Effects of Arm-Support Exoskeletons on Kinematics and Subjective Assessments During a Static Task

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Upper extremity work-related musculoskeletal disorders (WMSDs) continue to be an important health problem for workers in several industries (Bls.gov, 2018). Epidemiological studies indicate that risk factors for shoulder WMSDs include repetitive arm movement, prolonged or repetitive non-neutral postures, and, in particular, work height (Beach et al., 2012). Occupational exoskeletons are a rapidly emerging technology that have received increased attention as an intervention to control WMSD risks among workers (Nussbaum et al., 2019). Arm-support exoskeletons (ASEs) – designed to passively or actively augment shoulder demands – have the potential to reduce physical demands and fatigue in the shoulder region, thereby reducing shoulder WMSD risks (de Looze et al., 2016). Many earlier studies have reported that ASE use can reduce biomechanical and metabolic demands during overhead tasks (de Vries et al., 2020; Kim & Nussbaum, 2019; Kim, Nussbaum, Esfahani, et al., 2018; Schmalz et al., 2019; Smets, 2019; Spada et al., 2019). However, some studies have also found undesired effects of using ASEs, such as a decrease in end-point precision and shoulder range-of-motion (Kelson et al., 2019; Kim, Nussbaum, Mokhlespour Esfahani, et al., 2018). The aim of this study was to quantify the usability of three commercially available ASEs that have distinct design characteristics: the shoulderX™ V3 (SuitX™, Emeryville, CA, USA), the Ekso EVO (Ekso Bionics, Richmond, CA, USA), and the Paexo Shoulder (Ottobock, Duderstadt, Germany), and their effects on upper extremity kinematics.

A convenience sample of 10 participants completed static overhead tasks in a laboratory environment. Specifically, participants held a right-angled power nut runner (~2.3 kg) in one hand, placed the end-effector on a work target, and a trial involved exerting a normal force within the range of 13-20 N for 30 seconds. The target had a triaxial load cell (AMTI, Watertown, MA, USA), which was attached to a height-adjustable platform. A repeated measures design was employed, in which participants performed a single trial of each experimental condition under all combinations of *Intervention*, force *Direction*, and target *Height*. The four *Intervention* levels were No device (ND), Ekso EVO (EV), shoulderX™ (SX), and Paexo Shoulder (PX). The two *Directions* were forward vs. upward, and the three *Height* levels were low, medium, and high.

Whole-body kinematics was monitored at 15 Hz, using two Azure Kinect systems (Microsoft Corporation, Seattle WA) which were positioned orthogonally (sagittal plane and frontal plane) ~2.5m from the participants. The Azure Kinect data was saved in Matroska video format, from which mean elbow and shoulder flexion angles were calculated. After each trial, subjective ratings of perceived exertion (RPEs) were obtained for the neck, shoulder, elbow, wrist/hand, and the upper back, using the Borg-CR-10 scale (Borg, 1998). After each trial that involved an ASE, participants were also asked to complete a modified System Usability Scale (SUS). The 10 original questions in the SUS can be found in Bangor et al. (2008) and Brooke (1996). We modified the questions to refer to an exoskeleton, rather than a “system”.

Separate repeated-measures analyses of variance (ANOVAs) were performed to test the effects of *Intervention*, *Direction*, and *Height* on each of the outcome measures (mean flexion angles, ratings of perceived exertion, and responses to the SUS questions). Significant effects were followed by Tukey’s HSD post hoc pairwise comparisons, and simple effects testing, where necessary. Statistical significance was determined at $p<0.05$.

There were significant main effects of *Intervention*, *Height*, and *Direction* on mean elbow angles. Compared with the ND condition, using the EV, PX, and SX significantly reduced mean elbow flexion angle, by ~11º, ~18º, and ~22º, respectively. Using the SX led to smaller mean elbow flexion angles when compared with either PX or ND. There were also significant main effects of *Intervention* and *height* on mean shoulder angle. Compared with the ND condition, using the PX and SX led to significantly lower mean shoulder flexion angles, by ~25º and 14º, respectively. Mean shoulder flexion angle was ~11º lower when using the PX compared with either the SX or EV. Notably, there were no significant interactive effects involving *Intervention.*

There were significant main effects of *Intervention* on RPEs at the neck, shoulder, elbow, wrist/hand, and upper back. For the neck, using the SX led to significantly lower RPEs than with ND. Significantly lower RPEs were found at the shoulder and elbow when using the EV compared to the ND, SX, and PX. Using the EV led to significantly lower wrist/hand RPEs compared with the PX. At the upper back, RPE values in the ND condition were significantly higher than using any of the three ASEs. None of the interaction effects involving *Intervention* were significant. There were significant differences between the three ASEs in the overall SUS score. Using the EV led to a significantly higher overall score (~26%) than the PX, indicating that participants found the EV easier to use. There were also significant differences between ASEs for responses several specific questions. For whether the exoskeleton would be used frequently, PX led to lower scores compared to SX and EV. For whether the exoskeleton was easy to use, the EV led to higher scores than PX. For whether the exoskeleton functions are well integrated, PX led to lower scores than either the EV or SX.

Our results indicate that each ASE was used in postures involving less elbow and shoulder flexion/extension. Using these ASEs reduced perceived exertion, though these reductions differed between specific ASE designs and body regions. Notably, none of the ASEs attained a 70% overall SUS score. Hence, additional research is suggested to continue to enhance ASE usability.

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