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Biomechanical Evaluation of the Effect of Three Trunk Support Exoskeletons on Spine Loading During Lifting

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Abstract To evaluate the biomechanical effect of exoskeletons during lifting, three studies were performed to compare spine compression during lifting without and with three exoskeletons (Laevo, Robo-Mate, SPEXOR). In these studies, participants (11, 10 and 10, respectively) lifted boxes (10, 15 and 10 kg, respectively) from ankle height. Spine compression reductions ranged from minor changes in the first exoskeleton to 17% and 14% reductions in the second and third exoskeleton, respectively. Lumbar flexion was increased by the first exoskeleton while it was reduced by the second and unaffected by the third. Effects of exoskeletons on spine compression were affected by support moments, reductions in lifting speed and subtle changes in lifting style. Modifications of design and control could help to improve the timing and magnitude of support of exoskeletons during lifting.

1 Introduction

Worldwide, low back pain (LBP) affects about 37% of the population each year [1] and the recurrence rate is about 33% within a year [2]. Additionally, effect sizes of treatments are moderate at best [2]. Consequently, more focus on prevention seems warranted. Cumulative occupational low back loading has been shown to be a risk factor for LBP [3]. This suggests that reduction of spine loading during activities such as manual lifting could be effective in reducing the risk of LBP. However, only small effects of interventions to reduce low back loading have been found [4], which might be attributable to interactions between lifting style and task conditions [5].

Trunk support exoskeletons might contribute to reduction of spine loading during manual work. While substantial effects of such devices have been reported for static work [6], a thorough evaluation of biomechanical effects during manual lifting was

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lacking until recently. Therefore, we recently performed a biomechanical analysis of the effects of three trunk support exoskeletons during dynamic lifting [7–9]. In this paper we compare findings between those devices. We hypothesized that each of the devices reduces spine loading during dynamic lifting.

2 Material and Methods

2.1 Participants, Exoskeletons and Procedure

After approval of the local ethics committee, three studies were performed to evaluate the biomechanical effect of three trunk support exoskeletons, that represented a substantial range of support methods and magnitudes. Symmetrical dynamic lifts were performed without and with exoskeleton using a box with handles slightly above the ankle joint. In the first study, 11 male participants used two versions of a light weight passive (commercially available) device, the Laevo [7], while lifting a 10 kg box from a near and a far location. In the second study, 10 male participants lifted a 15 kg box with a prototype actuated exoskeleton (Robo-Mate [10]), using three lifting techniques (stoop, squat, free) [9] and three modes of controlling the EXO (mode 1: support based on trunk inclination; mode 2: support based on forearm EMG; mode 3: 50% of the support based on each of modes 1 and 2). In the third study, 10 male professional luggage handlers lifted a 10 kg box with a newly developed passive exoskeleton (SPEXOR [11]), using the same three lifting techniques [8]. This device is also still a prototype. It contains features such as two joints, misalignment compensation, and stronger support, but it is substantially heavier than the Laevo.

2.2 Measurements and Analyses

During lifting, 3D kinematics of the lower and upper legs, pelvis and trunk were recorded (50 samples/s; Optotrak opto-electronic motion analysis system). Ground reaction forces were recorded (200 samples/s) using a 1.0 by 1.0 m custom-made force plate. Surface EMG was recorded (1000 samples/s) bilaterally on five back and abdominal muscles.

Using inverse dynamics, 3D net moments of subject plus exoskeleton at the lumbo-sacral joint (L5-S1) were calculated [12]. Support moments of the two passive exoskeletons were calculated from measured bending angles, in combination with angle-moment relations measured prior to the lifting experiment. For the actuated exoskeleton, support moments were measured in the motors at the hip joints. Subject-moments were calculated by subtracting exoskeleton support moments from net moments.

Net moments, lumbar flexion and trunk muscle activity normalized to maximum voluntary contraction, were used as input to an EMG-driven trunk muscle model [13] to calculate compression forces at the L5-S1 joint. Exoskeleton support moments during peak loading, subject moments, compression forces and peak lumbar flexion and trunk velocity were tested for effects of exoskeletons using repeated measures ANOVAs for each experiment separately.

3 Results

In all three studies, average total net moments during ankle height lifts ranged between 200 and 300 Nm. The maximum support the devices could generate, was about 30, 40 and 50 Nm, for the lightweight, actuated, and new passive exoskeleton.

With the light weight passive exoskeleton (Laevo) support moments during peak loading were less than 20 Nm. As a result, for far lifts, peak spine compression slightly decreased, by 5% averaged over the two versions of the exoskeleton. For near lifts, support effects were counteracted by slight changes in lifting style, resulting in non-significant changes in compression forces.

The actuated exoskeleton (Robo-Mate) generated, at the instant of peak spine loading, support moments of on average 17 Nm. Nevertheless, spine compression, averaged over lifting techniques, decreased by 17%. This decrease only slightly varied over lifting techniques (stoop, squat or free) and did not depend on control mode.

The new passive exoskeleton (SPEXOR) generated a support moment of 33 Nm at the instant of peak spine loading. It resulted in a decrease of spine compression of 14%, and this did not depend on lifting technique.

In all studies, lifting with the exoskeleton resulted in a reduction of peak trunk angular velocity (by 17, 26 and 17%, respectively). Lumbar flexion increased (8%) with the light weight exoskeleton, decreased (28%) with the actuated exoskeleton and was unaffected by the new passive exoskeleton.

4 Discussion

In this study, we evaluated the biomechanical effects of three exoskeletons on low back loading during lifting. The actual support of the exoskeletons during peak spine loading was substantially lower than the maximum the devices could generate. The main reason is that peak spine loading during lifting occurs early during the upward phase of the movement, when the trunk accelerates upward. In this phase, passive exoskeletons do not generate their maximum support. Additionally, the lightweight exoskeleton suffered from hysteresis [7], and the motors in the actuated exoskeleton failed to generate the intended peak torque during upward acceleration.

Spine load reductions were not fully consistent with exoskeleton support. Specifically, for the lightweight exoskeleton subtle changes in lifting style counteracted the effect of the support. For the actuated exoskeleton, the reduction in spine compression (17%) was larger than expected, based on the support moment (17 Nm). This was mainly due to a substantial reduction in lifting speed when using the exoskeleton. For the new passive exoskeleton, only minor changes in lifting style were found, and the resultant reduction in compression force (14%) was consistent with the support moment (33 Nm). Based on our findings we would recommend for future design of exoskeletons to increase the magnitude of the support, and to better align the timing of peak support with peak spine loading. Evaluation of exoskeletons should not be based on EMG alone, as kinematics may change when wearing an exoskeleton, which requires correction of EMG. Furthermore, safety and versatility in tasks other than lifting should be evaluated.

5 Conclusion

Peak spine compression during lifting was reduced by each of the three exoskeletons tested for the present study. The new passive exoskeleton reduced spine compression more than the lightweight passive exoskeleton. Additionally, spine load reductions when wearing the exoskeletons were affected by changes in lifting style and lifting speed. Design changes (for passive exoskeletons) and control and motor changes (for actuated exoskeletons) should enhance the timing and magnitude of their support.

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