physical demands on the back muscles and consequently mitigate the risk of lower back pain [10], [11].

Through the literature, a variety of back-support exoskeletons have been proposed, each with different design and setting levels. To evaluate the effectiveness of them, various objective metrics have been analyzed in previous studies [12]. Energy expenditure [13], [14], metabolic rate [13], [15], muscle activity [14], [16], and posture-based metrics [16], [17] are the most prevalent ones. For example, Alemi et al. [14] showed that a passive back-support exoskeleton could reduce energy expenditure by 4%-13% during repetitive lifting tasks. Previous studies showed that metabolic rate can be minimized by using an exoskeleton and through human-in-the-loop optimization [18], [19]. Numerous studies also evaluated back-support exoskeletons based on their impact on muscle activity measured by electromyography (EMG) sensors [16], [17]. Kermavnar et al. [12] showed that back-support exoskeletons could reduce back muscle activity by up to 60%. Posture-based or kinematic metrics, such as range of motion (ROM) [20], [21], have also been used to evaluate the movement restriction imposed by exoskeletons and the consequent discomfort it creates.

While these objective metrics provide valuable insights about exoskeleton evaluation, for an exoskeleton to be seen as valuable by its users, it must deliver an experience that clearly demonstrates its worth [22], [23]. Without an intuitive and easily perceivable grasp of its benefits, potential users may hesitate to

This project was funded by the Natural Sciences and Engineering Research Council of Canada in partnership with Alberta Innovates (Grant # ALLRP 567348 – 21).

adopt exoskeletons. Therefore, it is important to know how measurable metrics, such as changes in muscle activity and ROM, represent the actual biomechanical support and comfort level perceived by users. This can then be used as guidelines in the design of exoskeletons to ensure they provide perceivable support to the users and therefore increasing their chances of successful adoption.

While the relationship between users' perceptions and objective biomechanical metrics has been investigated for lower-limb exoskeleton, there is limited research on this relationship for back-support exoskeleton. Medrano et al. [15] showed that users could not reliably perceive a reduction in metabolic rate provided by an active ankle-support exoskeleton, while the mean reduction in metabolic rate over the past decade is 9.6% ± 4.5%. Knowing these rationales behind users' perception helps in the design and adoption process of exoskeletons. Through literature, muscle activity and ROM are among the most prevalent kinetic and kinematic metrics used for the evaluation of back-support exoskeletons [24]. Therefore, it is important to know how changes in these metrics are related to users' perception in different aspects, e.g., biomechanical support and comfort. To this end, understanding how humans perceive changes between different sets of exoskeletons and subsequently how this perception relates to measurable biomechanical metrics is required. At the same time, the users' perceptions are not always reliable as sometimes the change in biomechanical support and comfort might not be noticeable by the users. Therefore, it is crucial to investigate a minimum amount of change that users perceive. Previous studies [15], [25], [26] have used the just noticeable difference (JND) method to find the minimum detectable change in different physiological and non-physiological measurements. For example, the JND for the perceived trunk posture was found to be 2°-7° [27].

This study aimed to investigate to what extent changes in lower back muscle activity and ROM represent users' perceptions when wearing a back-support exoskeleton. For this purpose, a passive back-support exoskeleton with different configuration options was used. The results obtained from pairwise comparisons of different exoskeleton configurations, done by users, have been compared with objective measurements collected by wearable sensors. This examination aimed to determine how accurately users select the exoskeleton that offers a greater reduction in muscle activity as the one that provides more biomechanical support and to determine how users' comfort selection is related to the changes in ROM.

II. Methods

A. Participants

Four healthy individuals (two females and two males, age: 28 ± 4 years, weight: 80 ± 18 kg, and height: 170 ± 7 cm) without any previous back injuries were recruited to participate in the experiments. The study was approved by the research ethics board of the University of Alberta, ID: Pro00109264.

B. Exoskeleton

The Apex exoskeleton (HeroWear, Nashville, USA) was used in this study (Fig. 1). This exoskeleton weighs 1.5 kg and uses soft elastic bands to generate assistive torque about the

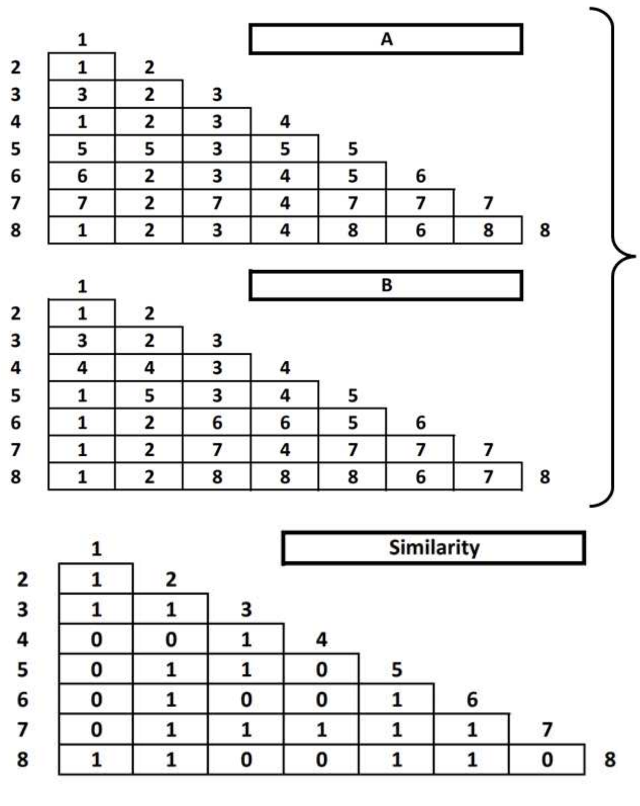
Fig. 1. Apex exoskeleton. There are eight configurations of the elastic bands as a combination of four sizes (1-4) and two strength levels (low and high).

lumbar spine. The two elastic bands connected the upper-body section (a backpack with shoulder and chest straps) to the thigh sleeves.

C. Experimental Procedure

The experimental procedure consisted of both subjective and objective assessments, each with two tasks: static trunk bending and weight lifting. During the static trunk bending, participants maintained a 40° angle posture of trunk while holding a 5 lb object in their hand for 20 seconds. The 40° angle was monitored both visually and with the aid of a custom-made goniometer placed beside the participants. During the lifting task, participants lifted a 5 lb object from a height of 30 cm above the ground to the waist level. The 5 lb load was selected to ensure participant safety and minimize fatigue during repeated trials. The 30 cm lift height represents a common starting height for objects placed on the floor in various occupational settings, allowing for consistency in lower back activation without excessive joint strain. Eight different configurations, combining four sizes and two strength levels of support bands (high and low), were tested. During the subjective assessment, participants tried these eight different exoskeleton configurations to familiarize themselves with the level of support and comfort each provided, ensuring they could make informed comparisons. They made 28 pairwise comparisons, 8 choose 2, with the eight exoskeleton configurations to compare all possible pairs (see Fig. 2). After each pair of trials (with two different configurations), participants were asked to make a forced comparison, selecting the configuration that provided greater biomechanical support, or lower back relief, and comfort, assessed separately. Also, they were asked to make a forced comparison between the pair to select the preferred one overall, considering biomechanical support and comfort, altogether. It should be noted that the trial and task order were randomized to prevent any fatigue or bias. Participants were asked to rest

For the objective assessment, participants were equipped with EMG sensors (Tringo Avanti EMG sensor, Delsys, USA)



$$\textbf{Similarity Index}\ (\%) = \frac{16}{28} \times 100 = 57.14\%$$

Fig. 2. An example of similarity index calculation between Matrices A and B that show pairwise comparisons among all settings. These matrices can be results obtained from users' subjective preferences for comfort, biomechanical support, and overall or objective measurements for muscle activity and ROM.

attached to their lower back muscles (Latissimus and Thoracolumbar) as well as inertial measurement unit (IMU) sensors (MTws, Xsens Technologies, NL) on the left and right upper and lower leg, chest, and pelvis. They repeated the same tasks performed during the subjective part, static trunk bending and weight lifting, each four times to ensure reliability and consistency in the data by reducing variability and potential outliers in the measurements.

During both tests, muscle activity data, with a sampling frequency of 2,148 Hz, and IMU data, with a sampling frequency of 80 Hz, were collected. To normalize the muscle activity, maximum voluntary contraction tests were performed for all back muscles at the beginning of the experiments [28].

D. Data analysis

First, all EMG data were filtered with a 4th order bandpass Butterworth filter with cut-off frequencies of 10 Hz and 500 Hz. Then, EMG data were normalized to its corresponding maximum voluntary contraction measurements. The mean, median, 90th percentile, and root mean squared (RMS) values of normalized muscle activity were calculated to compare different exoskeleton settings. In a separate study, the minimum detectable change in mean, median, and 90th percentile of lower-back muscle activity was found using the JND method. The average JND values found for the mean, median, and 90th percentile of EMG amplitude are 27.9%, 29.4%, and 20.1%, respectively. Thus, an EMG analysis was performed considering the JND values. For each pairwise comparison, if the change in each measure was lower than their corresponding JND values, that pair was discarded. This is because such differences are unlikely to be perceived accurately by users, making their responses for those pairs unreliable.

To determine the joint angles using IMUs, a functional calibration method, as described in [29], was used to align the IMUs' inertial frames with the body's anatomical frames. For this purpose, after attaching the IMUs, participants were instructed to stand still for 5 seconds, followed by performing 10 flexion and extension movements of the legs and arms while keeping their knee and elbow joints locked. Subsequently, segment orientations were estimated using the sensor fusion algorithm suggested by [30], [31]. Using segment orientations, knee and trunk joint angles, and subsequently their ROMs, were calculated. JND value for joint angles was considered to be 4° [27].

Different comparisons between subjective outcomes were done to obtain the similarity between them. Also, the comparison between the 28 pairwise assessments from the subjective evaluations and their corresponding objective measurements was conducted to evaluate the accuracy of participants' perceptions.

E. Similarity Analysis of Subjective and Objective Metrics

Matrices A and B (Fig. 2) were derived from users' subjective preferences and objective measurements related to comfort, biomechanical support, muscle activity, and joints ROM. For subjective preferences, matrix A was constructed based on user feedback regarding comfort and support. For ROM, matrix B was constructed by comparing each pair of configurations and selecting the exoskeleton configuration that allowed for a greater ROM. Similarly, for muscle activity, matrix B was constructed by choosing the setting that resulted in a greater reduction of muscle activity mean, median, and 90th percentile, each separately, between each pair.

In this analysis, if $A_{ij} = B_{ij}$, the output matrix was assigned "1" ($S_{ij} = 1$); conversely, if $A_{ij} \neq B_{ij}$, 0 was assigned to the corresponding cell of the output matrix ($S_{ij} = 0$). To obtain the similarity index, the proportion of pairs assigned a score of '1' out of the 28 pairs was calculated as the "similarity index" (see Fig. 2 and Equation (1)).

$$Similarity\ Index_{AB}\ (\%) = \frac{\sum_{i=1}^{8}\sum_{j=1}^{8} S_{ij}}{28} \times 100$$
$$S_{ij} = \begin{cases} 1 & if\ A(i,j)\ and\ B(i,j)\ are\ the\ same \\ 0 & Otherwise \end{cases} \quad (1)$$

For obtaining the similarity index between objective and subjective outcomes, matrix A was constructed based on subjective feedback (biomechanical support or comfort perceptions) and matrix B was constructed based on objective measurements (muscle activity or ROM). To obtain the similarity index between different subjective feedback, both matrices were constructed based on subjective feedback.

The second method to find the correlation between objective and subjective metrics was using the Point-Biserial (PB) correlation coefficient, a special case of the Pearson's correlation coefficient. PB correlation finds the correlation between a continuous variable and a binary variable (Equation (2)). In this study, continuous variables were joint ROM as well as mean, median, and 90th percentile of EMG recordings, and the binary variable was subjective feedback.

$$\rho_{PB} = \frac{\left(\bar{X}_1 - \bar{X}_0\right)}{s}\sqrt{\frac{n_0 n_1}{n^2}} \quad (2)$$

where, X_1 and X_0 are the mean of the continuous variable for the group where the binary variable is 1 and 0, respectively, s is the standard deviation of the continuous variable, n_1 and n_0 are the number of observations where the binary variable is 1 and 0, and n is the total number of observations, which was 28 in this study.

III. Results

A. Subjective Feedback

The results indicate that users' overall preferences were similar to their comfort and biomechanical support preferences with the median similarity index of 57.0 [37.5 73.2]% and 62.5 [48.2 71.4]%, respectively (Fig. 3). There was no significant difference between comfort and biomechanical support similarity indexes. These results suggest that neither comfort nor biomechanical support was a predominant factor in determining users' final preferences. In other words, depending on the exoskeleton's configuration users may prioritize one of these factors.

Among 28 comparisons, four were between elastic bands of the same size but different strength levels (low and high). On average, users selected the high-strength elastic bands for comfort, biomechanical support, and overall preferences in 6.3%, 75%, and 18.75% of comparisons (Fig. 4). Users selected the high-strength elastic bands for biomechanical support significantly more than for comfort and overall preferences.

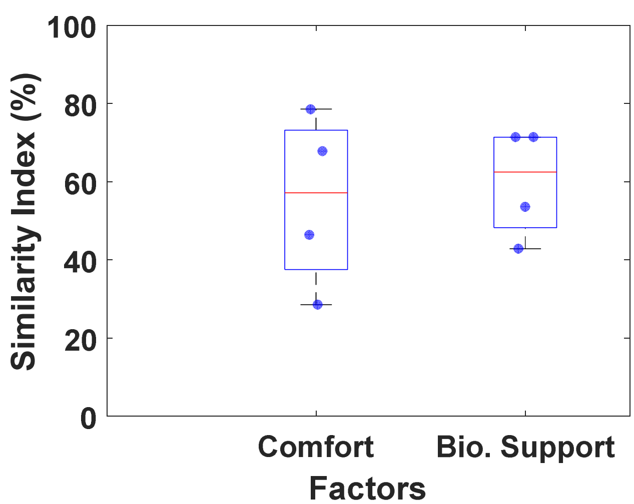


Fig. 3: Similarity index calculated between users' preferences for comfort and biomechanical support with their overall preferences

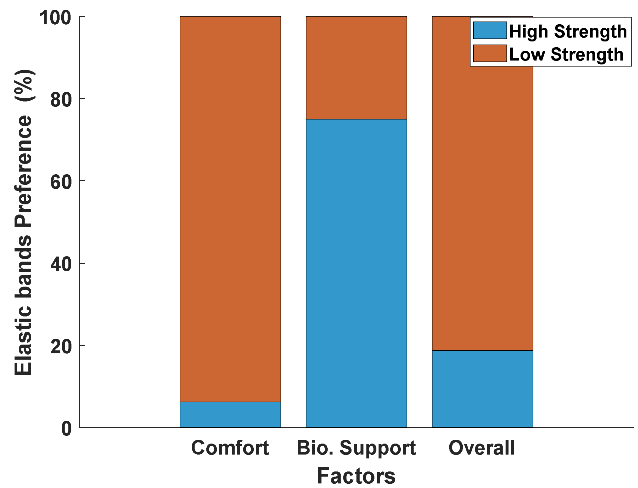


Fig. 4: The average users' preferences: percentages of selections of high and low strength elastic band with the same size

B. Similarity between objective measurements and subjective feedbacks

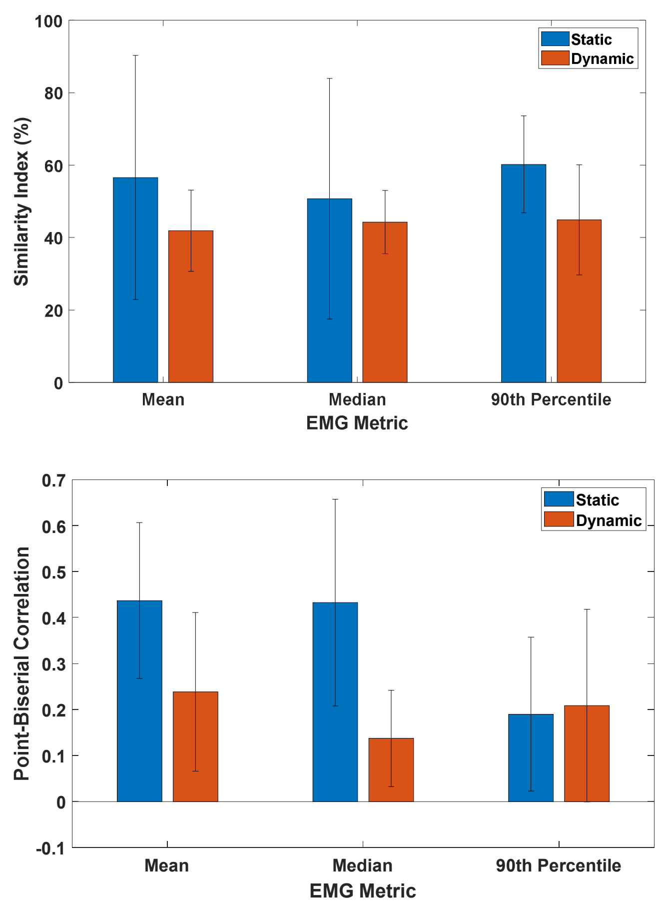


Fig. 5: Similarity index and PB correlation coefficient calculated between users' preferences for biomechanical support and different EMG metrics

Results showed that both similarity index and PB correlations between EMG measures (mean, median, and 90th percentile) with subjective perceived biomechanical support were higher in the static task compared to dynamic task (Fig. 5). For example, the average similarity index between mean value of EMG amplitude and users perceived biomechanical support was 56 ± 33 and 41 ± 11 for static and dynamic tasks, respectively. Additionally, the average PB correlation between mean value of EMG amplitude and users perceived biomechanical support was 0.43 ± 0.16 and 0.23 ± 0.17 for static and dynamic tasks, respectively.

The correlation between trunk ROM and users' perceived comfort was higher than the correlation between knee ROM and users' perceived comfort (Fig. 6). In other words, trunk ROM was prioritized over knee ROM when comparing the comfort across different settings of the exoskeleton.

IV. Discussion

Previous research has shown that back-support exoskeletons can provide assistance to users in physically demanding tasks such as trunk bending and weight lifting. While various metrics have been used to evaluate the efficacy of exoskeletons, user feedback was found to be a crucial part of the adoption process [22], [32]. Therefore, knowing which factors (such as comfort and biomechanical support) are important to users when

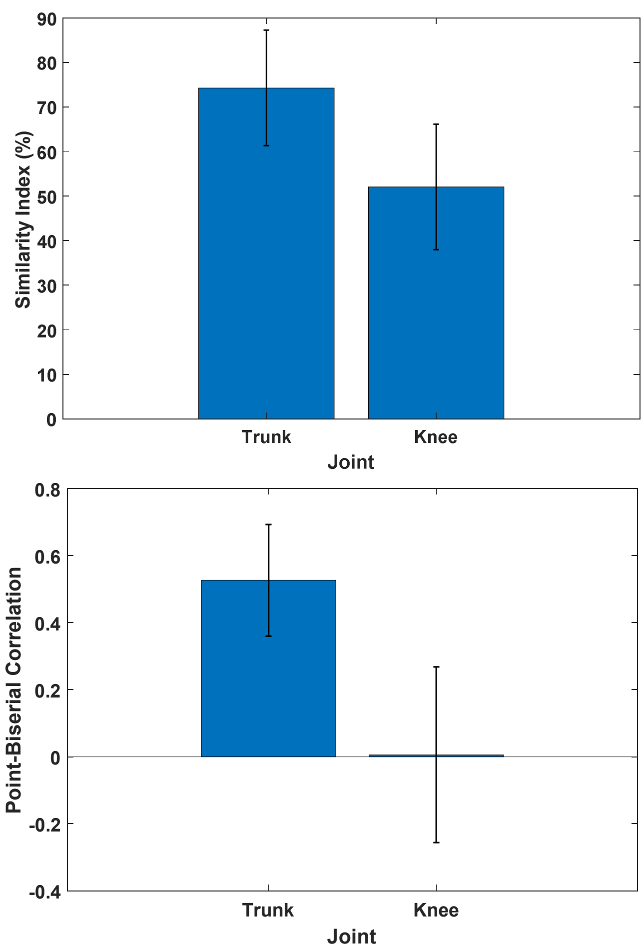


Fig. 6: Similarity index and PB correlation coefficient calculated between users' preferences for comfort and biomechanical support with their overall preferences.

selecting their preferred exoskeletons is important. It is also essential to understand the relationship between subjective feedback and objective metrics to develop guidelines that helps for designing exoskeletons that provide maximum benefits to the users. In this study, we explored both the relationships among subjective factors and between subjective feedback and objective biomechanical metrics.

This study assumed that biomechanical support and comfort are the primary factors in user preference for exoskeleton users, based on our preliminary findings. These results showed that user preferences for other factors, such as mobility and pain, closely aligned with their preferences for either biomechanical support or comfort. Building on this assumption, the study investigated how closely users' overall exoskeleton preferences align with their comfort and biomechanical support preferences. It was found that none of these two factors were predominant when a wide range of exoskeleton options, in terms of their support and movement restriction, were compared together (Fig. 3). While the logic behind users' overall exoskeleton configuration selection remains unknown, this study investigated how comfort and biomechanical support correlate with biomechanical measurements.

While EMG analysis has been used for a long time as an indicator of load on muscles, our results indicate that the EMG metrics represent human perception of biomechanical support only to a limited extent (Fig. 3) . In other words, EMG metrics did not fully capture the load perception on the lower back muscles. It appears that, similar to comfort, humans use a more complex internal model than what central nervous system employs to interpret the perception of load. Other biomechanical indicators, such as joint load and forces, might better represent the users' perceptual support. In other words, indicators that have more linear and direct relations with muscle loading might be better perceived by users than muscle activity obtained by surface EMG sensors. This is partly because muscle activity obtained by EMG sensors can be affected by many other factors, such as sensor placement and movement artifacts.

Generally, what users consider as comfort is complex and might be individual-specific. However, the first step toward finding this complex function is to see how comfort is correlated with biomechanical measurements. In this study, we examined the correlation between comfort with trunk and knee joint ROMs. In other words, we hypothesized that movement restriction was a part of discomfort. This has been seen in previous research as well, where it is found that users reported discomfort with exoskeletons because it reduced movement flexibility [17]. Fig. 6 showed high similarity index and PB correlation coefficients between users' comfort and trunk ROM, unlike those observed for the knee. In other words, users preferred the exoskeleton setting that allowed a larger trunk ROM as the one that was more comfortable in 74.4% of cases.

As Fig. 4 indicates, while high-strength elastic bands are favored, compared to low-strength ones, for their higher biomechanical support, users perceive them as less comfortable. Average trunk ROM data showed that exoskeleton settings with high-strength elastic bands restrict users' movement more than those with low-strength elastic bands. This difference explains the low comfort level that users was perceived from high-strength elastic bands, considering that a high correlation exists between users' perceived comfort and trunk ROM (Fig. 6). As such, the body joints ROM can be used in the future as an indicator of users' comfort, or can be integrated with other objective functions to maximize users' satisfaction.

This study has limitations that should be considered when interpreting the results. First, the results were for two common dynamic (weight lifting) and static (trunk bending) tasks. The results may differ for other tasks, especially when they are not bilaterally symmetrical [33]. Second, the average JND values of muscle activity and joint ROM were used for all participants. However, it is recommended to have individual-specific JND values as individuals' perceptions are different. Finally, As a preliminary study, the current work is limited by a small sample size. Future experiments will be conducted with more participants and incorporate additional factors, e.g., pain, mobility, and stability, to enhance the depth and applicability of the results.

CONCLUSION

This study explored the relationship between objective metrics, back muscle activity (measured through EMG) and ROM of knee and trunk joints, and subjective user feedback, perceived comfort and biomechanical support, in the evaluation of back-support exoskeletons. The findings indicated that while EMG metrics can partially reflect users' perception of biomechanical support, they do not fully capture the complex nature of users' perception of load. Conversely, trunk ROM shows a strong correlation with perceived comfort, suggesting that reduced movement restriction is associated with greater discomfort. Users' preferences for exoskeletons were influenced by a balance of comfort and support, with no single factor being dominant across all scenarios. This research laid the groundwork for understanding how different biomechanical indicators align with user perceptions of the exoskeleton efficiency and highlighted that users consider a broader range of factors when selecting their preferred exoskeleton setting. The study also emphasized the need for further research to identify more sensitive objective metrics that align with users' perceptions. Such insights could help develop a more comprehensive objective function that better represents the complex factors influencing user preference and satisfaction when wearing an exoskeleton that can contribute to the optimized design and adoption of user-friendly exoskeletons.

ACKNOWLEDGMENT

We acknowledge that this project was funded by the Natural Sciences and Engineering Research Council of Canada in partnership with Alberta Innovates (Grant # ALLRP 567348 – 21).

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