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Range of Motion from Four Passive Shoulder Exoskeletons

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Abstract: Passive exoskeletons are wearable external mechanical devices that are intended to provide support to various body parts with an objective of reducing muscle fatigue that develops when body joints (e.g., shoulder, back) are in sustained awkward postures to perform manual tasks. Different exoskeleton designs may result in decrements of motion capability about a joint (e.g., shoulder). This reduced motion may be detrimental if the tasks performed require body joint postures greater than the exoskeletons allow. The objective of this study was to identify differences or limitations in the ability of wearers of four passive exoskeletons to move their shoulders/arms in various directions compared to not wearing an exoskeleton. A total of 18 (9 males, 9 females) experienced manufacturing employees participated in the range of motion testing of four passive shoulder exoskeletons. Evaluation consisted of a quantitative assessment of the participants' maximum shoulder flexion/extension, abduction/adduction, and horizontal flexion/extension wearing an exoskeleton compared to the same motions without an exoskeleton using video motion capture. Shoulder joint angles were calculated based on the International Society of Biomechanics standards for reporting joint motion. The exoskeletons did not affect the ability to reach up in front of the body (shoulder flexion) but did reduce the ability to reach behind the body (shoulder extension) compared to not wearing an exoskeleton. Three of the four exoskeletons resulted in a significant decrease in maximum shoulder abduction and all exoskeletons significantly reduced shoulder adduction (reaching down across the body). All exoskeletons significantly reduced maximum shoulder horizontal flexion and two exoskeletons significantly reduced shoulder horizontal extension. The exoskeletons included in this study limited the maximum range of motion in some movements, generally motions across the body or behind the body. The observed limitations were largely consistent across all exoskeletons. Shoulder exoskeleton range of motion quantification is necessary to assess functionality, however, it is also necessary to evaluate these exoskeletons in worksite studies and obtain user preferences.

Keywords: Range of motion, passive shoulder exoskeletons, motion capture system

1. Introduction

Recent advances in wearable technology have resulted in the development and strong interest in wearable exoskeletons to assist the users with their manual work activities. Passive exoskeletons are wearable external mechanical structures that utilize materials, springs, or dampers to store energy harvested from human motion, ultimately using this stored energy to support a posture or motion (de Looze et al, 2016).

Recent occupational injury statistics (BLS, 2020) indicated that 14.9% of lost-time cases in 2019 involved the shoulder region, and although lost-time shoulder cases were less than half of lost-time back cases (3.9 vs. 9.6 cases per 10,000 FTE), shoulder cases resulted in approximately three times the duration of lost-time compared to cases involving the back (22 days vs. 7 days). Manual work involving sustained and/or repeated arm elevation and working with the elbows above shoulder level increases the risk for work-related musculoskeletal disorders (WMSDs) of the shoulder (Waersted et al, 2020). Numerous laboratory studies have been performed assessing the impact of various passive upper limb exoskeletons on simulated occupational tasks such as overhead drilling and wiring (Kim and Nussbaum, 2019), with most studies showing reduced shoulder muscle activity when utilizing the exoskeletons. Thus, interest in passive shoulder exoskeletons is increasing from several industry sectors (e.g., manufacturing, construction) as a potential intervention to reduce the incidence and cost of work-related musculoskeletal disorders of the shoulder (e.g., rotator cuff tendinitis).

While a recent review of the passive upper limb exoskeleton research literature found moderate evidence that passive upper limb exoskeletons reduce shoulder muscular demands for overhead work (McFarland and Fischer, 2019), some

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evidence suggests that exoskeletons may alter or limit joint postures and range of motion. Kim et al (2018) evaluated the impact of an EksoVest (Ekso Bionics, Richmond, CA, USA) passive shoulder exoskeleton on the maximum range of motion of the dominant shoulder and found that maximum shoulder flexion and shoulder abduction capability decreased by 4.3° and 16.2°, respectively. Pacifico et al (2020) assessed the impact of the MATE (Comau, Turin, Italy) passive shoulder exoskeleton on shoulder postures when performing specific tasks such as overhead tracing and seated repetitive reaching. Results indicated there was little change in shoulder flexion-extension angles for these tasks with the exoskeleton, however there was a large decrease in shoulder abduction-adduction capability performing these tasks when wearing the exoskeleton. It is important to develop a more thorough understanding of the range of motion limitations imposed by the passive shoulder exoskeletons as some tasks in various industries require extreme reaches in different directions, and exoskeletons may reduce the ability of workers to perform such tasks. Thus, the main objective of this study was to perform a more thorough assessment of more recently developed passive shoulder exoskeletons to quantify the benefits and limitations in terms of shoulder joint range of motion.

2. Methods

2.1 Participants

The participants for this study consisted of 18 (9 males, 9 females) experienced employees recruited from a local aircraft manufacturing facility. The mean (SD) age, stature, body mass, body mass index, and aircraft manufacturing experience was 43.0 yrs (7.5), 177.9 cm (14.1), 108 kg (21.1), 35.2 kg/m^2 (12.8), and 21.7 yrs (8.1) respectively for male participants, and 43.7 yrs (7.4), 161.1 cm (5.6), 70.2 kg (12.9), 27.0 kg/m^2 (4.3), and 15.2 yrs (6.7), respectively for the female participants.

2.2 Experimental Equipment

Four different passive shoulder exoskeletons were utilized in this investigation (Figure 1), including a ShoulderX (SuitX, Emeryville, CA, USA), an EksoVest (Ekso Bionics, Richmond, CA, USA), a Skelex 360XFR (Skelex, Rotterdam, The Netherlands), and a Paexo (Ottobock, Duderstadt, Germany).

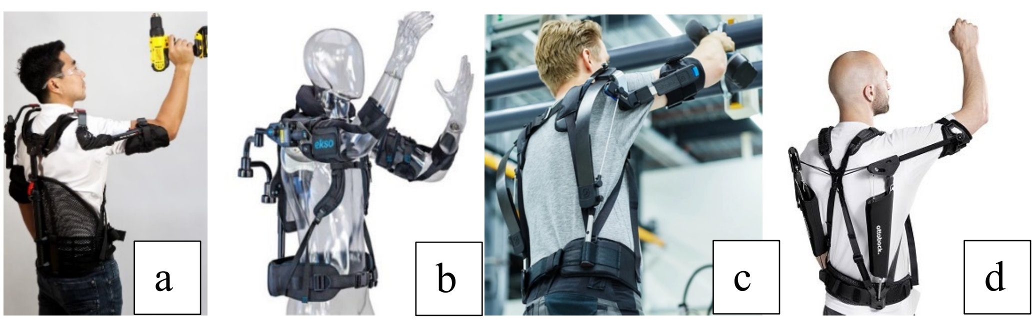

Figure 1. Passive shoulder exoskeletons tested in a controlled laboratory environment: (a) ShoulderX V2 by SuitX, (b) EksoVest by Ekso Bionics, (c) Skelex 360 XFR, and (d) Paexo by Ottobock.

A high-resolution infrared 15-camera 3D motion capture system (Motion Analysis Corp., Santa Rosa, CA) was utilized to quantify the maximum range of motion of the shoulder in each direction of interest. Reflective markers placed on various locations of the participant's body and exoskeleton were utilized to identify body part locations in three-dimensional space by the infrared cameras and the associated software (Cortex, Motion Analysis Corp., Santa Rosa, CA).

2.3 Testing Procedure

Upon arrival to the laboratory, participants were briefed on the study objectives and protocol, and signed an informed consent form approved by the Wichita State University Institutional Review Board for Human Subjects Research. Demographic (age, years of aircraft manufacturing experience) and anthropometric dimensions (e.g., stature, body mass) were recorded followed by the application of the reflective markers. Reflective markers, which are identified in three-dimensional space by the infrared cameras, were secured on the participants using double-sided tape on the following bilateral locations: acromion, anterior shoulder joint center, posterior shoulder joint center, humerus medial epicondyle, humerus lateral epicondyle; and torso locations: spinous process of the 7th cervical (C7) and 8th thoracic (T8) vertebrae, sternoclavicular joint, and the suprasternal notch. When participants were wearing an exoskeleton, it was sometimes necessary to reposition markers to allow for proper fitting of the exoskeleton, particularly around the shoulder joint and T8. In such cases, additional markers were placed on the acromioclavicular joint to identify the shoulder joint center and bilaterally equidistant to T8 to identify the location of T8.

Each participant was given instructions and demonstrations from research assistants on how to perform the maximum shoulder flexion and extension, maximum horizontal shoulder flexion and extension, and maximum vertical shoulder abduction and adduction motions (Figure 2). Participants were instructed to stand upright keeping their shoulders parallel to the floor and perform the various shoulder motions as far as they could while keeping their elbow fully extended and without twisting their torso. For the exoskeleton conditions, participants were fitted to each exoskeleton per the manufacturer instructions and the resistance levels of the exoskeletons were either turned off or in the low-level position if the exoskeleton did not have an on/off capability. For the extension/flexion and shoulder abduction/adduction motions, participants were instructed to perform the motion starting with their thumbs pointing forward. For the horizontal extension/flexion participants were instructed to perform the motion starting with their thumbs pointing upward. Participants performed two repetitions of each motion of interest in a slow, smooth, and comfortable pace. The no-exoskeleton condition was always the first condition the participants completed, followed by the four exoskeletons in a randomized order. The no-exoskeleton condition was always the first condition to allow participant feedback (not reported here) for each of the exoskeletons in comparison to the no-exoskeleton condition. The testing order of the shoulder motions was also randomized for each exoskeleton.

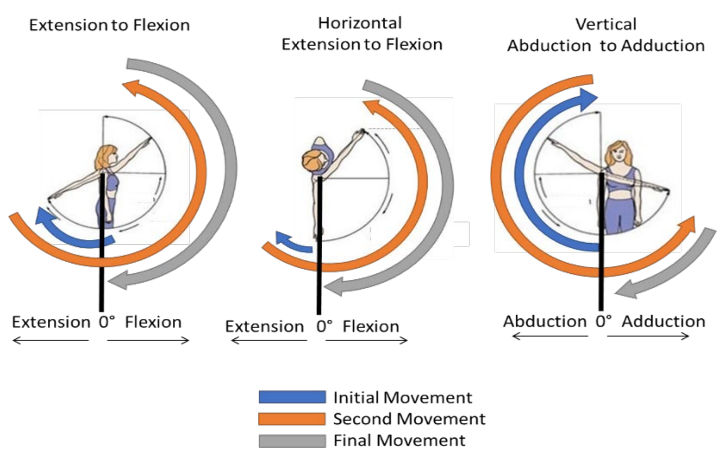

Figure 2. Arm movement sequence used to acquire shoulder joint maximum range of motion with and without passive shoulder exoskeletons.

2.4 Data and Statistical Analysis

The reflective marker positions were recorded by the 15-camera motion capture system at 120 Hz, where the marker data were processed and smoothed using a 4th order zero phase shift Butterworth filter with a 10 Hz cut-off frequency. Maximum shoulder joint angles (e.g., vertical flexion and extension, etc.) were determined based on the International Society of Biomechanics standards for reporting joint motion (Wu et al 2005). For vertical shoulder extension, negative values indicate reaching behind the body. Shoulder adduction negative values indicate moving the shoulder/arm across the midline of the body and positive values indicate not reaching the midline of the body; horizontal extension negative values indicate moving the arm behind the body.

Descriptive statistics (mean, standard deviation) were determined for each of the range of motion variables (e.g., maximum shoulder flexion, maximum shoulder abduction, etc.) for all exoskeletons and the no-exoskeleton condition. For each ROM variable tested, a one-way repeated measures ANOVA was performed to determine if exoskeletons had an impact on the maximum shoulder joint motion capability. The independent variable was the exoskeleton condition, and the dependent variables were the maximum joint angles (i.e., maximum shoulder flexion, maximum shoulder extension, maximum shoulder abduction, maximum shoulder adduction, maximum horizontal flexion, and maximum horizontal extension). Although both right and left arms were texted individually, the exoskeletons were assumed to act symmetrically on both the right and left arms. As such, right and left arm data were combined for each shoulder direction tested. For all

ANOVAs performed, significant exoskeleton effects ($p \leq 0.05$) were investigated via a Tukey HSD assessing all pairwise comparisons while controlling for a Type I error.

3. Results

The mean (SD) maximum shoulder motion capability for each direction of motion tested for each exoskeleton and the no-exoskeleton across all 18 participants is shown in Table 1. For all directions tested the one-way ANOVAs indicated that exoskeletons significantly impacted the maximum movement of the shoulder ($p<0.0001$). For each direction tested Tukey follow-up post-hoc test results are shown in Table 1, where exoskeletons with the same letters are not significantly different from each other.

Table 1. Mean (SD) shoulder joint angle (in degrees) as a function of direction and exoskeleton condition (right and left sides combined). Within each direction, exoskeletons with the same superscript letter are not statistically different.

Exoskeleton	Vertical Flexion ($p<0.0001$)	Vertical Extension ($p<0.0001$)	Abduction ($p<0.0001$)	Adduction ($p<0.0001$)	Horizontal Flexion ($p<0.0001$)	Horizontal Extension ($p<0.0001$)
None	^{AB}160.9 (7.8)	^{A}-62.3 (12.7)	^{A}174.3 (13.3)	^{A}-10.0 (13.7)	^{A}116.3 (10.5)	^{A}-31.5 (11.5)
ShoulderX	^{A}158.7 (11.5)	^{B}-46.8 (13.9)	^{C}163.1 (13.1)	^{B}0.6 (17.5)	^{B}111.0 (12.1)	^{AB}-30.5 (10.9)
EksoVest	^{BC}163.8 (9.5)	^{BC}-40.6 (12.0)	^{BC}165.3 (15.4)	^{B}2.3 (12.5)	^{C}105.0 (12.3)	^{A}-31.1 (9.9)
Skelex	^{BC}162.8 (8.7)	^{BC}-41.2 (11.9)	^{C}164.3 (13.3)	^{B}-1.8 (14.8)	^{B}108.9 (9.8)	^{C}-17.0 (13.4)
Paexo	^{C}164.9 (9.9)	^{C}-38.2 (15.3)	^{AB}170.5 (13.2)	^{B}-2.4 (16.2)	^{B}111.1 (9.6)	^{B}-26.6 (10.5)

To assist in visually demonstrating where differences in maximum shoulder motion were present when wearing an exoskeleton compared to not wearing an exoskeleton, the mean difference of each exoskeleton compared to not wearing an exoskeleton are shown in Figure 3 (flexion/extension) and Figure 4 (abduction/adduction and horizontal flexion/extension).

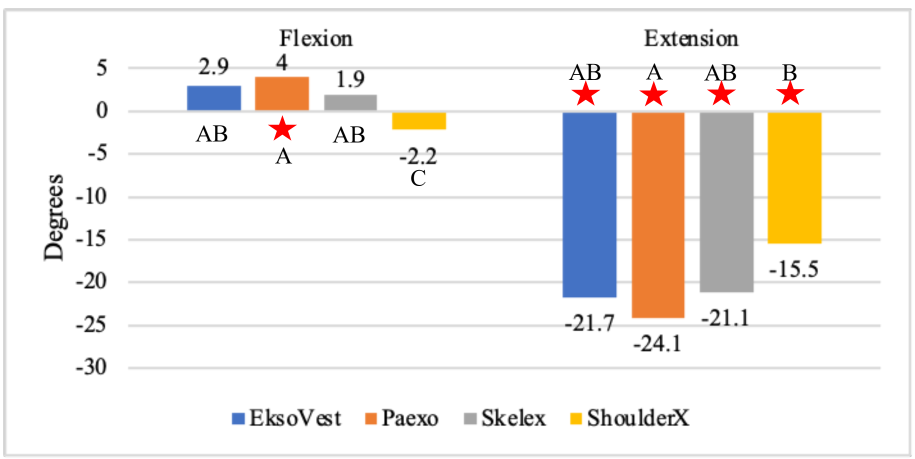

Figure 3. Difference (degrees) in maximum vertical shoulder flexion and extension for each exoskeleton from the no-exoskeleton condition. Positive values indicate greater motion capability with an exoskeleton, negative values indicate decreased motion capability with an exoskeleton, compared to the no-exoskeleton condition. Exoskeletons with the same letters indicate no significant difference between each other whereas red stars indicate significant difference between the exoskeleton and no exoskeleton.

Figure 3 shows the difference between exoskeletons and not wearing an exoskeleton for maximum shoulder flexion and extension capability along with the results from the Tukey HSD post-hoc follow-up tests. Wearing exoskeletons had little impact on maximum shoulder flexion capability, where the Paexo allowed increased shoulder flexion capability compared to not wearing an exoskeleton. The other three exoskeletons did not significantly impact maximum shoulder flexion capability. Also shown in Figure 3, all exoskeletons significantly decreased the maximum shoulder extension capability (15.5° to 24.1° decrease).

Figure 4a shows the difference between exoskeletons and not wearing an exoskeleton for maximum shoulder abduction and adduction capability along with the results from the Tukey HSD post-hoc follow-up tests. All exoskeletons, except for the Paexo, significantly altered (9° to 11.2° decrease) the maximum shoulder abduction capability, and all exoskeletons significantly reduced (7.6° to 12.3°) the ability to maximally reach down and across the body (adduction).

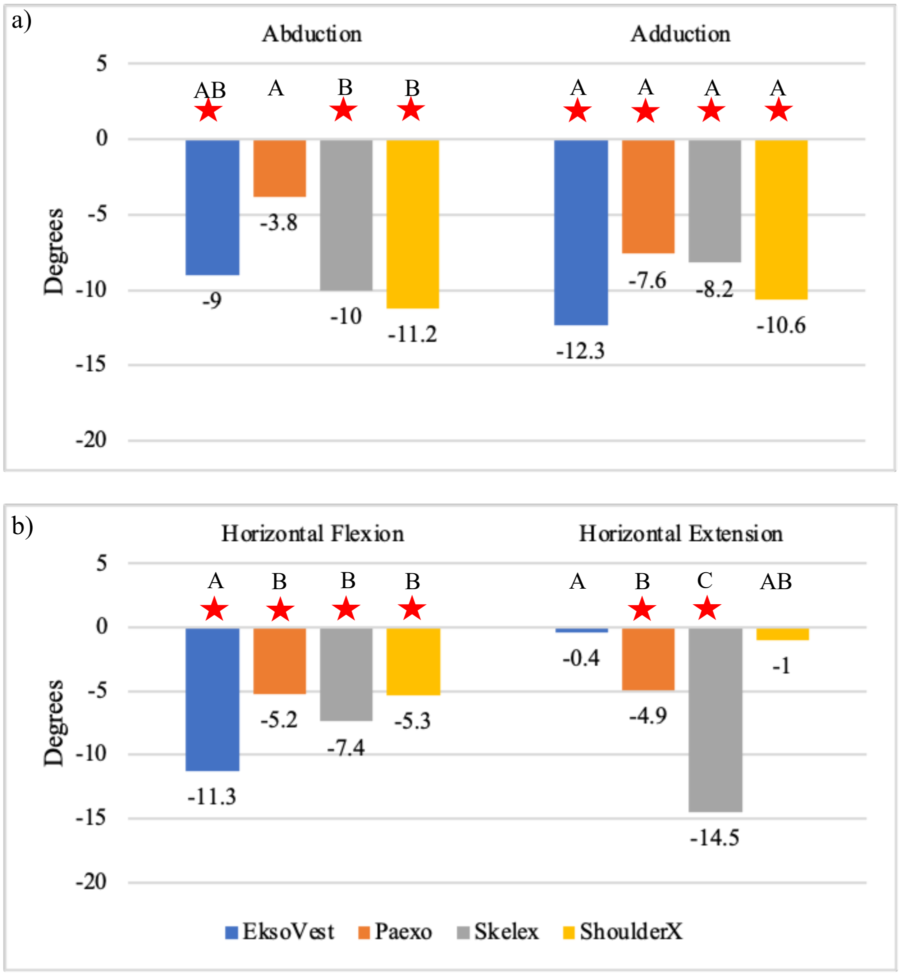

Figure 4. Difference (degrees) in maximum a) shoulder abduction and adduction and b) horizontal shoulder flexion and extension for each exoskeleton from the no-exoskeleton condition. Positive values indicate greater motion capability with an exoskeleton, negative values indicate decreased motion capability with an exoskeleton, compared to the no-exoskeleton condition. Exoskeletons with the same letters indicate no significant difference between each other whereas red stars indicate significant difference between the exoskeleton and no exoskeleton.

Figure 4b shows the difference between exoskeletons and not wearing an exoskeleton for maximumly reaching horizontally across the body (flexion) and reaching horizontally behind the body (extension) along with the results from the Tukey HSD post-hoc follow-up tests. Horizontal flexion was significantly reduced by all exoskeletons (5.2° to 11.3°) with the EksoVest resulting in the largest decrease. Horizontal extension was significantly reduced by the Paexo and Skelex, where the Skelex resulted in the largest decrease.

4. Discussion

Because upper extremity exoskeletons are being utilized to reduce the risk for WMSDs of the shoulder in a growing number of work environments, the objective of this study was to perform a thorough assessment of current passive shoulder exoskeletons to quantify the benefits and limitations of shoulder joint range of motion, which could help identify postures and the associated tasks that could benefit from exoskeleton use. One important finding was the exoskeletons tested did not reduce the ability of the users to flex their shoulder. Another important finding was most of the exoskeletons did encumber all the other shoulder motions tested, i.e., extension, abduction, adduction, horizontal flexion, and horizontal extension.

The exoskeletons tested did not reduce the maximum shoulder flexion angle compared to the no exoskeleton case, however, significant reductions in the shoulder extension angle due to the exoskeletons were observed. For each of the exoskeletons, the overall reduced range of flexion/extension motion (i.e., extension motion) was around 17° to 20°. These results are similar to those reported elsewhere (Kim et al., 2018; Kudernatsch and Peterson, 2018) and are consistent with the design goals of the exoskeletons tested, namely to support anterior overhead work. The reduced extension range of motion would likely only impact workers if they try to reach posteriorly, e.g., for items on a tool belt, or if they fell backwards.

Shoulder joint abduction/adduction and horizontal flexion/extension motion ranges were reduced by the exoskeletons in most cases. These findings are similar to those reported previously for abduction (Kim et al., 2018; Kudernatsch and Peterson, 2018) and adduction and horizontal flexion/extension (Kudernatsch and Peterson, 2018). While these motion limitations are important, it is questionable whether repetitive tasks would and/or should be conducted at these extreme ranges of motion. To this effect, the reduced range of motion resulting from the exoskeletons may serve a benefit by limiting the capacity to work at the joint motion range extremes.

This study should be viewed with several methodological limitations. First, this was a controlled laboratory study with short term exposures, thus, long term impact on shoulder joint range of motion cannot be determined. Second, these were controlled planar motions that may not be representative of tasks that occur in a work environment. Third, other factors that may be important in determining exoskeleton range of motion were not studied, e.g., sizing and comfort.

In conclusion, this study found that multiple passive shoulder exoskeletons resulted in reduced shoulder joint range of motion. The results of this study emphasize the importance of understanding the postures associated with the tasks to be performed when selecting an exoskeleton and/or whether to utilize an exoskeleton. While these laboratory results provide useful information regarding limits to viable work postures, it is necessary to evaluate these exoskeletons in worksite studies.

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