laevo
exoskeletons

Laevo White Paper - April 2023
Written for professionals in biomedical sciences, health and safety, ergonomics and equivalent fields.

The effect of the Laevo FLEX exoskeleton on muscle activity and perceived exertion

J. Schnieders, V. van Harmelen and S.J. Wagemaker[1]
[1] *Project Manager, Research and Development, Laevo Exoskeletons B.V., The Netherlands*

Abstract. In this study, the effect of the Laevo FLEX lower back exoskeleton on muscle activity and perceived exertion in static bent-forward postures is assessed.
Nine participants maintain six prescribed static bent-forward postures for two minutes, in a condition with and without the exoskeleton. The activity of two back muscles (m. Erector Spinae Longissimus (LM) and m. Erector Spinae Iliocostalis (ILIO)) and three abdominal muscles (m. Rectus Abdominis (RA), m. Obliquus Externus Abdominis (EA) and m. Obliquus Internus Abdominis (IA)) is measured through electromyography (EMG). Participants rate their perceived exertion after each trial on the Borg scale. To enable meaningful comparison between the conditions, the uniformity of the postures is ensured by prescribing and monitoring a pelvic and trunk angle in each posture, and the muscle activity is normalized with respect to Maximum Voluntary Contraction (MVC).
The measured back muscle activity of 8-17%MVC without and 6-13%MVC with exoskeleton is in line with previous studies on muscle activity in static postures.
In the condition with Laevo FLEX exoskeleton, reduced back muscle activity is found in all postures. Averaged over the participants, the muscle activity reduction of the LM is between 16% and 34% and of the ILIO between 19% and 42%, depending on the posture. As expected, the muscle activity of the abdominal muscles (RA, EA, IA) is low (<6%MVC), indicating minimal activity of the abdominal muscles with and without the exoskeleton.
In all postures, a significantly lower perceived exertion rate was observed in the condition with the Laevo FLEX. Averaged across all postures and participants, the mean of the Borg scale without the Laevo FLEX exoskeleton equals 12 ('somewhat hard'), compared to 9.3 ('very light') with the Laevo FLEX exoskeleton.
The Laevo FLEX reduces the load on the back muscles in static bent-forward postures and maintaining them becomes less strenuous and more comfortable.

**Correspondence to*: S.J. Wagemaker (bas@laevo.nl)

1 Introduction

More than seven out of ten people suffer from low back pain (LBP) at least once in their life (Thiese et al., 2014). LBP was found to be the top cause of worldwide productivity loss and due to the high prevalence of LBP (Knezevic et al., 2021), it is one of the main causes of years lived with disability (Vlaeyen et al., 2018). Even if the risk factors of LBP are well known, it is difficult to avoid the burden of the lower back for jobs where flexibility and adaptability of the human workers are required (Hunter, 2001). Often those jobs contain unnatural positions and an overload of the back (Punnett et al., 2005) due to bending and lifting (Griffith et al., 2012).
Lower back exoskeletons (*external skeletons*) are wearable devices designed to reduce the risk of LBP while maintaining human flexibility. These exoskeletons support the low back region by providing a support torque around the hip joint when bending or reaching forward. The support torque reduces the biomechanical load on the lower back.

In this study, the effect of the Laevo FLEX exoskeleton on the perceived exertion and the activity of the back and abdominal muscles is measured, for a condition with and without the exoskeleton. The effect of the exoskeleton is determined by measuring muscle activity through electromyography (EMG) and quantifying the perceived exertion with the Borg scale.
This study focuses on static bent-forward postures, described by the lumbar flexion angle. A bent-forward posture (or lumbar flexion angle) can be reached by multiple orientations of the pelvis and trunk. To enable a fair comparison of muscle activity in multiple conditions, it is crucial that the postures of the participants are uniform across those conditions. This is established by prescribing and monitoring the angle of the pelvis (pelvic angle) and trunk (trunk angle) of each posture.

Figure 1: The Laevo FLEX lower back exoskeleton.

LF angle		Pelvic angle	Trunk angle	Posture
15°	PD	35°	50°	1
	HP	20°	35°	2
20°	PD	40°	60°	3
	HP	25°	45°	4
30°	PD	40°	70°	5
	HP	25°	55°	6

Table 1: Six predefined static postures with corresponding lumbar flexion angle (LF), pelvic angle and trunk angle. Three postures are pelvic dominant (PD) and three postures are half-pelvic (HP). The lumbar flexion angle is calculated by subtracting the pelvic angle from the trunk angle.

2 Method

2.1 Participants

Nine healthy participants (6 female, 3 male, age: 24.1 ± 7.7 years, mass: 71.7 ± 7.4 kg, height: 1.75 ± 0.1 m), participated in this study. Among the participants were students as well as workers, and inexperienced exoskeleton users as well as experienced exoskeleton users. No history of LBP or other constraints was found in any of the participants.

2.2 Exoskeleton

The exoskeleton (Laevo FLEX, Figure 1) is a passive (spring-based) lower back exoskeleton. The Laevo FLEX provides a support torque around the main joint of the exoskeleton, which is aligned with the trochanter major of the user. The trochanter major represents the approximate location of the human hip joint. The support torque is generated by multiple springs inside the exoskeleton. These springs store gravitational energy when the user bends down and return this energy when the user comes back up, making the bending movement less strenuous. The Laevo FLEX is available with different actuator spring strengths: ultra-strong (100%), strong (85%), medium (70%), light (55%) and ultra-light (40%). For more information about the spring strengths and corresponding support torques, see Van Harmelen et al., 2022. The weight of the exoskeleton is 4.0-4.4kg, depending on the size.

2.3 Protocol

Participants are asked to enter and maintain three lumbar flexion (LF) angles. The lumbar flexion angle is calculated by subtracting the pelvic angle from the trunk angle (Larid et al., 2018). For each of the three lumbar flexion angles, a pelvic-dominant (PD) and half-pelvic (HP) posture are defined, resulting in a total of six static postures (see Table 1). The postures are reached via a stoop technique (knees are extended) (see Figure 3). The participants are asked to maintain the six postures in two conditions: with and without the Laevo FLEX exoskeleton. The size of the exoskeleton and the strength of the actuator springs are selected to fit the body size and weight of each participant, according to the sizing tool available on the Laevo website.

Each posture is maintained for two minutes and muscle activity of two back muscles and three abdominal muscles is measured (see Section 2.4). After each trial, the participants rate their exertion on the Borg scale. The Borg scale ranges from 6 (perceiving "no exertion at all") to 20 (perceiving a "maximal exertion"). In between the single trials, participants are given a three-minute rest to minimize the effect of previous trials on the subsequent ones. In total, each participant performs 2x6 trials.

The order of the two conditions is randomized across the participants to minimize bias. Prior to the measurement, participants perform training to familiarize themselves with the exoskeleton and to make sure the participant can enter and maintain the predefined postures.

2.4 Measurement

To measure the muscle activity, five pairs of pre-gelled snap-on surface EMG electrodes are placed on two back muscles (m. Erector Spinae Longissimus (LM) and m. Erector Spinae Iliocostalis (ILIO), see Figure 2) and three abdominal muscles (m. Rectus Abdominis (RA), m. Obliquus Externus Abdominis (EA) and m. Obliquus Internus Abdominis (IA)). The activity of the muscles is recorded using the SAGA 32+ amplifier (TMSi, Enschede, The Netherlands). The electrodes are placed according to Hermens et al., 2000 and Kingma et al., 2010 with an inter-electrode distance of 25mm, see Figure 3. Before the attachment of the electrodes, the skin was shaved and

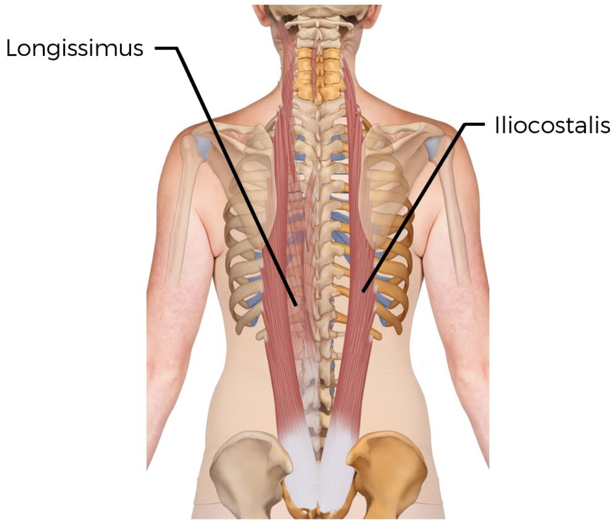

Figure 2: Back muscles of which the muscle activity is measured with EMG: m. Erector Spinae Longissimus (LM), Erector Spinae Iliocostalis (ILIO) (image adapted from www.learnmuscles.com).

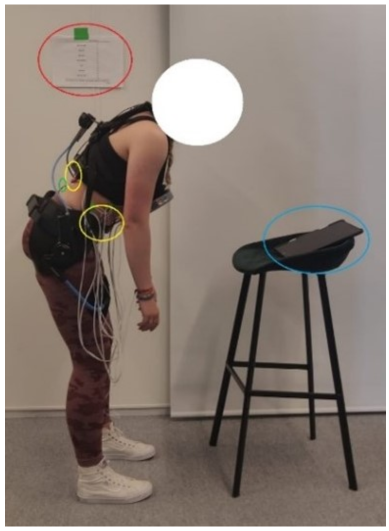

Figure 3: Example of a stoop-technique bending posture with the Laevo FLEX. The location of the EMG electrodes (yellow) and the IMU sensor for S1 (green) are indicated. The tablet (blue) is used for the monitoring of posture.

cleaned with alcohol to reduce skin impedance. The electrodes were attached unilaterally on the left side of the body. The patient ground was attached to a moistened wristband.
The measured muscle activity is normalized with respect to the maximum voluntary contraction (MVC). The MVC represents the maximal force-generating capacity of a muscle. To determine the MVC of each of the five muscles, the participants performed an MVC measurement according to McGill, 1991. The normalized muscle activity is expressed as %MVC. A value of 10%MVC indicates that the muscle exerted 10% of its maximal force-generating capacity.
The Xsens DOT system is used to ensure uniform postures of the participants during the complete measurement. One sensor, placed on vertebrae sacral S1, is measuring the pelvic angle and the second sensor, placed on the processus spinosus vertebrae T11, is measuring the trunk angle. The angles were streamed in real-time to ensure the posture is maintained during the two-minute measurement. In case a deviation of the posture was observed, the participant´s posture was corrected.

2.5 Data analysis

From each EMG measurement of two minutes, a period of 60 seconds (30-90 seconds) is analyzed. The directly measured variable is muscle activity in Volts per second. Raw EMG signals, including MVC-measurement data, are filtered with a band-stop Butterworth filter (49.5-50.5Hz) to filter out the electrical net disturbance. Additionally, a band pass filter (20-400Hz) is used to filter out any ECG disturbance and movement artefacts.

The EMG amplitudes are normalized with respect to the MVC measurement. The highest average of a 250ms time frame out of the three MVC measurements is used for normalization. The normalized EMG values are averaged across all participants, resulting in the %MVC of each of the five muscles in each of the six postures and two conditions.
To assess the perceived exertion rate, the mean of the Borg scale ratings across the participants is calculated for all six postures with and without the Laevo FLEX.
The Wilcoxon Signed Rank test was conducted to analyze differences in muscle activity between the postures and a paired t-test was used to analyze differences in the Borg scale ratings. A significance level was set at $p < 0.05$.

3 Results

3.1 Muscle activity of the back muscles

The measured %MVC of the two conditions averaged over the participants are shown in Table 2 and Figure 5a-e. In the condition with Laevo FLEX exoskeleton, reduced back muscle activity is found for every posture for both the LM and the ILIO. In Table 3, the reduction of %MVC of the back muscles averaged over the participants is shown for each posture. Averaged over all participants, the reduction of the muscle activity of the LM is between 16% (posture 2) and 34% (posture 6). For the ILIO, the reduction is between 19% (posture 2) and 42% (posture 6). The reduction was found to be significant for every posture for the LM. Significant reductions for the ILIO were found in every posture except posture 2.

Muscle		Posture 1	2	3	4	5	6	avg.
LM	w/o	16%	13%	18%	16%	17%	16%	16%
	w	13%	10%	12%	12%	13%	10%	12%
ILIO	w/o	12%	8%	13%	11%	13%	12%	12%
	w	8%	6%	8%	7%	9%	7%	8%
IA	w/o	5%	5%	5%	5%	4%	4%	5%
	w	5%	5%	4%	5%	4%	4%	5%
RA	w/o	2%	2%	2%	2%	2%	2%	2%
	w	2%	2%	2%	2%	2%	2%	2%
EA	w/o	4%	4%	4%	4%	4%	4%	4%
	w	4%	4%	3%	3%	3%	3%	3%

Table 2: Measured %MVC of each muscle in the condition with (w) and without (w/o) Laevo FLEX exoskeleton per posture (1-6), averaged over the participants. A value of 10%MVC indicates that the muscle exerted 10% of its maximal force-generating capacity. LM: longissimus, ILIO: iliocostalis, IA: obliquus internus abdominis, RA: rectus abdominis, EA: obliquus externus abdominis. See Figure 5a-e for a visual representation of this data.

Muscle	Posture 1	2	3	4	5	6	avg.
LM	**22%**	**16%**	**31%**	**27%**	**25%**	**34%**	26%
ILIO	**34%**	19%	**40%**	**33%**	**34%**	**42%**	34%

Table 3: %MVC-reduction by the exoskeleton in each of the six postures, averaged over the participants. In the last column, the reduction averaged over the postures is shown. Bold values represent statistically significant reductions. LM: longissimus, ILIO: iliocostalis. For the abdominal muscles (IA, RA, EA), the %MVC is considered too low to calculate the meaningful reduction levels. See Figure 5f for a visual representation of this data.

3.2 Muscle activity of the abdominal muscles

Low muscle activity was observed for the abdominal muscles (IA, RA, EA), see Table 2 in both conditions. This indicates minimal abdominal muscle activity with and without the exoskeleton. The measured muscle activity of the abdominal muscles is too low to draw meaningful conclusions about the differences in muscle activity between the two conditions.

3.3 Perceived exertion on Borg scale

The Borg scale is used to determine the perceived exertion after each measurement of two minutes. A lower exertion rating was observed with the Laevo FLEX for every posture, see Figure 4. Averaged across all postures and participants, the mean of the Borg scale shows a significant reduction: without the Laevo FLEX exoskeleton equals 12 ('somewhat hard'), compared to 9.3 ('very light') with the Laevo FLEX exoskeleton.

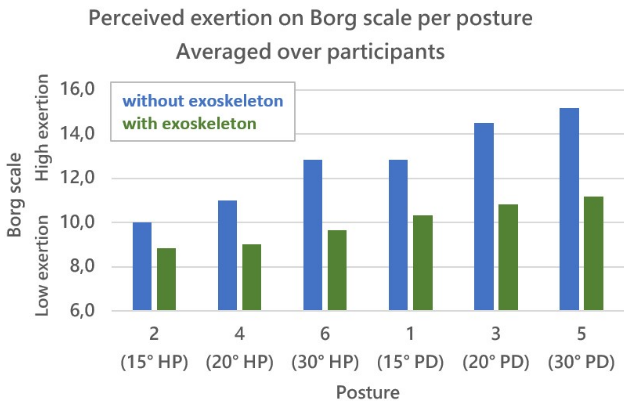

Figure 4: Results of exertion rating on Borg scale, after each two-minute trial. The postures are sorted in order of half pelvic and pelvic dominant.

4 Discussion

This study focuses on the measurement of muscle activity in prescribed static bent-forward postures. It is crucial to monitor and control the posture during the measurement to exclude the effect of non-uniform postures on muscle activity. A bent-forward posture can be reached by multiple orientations of the pelvis and trunk. If not done correctly, the measured muscle activity is affected by arbitrary variation in postures. The effect of the posture on perceived exertion can be seen in the results of the exertion rating (Figure 4). Postures 1 and 2, 3 and 4 and 5 and 6 correspond to identical lumbar flexion angles, but the exertion is experienced differently. This implies that the amount of effort to maintain a specific lumbar flexion angle is influenced by the ratio between the pelvic and trunk angle.
A disadvantage of prescribing static postures in both conditions is that not the full range of motion of the lower back is captured. The exoskeleton will enable some users to maintain certain postures that they would normally not maintain without the exoskeleton. Besides, the prescribed postures can feel 'unnatural' to some participants. However, monitoring and controlling the postures is a simple and straightforward method to ensure measuring the effect of the support of the exoskeleton.

The measured back muscle activity of 6-18%MVC, is in line with previous studies on muscle activity in static postures. The found reduction of muscle activity by the Laevo FLEX (16-42% averaged across the participants) indicates that the Laevo FLEX reduces the load on the lower back muscles. The effectiveness of the Laevo FLEX varies between users, for example, due to anatomical differences. Besides, the effectiveness can depend on the type and frequency of the movements.

Muscle activity of the abdominal muscles of 2-5%MVC with and without the exoskeleton is measured. Since the muscle activity is low, no meaningful conclusions can be drawn about the differences between the two conditions.
Participants rated their perceived exertion after holding each posture for two minutes. While wearing the Laevo FLEX, the perceived exertion is rated significantly lower on the Borg scale compared to the condition without wearing the Laevo FLEX. This indicates that less exertion is experienced while maintaining static bent-forward postures when wearing the Laevo FLEX.
The back muscle activity can be a metric to indicate the risk of developing back injuries. However, a reduction of muscle activity could also result from a transfer of the load from active to passive structures. This especially occurs at the end of the range of motion of the lumbar spine: torques that would normally be produced by the muscles are then taken over by stretched passive structures (Koopman et al., 2019). To minimize this effect in this study, it is ensured that the participants maintain specifically prescribed postures to prevent them to hang in their passive structures.
The activity of the back muscles is closely related to compression forces in the spine (Bosch et al, 2016). The reduction of the back muscle activity infers that the biomechanical load (and with that the musculoskeletal load) in the lower back region is reduced when wearing an exoskeleton during static bending tasks. This enforces the hypothesis that the risk of developing LBP will decrease when wearing the Laevo FLEX for static bending postures, taking into account that musculoskeletal load is a risk factor in developing LBP.

5 Conclusion

The results show reduced back muscle activity (up to 42% reduction of %MVC) and perceived exertion (from 12 ('somewhat hard') to 9.3 ('very light') on the Borg scale) in the static bent-forward postures with the Laevo FLEX exoskeleton. As expected, the muscle activity of the abdominal muscles is low in both the condition with and without the exoskeleton. The exoskeleton reduces the load on the back muscles in bent-forward postures and maintaining bent-forward postures is less strenuous and more comfortable with the exoskeleton.

6 Contact

Would you like to learn more about exoskeletons in general, or do you have specific questions about the EMG measurements? We would be very happy to tell you more! Please do not hesitate to contact us at www.laevo-exoskeletons.com/contact.

7 References

Griffith, L.E., Shannon, H.S., Wells, R.P. (2012). Individual participant data meta-analysis of mechanical workplace risk factors and low back pain. *American Journal of Public Health, 102*, 309-318.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C. & et al. (2000). Development and recommendations for SEMG sensors and sensor placement procedures. *J. Electromyogr. Kinesiol, 10*, 361-374.

Hunter, S.L. (2001). Ergonomic evaluation of manufacturing system designs. *Journal of Manufacturing Systems, 20*, 429-444.

Kingma, I., Faber, G.S., van Dieën, J.H. (2010). How to lift a box that is too large to fit between the knees. *Ergonomics, 53*, 1228-1238.

Knezevic, N.N., Candido, K.D., Vlaeyen, J.W.S., Van Zundert, J., Cohen, S.P. (2021). Low back pain. *The Lancet, 398*, 78-92.

Laird, R.A., Keating, J.L. Kent, P. (2018). Subgroups of lumbo-pelvic flexion kinematics are present in people with and without persistent low back pain. *BMC Musculoskelet Disord, 309*.

McGill, S.M. (1991). Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: implications for lumbar mechanics. *Journal of Orthopaedic Research, 9*, 91-103.

Punnett, L., Prüss-Ütün, A., Nelson, D.I. (2005). Estimating the global burden of low back pain attributable to combined occupational exposures. *American Journal of Industrial Medicine, 48*, 459-469.

Thiese, M.S., Hegmann, K.T., Wood, E.M. & et al. (2014). Prevalence of low back pain by anatomic location and intensity in an occupational population. *BMC Muscoluskelet Disord, 15*, 283.

Van Harmelen, V., Schnieders, J., Wagemaker S.J. (2022). Measuring the amount of support of lower back exoskeletons. *Laevo White Paper.*

Vlaeyen J.W.S., Maher C.G., Wiech K. & et al. (2018). Low back pain. *Nat Rev Dis Primers, 4*, 1-52.

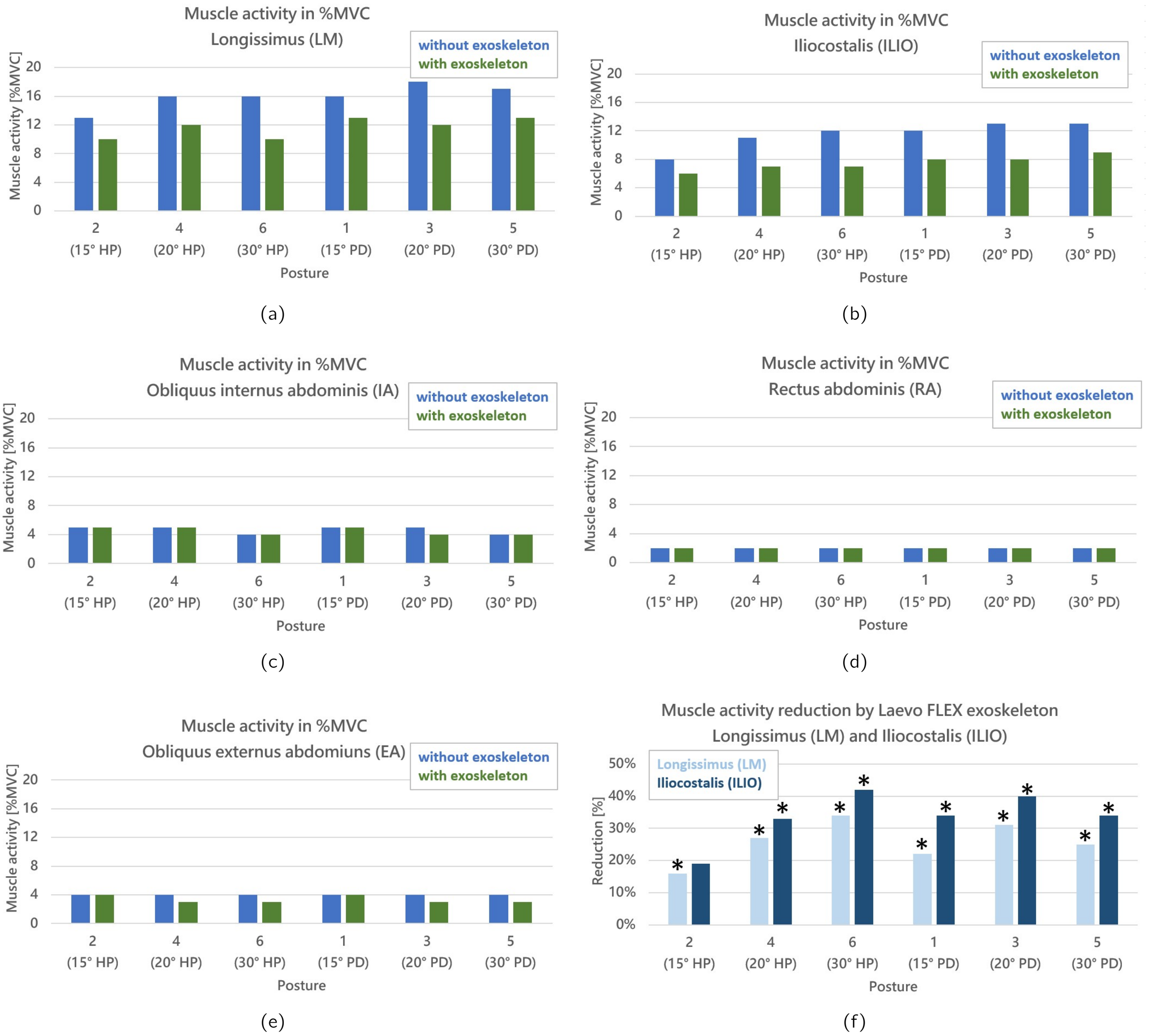

Figure 5: Figure a-e: Measured %MVC of each muscle in the condition with and without Laevo FLEX exoskeleton per posture (1-6), averaged over the participants. A value of 10%MVC indicates that the muscle exerted 10% of its maximal force-generating capacity. (a) LM: longissimus, (b) ILIO: iliocostalis, (c) IA: obliquus internus abdominis, (d) RA: rectus abdominis, (e) EA: obliquus externus abdominis.
Figure f: Muscle activity reduction by the Laevo FLEX exoskeleton of the two measured back muscles (longissimus (LM) and iliocostalis (ILIO))in the six static bent-forward postures. A star symbol (*) indicates a statistically significant reduction by the exoskeleton.
The postures are sorted in order of half pelvic and pelvic dominant.