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Abstract Estimation of low-back load can be used to determine the assistance to be provided by an actuated back-support exoskeleton. To this end, an EMG-driven muscle model and a regression model can be implemented. The goal of the regression model is to reduce the number of required sensors for load estimation. Both models need to be calibrated. This study aims to find the impacts of limiting calibration data on low-back loading estimation through these models.

1 Introduction

Using a back-support exoskeleton helps to reduce the low-back load during manual load handling, which may decrease the risk of low back pain. In actuated exoskeletons, the assistive moments are generated by active components, e.g., motors. These active components are operated by a control system that utilizes a reference signal to regulate the assistive moment [1]. A logical solution to reduce the low-back loading is to derive the reference signal from a real-time estimation of low-back load measures, such as moments around the L5/S1 joint.

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Using body kinematics and external forces/moments, the net moment around the L5/S1 joint (M_{Net}^{ID}) can be estimated through inverse dynamics (ID) [2]. The superscript here and below denotes the primary model used to determine the variable. M_{Net}^{ID} is counterbalanced by a combination of the moment generated by the human (M_{Human}) and any assistive device. M_{Human} consists of the moments generated by trunk muscles active forces (M_{Active}) and moments produced by trunk tissue passive forces ($M_{Passive}$). $M_{Passive}$ is coupled to lumbar flexion and cannot be compensated by any assistive moment by the exoskeleton. Moreover, it reaches substantial magnitudes at extreme flexion angles [3]. Thus, ignoring it leads to overestimating the required assistive moment. To avoid this overestimation, the reference signal should be determined based on M_{Active}.

M_{Active} and $M_{Passive}$ can be estimated separately through an EMG-driven muscle model (EMGMod) using 12 EMG channels from trunk muscles and the lumbar flexion angle [4, 5]. In order to circumvent the need for many sensors on the human body, a regression model (RegMod) can be fitted between signals recorded by two of the EMG sensors and built-in exoskeleton kinematic sensors as the input variables and M_{Active} as the output variable [6]. The advantage of RegMod over EMGMod is that RegMod requires fewer EMG sensors attached to the body to estimate M_{Active} for exoskeleton control. With fewer sensors, real-time M_{Active} estimation in the workplace becomes more feasible.

EMGMod and RegMod need to be calibrated for each individual through several lifting trials. The number and type of calibration trials might affect the practical feasibility of using the models for exoskeleton control. Therefore, limiting calibration trials might be beneficial. This study aims to determine the impacts of using limited data for calibration on the estimation accuracy of EMGMod and RegMod.

2 Material and Methods

Ten healthy male participants lifted and lowered 7.5 and 15 kg boxes from ankle height to upright posture without and with wearing an active back-support exoskeleton [7]. Lifting trials were performed with three different techniques and at three speeds. Ground reaction forces and moments, and body kinematics were recorded. In addition, back and abdominal muscle EMG activities were recorded, filtered and normalized to MVC.

Post-processing steps are as follows. First, M_{Net}^{ID} was calculated using a bottom-up ID model. Then, for trials with an exoskeleton, M_{Human}^{ID} was determined by subtracting the assistive moment generated by the exoskeleton from M_{Net}^{ID}. In trials without an exoskeleton, M_{Human}^{ID} equals M_{Net}^{ID}. Next, a combination of a limited number of trials without exoskeleton was selected and used as calibration trials to calibrate EMGMod, i.e., optimize parameters reflecting mechanical properties of trunk muscles and tissues for each participant. Employing calibrated EMGMod, M_{Active}^{EMGMod} was estimated, combined with corresponding EMG and kinematic signals, and used to calibrate RegMod.

Data of trials with exoskeleton were used to evaluate the calibration quality. First, M_{Active}^{EMGMod} and $M_{Passive}^{EMGMod}$ were calculated and summed to create M_{Human}^{EMGMod}. Then, root mean square error (RMSE) between M_{Human}^{EMGMod} and M_{Human}^{ID} was calculated to assess the calibration quality of EMGMod. Subsequently, M_{Active}^{RegMod} was calculated, summed up with $M_{Passive}^{EMGMod}$ to create M_{Human}^{RegMod}. Then, RMSE between M_{Human}^{RegMod} and M_{Human}^{ID} was calculated as a measure of RegMod calibration quality.

This procedure was repeated for different sets of calibration trials. Three sets were selected and the corresponding RMSE of EMGMod and RegMod were compared. The first set (QUASI) was a combination of trials that were performed with free lifting technique at a very slow speed. During these trials, dynamically-induced loads are limited; therefore, calibration can be conducted with a limited motion capture system. The second set (BESTOF6) was a combination that resulted in the lowest RMSEs in both models among all tested combinations of six trials. The third set (FULL) consisted of all 14 calibration trials available.

A series of paired T-tests were conducted on RMSEs to determine the impact of calibration sets on calibration quality. A significance level of $p = 0.05$ was used.

3 Results

RMSEs depended on the number and type of calibration trials. Figure 1 shows the RMSEs of EMGMod and RegMod for selected calibration sets.

Regarding EMGMod, the lowest RMSE was obtained by implementing the FULL set (RMSE = 20.29). RMSEs of QUASI (RMSE = 22.83, $p = 0.02$) and BESTOF6 (RMSE = 20.83, $p = 0.03$) sets were significantly larger. The difference between RMSE of QUASI and BESTOF6 was not statistically significant ($p = 0.05$).

For RegMod, the RMSE of QUASI (RMSE = 32.53) set was significantly larger than that of BESTOF6 (RMSE = 26.51, $p = 0.03$) and FULL (RMSE = 25.04, $p < 0.01$) sets. The difference between RMSE of BESTOF6 and FULL was not statistically significant ($p = 0.07$).

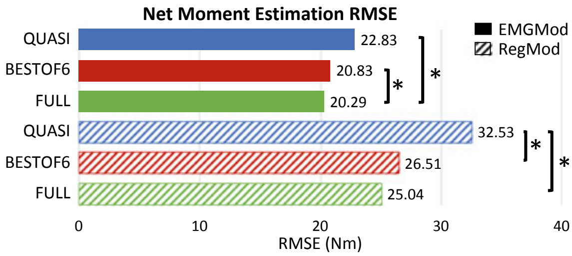

Fig. 1 Net moment estimation RMSE. QUASI, BESTOF6 and FULL represent the calibration sets that were used to calibrate the models. RMSEs of EMGMod depicted in full bars and RMSEs of RegMod depicted in hatched bars

4 Discussion

The resultant RMSEs show that EMGMod calibration was enhanced by implementing the FULL set. However, RMSEs of BESTOF6 and QUASI sets were only slightly higher. This suggests that EMGMod can be calibrated relatively accurately with just a few quasi-static calibration trials.

Resultant RMSEs of RegMod showed that the QUASI set resulted in considerably larger RMSE compared to BESTOF6 and FULL set. This can be a consequence of neglecting the effects of dynamically-induced loads when calibrating using the QUASI set. On the other hand, the lack of difference between RMSEs of BESTOF6 and FULL sets suggests that limited calibration of RegMod can result in similar calibration quality as a fully calibrated model.

It should be considered that some of the examined calibration sets result in considerably higher RMSEs than the BESTOF6 set, while the number of included trials was the same. This shows that not only the number of calibration trials is important, but also the selected lifting conditions is a factor to consider. The BESTOF6 set included trials with two choices for each lifting task characteristic, i.e., both weights lifted, two of the three speeds and two of the three lifting techniques.

Another issue that should be noted is that the RMSE of RegMod was always higher than that of EMGMod. One reason can be that RegMod was calibrated using an outcome of EMGMod, i.e., M_{Active}^{EMGMod}. Thus, estimation errors of EMGMod have adverse effects on the performance of RegMod. Another reason might be that RegMod employs a limited number of variables. This means that some relevant information might be neglected. Hence, additional minor errors in estimation are expected.

One limitation of this study is that both models were calibrated and examined over limited manual lifting conditions. However, in the workplace, manual liftings in other conditions and other tasks such as pulling and pushing are being done, which can be assisted with an exoskeleton. Thus, the estimation quality of the proposed models should be evaluated for other work-related tasks and conditions.

5 Conclusion

The current study shows that an EMG-driven muscle model can be calibrated relatively accurately with a few number of lifting trials. In contrast, a regression model requires more but still a limited number of trials for proper calibration. The present study showed that an appropriate set of calibration trials for a regression model should contain lifts with different loads, speeds and lifting techniques.

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