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Evaluation of a passive exoskeleton for static upper limb activities

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ABSTRACT

The aim of this study was to evaluate the effect of a passive upper body exoskeleton on muscle activity, perceived musculoskeletal effort, local perceived pressure and subjective usability for a static overhead task. Eight participants (4 male, 4 female) held a load (0 kg and 2 kg) three times overhead for a duration of 30 s each, both with and without the exoskeleton. Muscle activity was significantly reduced for the Biceps Brachii (49%) and Medial Deltoid (62%) by the device for the 2 kg load. Perceived effort of the arms was significantly lower with the device for the 2 kg load (41%). The device did not have a significant effect on trunk or leg muscle activity (for the 2 kg load) or perceived effort. Local perceived pressure was rated below 2 (low pressure levels) for all contact areas assessed. Half of the participants rated the device usability as acceptable. The exoskeleton reduced muscle activity and perceived effort by the arms, and had no significant negative effect on the trunk and lower body with regards to muscle activity, perceived effort and localised discomfort.

1. Introduction

Work-related Musculoskeletal Disorders (WMSDs) of the upper extremities are an important issue in the modern workplace (Shin et al., 2012). In the USA, the shoulder was involved in 13% of WMSD cases reported in 2011 (Bureau of Labor Statistics, 2012), second to the back with 42% of WMSD cases. Disorders related to the shoulder have been associated with overhead work, which is a frequent task conducted in industry (Shin et al., 2012; Phelan and O'Sullivan, 2014). A great deal of overhead tasks require workers to maintain prolonged static postures while exerting forces with the hand, which is well recognised as a risk factor for WMSDs (Rashedi et al., 2014). Overhead work is still widely conducted in industry despite the increase in automation. If a muscle has no opportunity to relax, the onset of muscular fatigue is rapid, even at low-force levels, which impairs muscle function (Ng et al., 2014). Continuous contraction of muscles can restrict blood flow, further accelerating fatigue (Ng et al., 2014). Overhead work often requires static postures when holding the weight of hand tools, while also exerting forces with the hand and supporting the deviated posture of the upper limb (Simoneau et al., 1996).

Industry 4.0 is a recent trend of automation and data exchange in manufacturing. This concept has been classified as the fourth industrial revolution, where cyber-physical systems monitor the physical processes of the factory and make decentralized decisions as a ‘smart factory’ (MacDougall, 2014). One of the philosophies of Industry 4.0 is technical assistance, whereby the system has the ability to assist humans with tasks that are difficult or unsafe (MacDougall, 2014). There are many manual handling tasks that could be automated but many others are difficult to do as they require human precision, skills, decision-making, flexibility and movement capabilities (Bos et al., 2002; Zurada, 2012; de Looze et al., 2016).

A further evolution from Industry 4.0 is Operator 4.0, which considers technology-augmented workers (Romero et al., 2016). One such enhancement could be the use of exoskeletons, which can help to reduce the trade-off between automation and manual tasks requiring human capabilities (Romero et al., 2016). An exoskeleton is a wearable technology to augment and assist human motion, thereby reducing the physical stress applied to the wearer, which, in turn should reduce the risk of developing WMSDs (de Looze et al., 2016; Romero et al., 2016). Exoskeletons can be classified as either active or passive. Active systems comprise of one or more actuators to augment the human's power, whereas passive systems use material compliance to provide gravity compensation, and/or spring/elastic members to store and release energy during movements to assist workers to perform physical movements (Matthew et al., 2015; de Looze et al., 2016).

The main application of exoskeletons to date has been for medical/

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rehabilitation purposes, where the devices are aimed at assisting and/or supporting physically weak, disabled or injured people with activities of daily living or rehabilitation exercises (Viteckova et al., 2013). A small number of exoskeletons have been designed for military applications to increase the muscular strength or carrying capability of soldiers (Anam and Al-Jumaily, 2012; Yan et al., 2015). With regards to industrial applications, the concept is fairly recent, and as such, research and development is still in its infancy with many concepts not tested beyond the laboratory (de Looze et al., 2016). Most industrial exoskeletons can be considered as either trunk exoskeletons that assist with trunk flexion/support to prevent back injuries, or upper body exoskeletons supporting the upper limbs in lifting or providing postural support (de Looze et al., 2016).

An upper body exoskeleton could be beneficial in assisting with static overhead work. In theory, a passive exoskeleton compensates for gravity, arm weight and the load being handled, thereby reducing risk of WMSDs. In a review conducted by de Looze et al. (2016), it is evident that commercially developed exoskeletons are mainly passive in nature with the focus on reducing physical load during dynamic lifting and static bending. The benefits of exoskeletons in reducing the physical load on the human have been proven in laboratory environments. Barrett and Fathallah (2001) reported that the PLAD, HappyBack and Bendezy passive trunk exoskeletons reduced Erector Spinae muscle activity levels by 21–31% for static bending while holding loads. Regarding active systems, Huysamen et al. (2018) studied the effect of an active trunk exoskeleton for dynamic lifting and reported a significant decrease in muscle activity of the Erector Spinae (from 55 to 45% MVC, a reduction of 27%) and Biceps Femoris (from 24 to 19% MVC, a reduction of 20%).

Various passive upper arm devices have been developed in the last few years including the Levitate exoskeleton. In a study conducted by Spada et al. (2017b), this exoskeleton revealed a positive effect for activities that involve a posture with raised arms, where, on average, work performance increased by 30% and fatigue was perceived to be less when wearing the exoskeleton than when not. However, little information is known on the potential benefits of these exoskeletons regarding the biomechanical strains associated with manual handling tasks. Theurel et al. (2018) assessed the physiological consequences of using a passive upper-limb exoskeleton (EXHAUSS Stronger®) during manual handling tasks and concluded that the exoskeleton effectively reduced the workload of the shoulder flexor muscles during manual lifting/lowering and stacking/unstacking tasks.

Previous research and developments have proven that it is a challenge to achieve both technically feasible and user-centred design exoskeletons with good usability. Studies on exoskeleton prototypes have shown that they do not always achieve their objectives initially by failing to meet the needs of the end users or stakeholders, i.e. physical loading was not reduced or low device acceptance (Almenara et al., 2017). In other instances, the key objectives were met by reduced loading of targeted muscle groups, but elsewhere on the body had increased loading and high localised discomfort caused by the forces applied by the exoskeleton on the body (de Looze et al., 2016). For instance, the EXHAUSS Stronger® passive upper limb exoskeleton increased antagonistic upper arm muscle activity, postural strains, cardiovascular demand and even changes in upper limb kinematics were noted (Theurel et al., 2018). Moreover, the three passive trunk exoskeletons mentioned above increased muscle activity of one or more leg muscles (Barrett and Fathallah, 2001).

The purpose of the current study was to perform an ergonomic assessment of a passive arm exoskeleton aimed at providing mechanical support to the upper limbs during static overhead work to reduce the risk of WMSDs. The hypothesis tested was whether a passive exoskeleton reduces muscle activity and perceived effort for a simulated overhead task. Specifically, the objectives were to assess the effect of the device on muscle activity, physical effort, local perceived pressure and subjective usability in a static overhead task. The exoskeleton was developed as part of the EU-funded project Robomate (www.robo-mate.eu).

2. Method

2.1. Participants and ethical approval

Four male and four female participants gave written consent to participate in the study (Means & SD: Age: 38years ± 10, Mass: 72.6 kg ± 7.87, Stature: 1761 mm ± 50). No participant had prior or current musculoskeletal disorders. The experiment was approved by the Research Ethics Committee of the Canton Zurich.

2.2. Experimental design

The independent variables were LOAD (0 kg and 2 kg) and SYSTEM (With Exoskeleton: ES, WithOut Exoskeleton: W-ES). The dependent variables were muscle activity (EMG: Biceps Brachii, Medial Deltoid, Erector Spinae at level L3 and T9, Rectus Abdominis, Biceps Femoris, Rectus Femoris, Tibialis Anterior and Gastrocnemius) and perceived effort of the arms, trunk and legs. Additionally, local perceived pressure and usability were assessed for the 'with exoskeleton' conditions.

The study comprised of four conditions (LOAD ×2, SYSTEM ×2) in a full factorial design, which were performed by each participant in a randomised order (for LOAD and SYSTEM). The 2 kg cylindrical load (diameter 5 cm) was held in the hand, whereas no load was held for the 0 kg conditions. The 2 kg load was chosen as being indicative of the common weight of a powered industrial hand tool.

This was the first evaluation of this nature of the arm exoskeleton, and therefore, on safety grounds, the tasks were limited to simple short duration overhead static exertions. The participants were requested to assume a predefined overhead reaching posture with the dominant elbow and shoulder both flexed at 90°, wrist in a neutral position, and knuckles facing upwards (forearm prone).

2.3. Procedure

On entering the laboratory, participants were informed of the testing procedure and equipment involved. Anthropometric measurements (stature and mass) were obtained followed by the preparation and placement of the EMG electrodes. After a detailed explanation and demonstration by the investigators, participants were required to practice the task and demonstrate their understanding of the subjective measurements being assessed. Testing commenced once the participants were proficient and comfortable with the testing requirements.

Each participant held the load overhead at a fixed height for 30 s. This was repeated three times for each condition with a rest of at least 1 min and 5 min between trials and conditions respectively to avoid fatigue.

In order to get to the overhead reach point, each participant was required to stand upright, with shoulder and elbow flexed at 90°, wrist in a neutral position and hand closed. Finally, the distance between the ground and knuckles was measured and set as the fixed overhead height for each participant. An adjustable stand, set to each participant's fixed overhead height, was placed next to and in-line with the arm being lifted. Each participant was required to line up the top of their knuckles with the height of the stand. EMG recording commenced once the hand and arm postures were correctly positioned and steady. EMG was recorded during the 30 s of each trial.

At the end of the experiment, participants performed two 3s Maximum Voluntary Contractions (MVCs) for each of the muscles examined (as per the SENIAM protocol, Hermens et al., 2000). Thereafter, two 10s Reference Voluntary Exertion (RVE) measurements were obtained for the upper limb muscles (Mathiassen et al., 1995). The RVE measurement required the participants to be seated with both shoulders abducted to 90° and elbows extended to 180° with palms facing