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Written for professionals in health and safety, ergonomics and equivalent fields.

Measuring the amount of support of lower back exoskeletons

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Abstract. Wearing a passive back exoskeleton is an effective method to mitigate risks on low back pain (LBP). An important characteristic of passive exoskeletons is the torque-angle curve, because it describes the amount of support that is provided to the user in different postures. The amount of support determines to what degree risks of LBP are reduced. Using a unique measurement setup, the torque-angle curves of the Laevo FLEX and Laevo V2.5 lower back exoskeletons are measured.
Especially at bending angles between 0-30°, it is important that a significant amount of support is provided to the user, since all bending motions start in this region. The torque-angle curves show that both the Laevo FLEX and Laevo V2.5 rapidly build up the support torque when slightly bending or leaning forward. This means that the user will experience 'direct' or 'fast' support and that each bending motion is supported effectively. In deep bending postures (bending angles between 60-120°), the amount of support of the Laevo FLEX and Laevo V2.5 is constant or decreasing. This is an important feature to prevent movement restrictions during deep bends and to ensure safety of the exoskeleton user.
The energy loss in the exoskeletons due to friction (hysteresis) is calculated as a metric of efficiency. The hysteresis is calculated to be below 28% and 51% for the Laevo FLEX and Laevo V2.5 respectively. This means that when using the FLEX, more than 70% of the energy that is put into the exoskeleton by gravity is returned to the user. For the Laevo V2.5, this is around 50%.

The torque-angle curve describes the primary function of the exoskeleton: reducing risks of injuries. This white paper is a first step to promote the torque-angle curve of passive exoskeletons. Using the torque-angle curve, simple, objective and straightforward comparison of different exoskeletons is possible.

1 Introduction

Low back pain (LBP) results in more physical disability than to any other condition. LBP has a prevalence of 75-84% and with the ageing population the problem is only getting worse (Hoy et al., 2014). This prevalence means that 75-84% of the general population will suffer from an episode of LBP once in their life. Additionally, 30% of all work-related musculoskeletal disorders are located in the low back region (Eurostat, 2010). Employees who suffer from LBP not only deal with physical, but also psychological problems because of their inability to work. Besides, financially both employer and employee suffer. In the US, direct and indirect healthcare costs because of LBP account for 85 and 238 billion dollars every year (Ma et al., 2014). Compression of the spine has been shown to be an important risk factor for developing LBP (Coenen et al., 2013).

Lower back exoskeletons (*external skeletons*) are wearable devices that are designed to reduce the risk on LBP. These exoskeletons support the low back region by providing a support torque around the hip when bending or reaching forward. This support torque depends on the posture, or more specifically, the position (angle) of the torso with respect to the thighs.
The support torque can be described by a torque-angle curve. The torque-angle curve is a crucial characteristic of the exoskeleton, since it describes the amount of support (and thus the reduction in risks of LBP) the user will receive during his/her job. To enable objective and straightforward comparison of passive exoskeletons, it is important that torque-angle curves are publicly accessible. Unfortunately, very few information is available about the torque-angle curves of exoskeletons.
In this white paper, the torque-angle curves of the Laevo FLEX and Laevo V2.5 exoskeletons (Figure 1) are measured using a unique measurement setup and important characteristics of the torque-angle curves are highlighted.

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2 Method

2.1 Exoskeletons

Laevo FLEX

The Laevo FLEX (Figure 1) provides a support torque around the main joint of the exoskeleton, which is located at 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 energy while bending down and return this energy while coming up, making the bending movement less physically demanding. This reduces the risk of LBP. The Laevo FLEX is available with different strengths of actuator springs: 100%, 85%, 70%, 55% and 40%. The weight of the exoskeleton is 4.0-4.4kg, depending on the size of the exoskeleton.

Laevo V2.5

The concept of the Laevo V2.5 (Figure 1) is similar to the Laevo FLEX. One of the biggest differences is that the Laevo V2.5 has a chestpad instead of a textile vest. The Laevo V2.5 is a lightweight (2.8-3.0kg) device and provides less support compared to the Laevo FLEX.

2.2 Torque-angle curves

The torque-angle curve of a lower back exoskeleton describes the amount of provided support in different postures. The amount of support is described by the torque around the hip (measured in Newton meter (Nm)), at the location of the Trochanter Major. Alternatively, the amount of support can be described by the torque around the L5-S1 lumbar spine segment. However, since the Laevo exoskeletons exert a support torque around the hip joint, it is more convenient to describe the amount of support by the torque around the hip.

The posture, i.e. flexion/extension of the torso with respect to the thighs, is described by the bending angle. The bending angle (β) is defined as the difference between the thigh-torso angle in upright posture (α_0) and in bent-forward posture (α), or mathematically: $\beta = \alpha_0 - \alpha$. Typical stooping (bending from the hip) and squatting (bending from the hip and legs) postures that correspond to a set of bending angles illustrated in Figure 3.

2.3 Measurement setup

The support torque is measured using a measurement setup that resembles the natural bending movement (see Figure 2 and 4). The measurement setup consists of a mannequin torso (representing the human torso), a rotational joint (representing the Trochanter Major) and base (representing the hip and thighs). The measurement setup is connected to a tensile machine (M250-2.5CT) via a steel cable to measure the force required to flex and extend the measurement setup about the joint. Using a digital angle meter, the bending angle is measured. A counter weight ensures that the steel cable is tensioned and to enable a reference measurement without exoskeleton.

2.4 Protocol

Firstly, the reference measurement without exoskeleton is performed, solely influenced by gravity. Secondly, the measurement with exoskeleton is performed. To ensure repeatability, the initial position and the maximum bending angle are defined in the software of the tensile machine. The maximum bending angle is set to 115°(see Figure 4). For the Laevo FLEX, five actuation spring strengths are tested: 100%, 85%, 70%, 55%, and 40%. The Laevo V2.5 is only available with one actuator spring strength.

Figure 1: The Laevo FLEX (left) and Laevo V2.5 (right) exoskeletons. Both exoskeletons provide a support torque around the hip to reduce risks on low back pain.

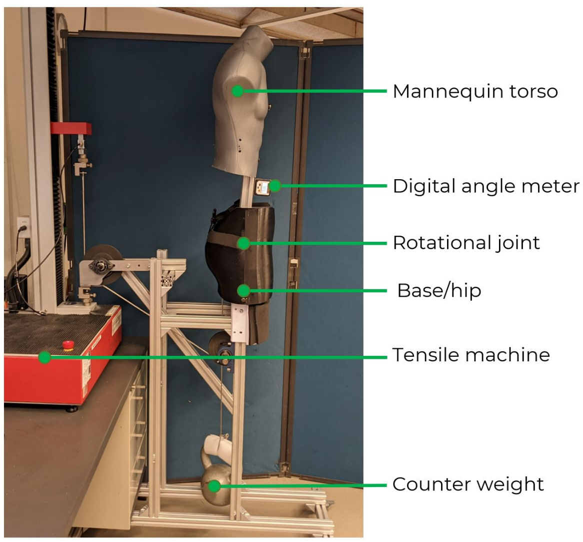

Figure 2: Measurement setup to measure the support torque and bending angle

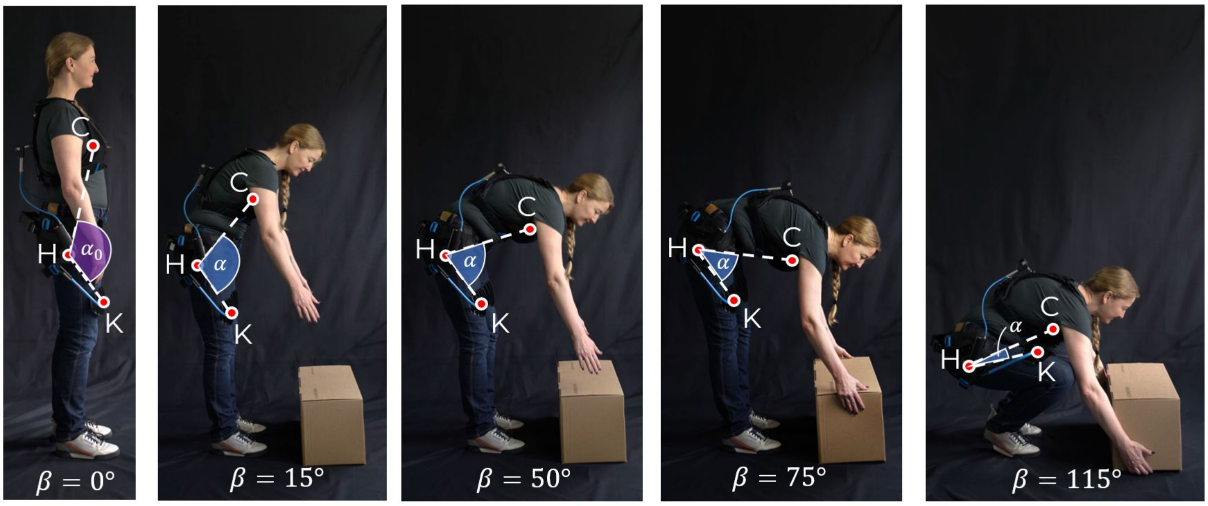

Figure 3: Typical postures corresponding to a bending angle (β) of 0°, 15°, 50°, 75°and 115°. The bending angle (β) is equal to the difference between the thigh-torso angle (the angle between the line hip-knee (H-K) and the line hip-chest (H-C)) in upright (α_0) and in bent-forward position (α), or mathematically: $\beta = \alpha_0 - \alpha$.

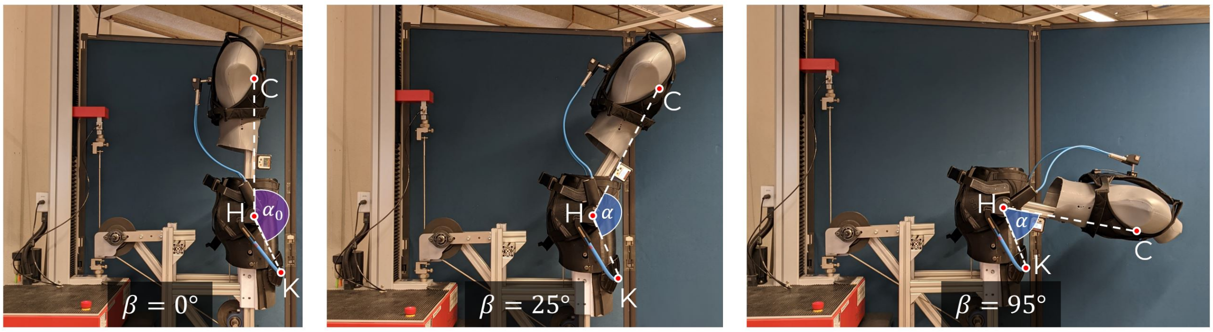

Figure 4: Measurement setup corresponding to a bending angle (β) of 0°, 25°and 95°. The bending angle (β) is equal to the difference between the thigh-torso angle (the angle between the line hip-knee (H-K) and the line hip-chest (H-C)) in upright (α_0) and in bent-forward position (α), or mathematically: $\beta = \alpha_0 - \alpha$.

2.5 Data analysis

The tensile machine measures the travelled distance and force exerted on the load sensor, and is connected with the steel cable to the measurement setup. The measured force and travelled distance are mathematically converted to respectively torque and bending angle. The torque is corrected for the influence of gravity and the counter weight by subtracting the gravity-induced torque and the torque of the counter weight from the calculated torque. This results in the support torque (or torque-angle curve) of the exoskeleton.

An important performance characteristic of an exoskeleton is the friction in the exoskeleton (*hysteresis*). Hysteresis is a metric to determine the efficiency of the exoskeleton. The hysteresis is primarily caused by mechanical friction in the mechanisms inside the exoskeleton. The more hysteresis, the more friction and the less support is provided to the user. The hysteresis is defined as the percentage difference between the energy that is put into the exoskeleton by gravity (*input energy)* and the energy that is returned by the exoskeleton to the user (*returned energy*). In technical terms, the input energy is represented by the area underneath the flexion torque-angle curve, the returned energy by the area underneath the extension torque-angle curve. The returned energy is a metric to summarize the amount of support along the complete range of motion of exoskeleton in a single number.

3 Results

The results of the measurements of the Laevo FLEX and the Laevo V2.5 are shown in Figure 5. The most important numbers are summarized in Table 1. The green line represents bending forward (flexion) and the blue line represents coming up (extension). The distance between the flexion and extension curves is caused by hysteresis. The maximum support torque of the Laevo FLEX equals approximately 52Nm. For the Laevo V2.5 this is approximately 30Nm. The hysteresis of the Laevo FLEX is below 28%. The hysteresis of the Laevo V2.5 is below 52%.

4 Discussion

The maximum torque that is measured for the Laevo FLEX and Laevo V2.5 equals respectively 52Nm and 30Nm. The measured values represent the torque that the user *experiences*. The torque that is actually *exerted* by the exoskeleton is higher, because the exoskeleton has to 'support' the weight of its own upper part.

The hysteresis is calculated to be below 28% and 51% for the Laevo FLEX and Laevo V2.5 respectively. This means that when using the FLEX, more than 70% of the energy that is put into the exoskeleton by gravity is returned to the user. For the Laevo V2.5, this is around 50%. It is important to note that the energy that is put into the exoskeleton is put in by gravity (using the weight of the user's torso) and not actively by the user.

Typical postures that correspond to certain bending angles are shown in Figure 3. Bending from the lower back (*stooping*) usually reaches a bending angle of approximately 75°. When *squatting*, a maximum bending angle of approximately 115°can be obtained.

All bending motions start at a bending angle between 0°and 30°. Therefore, especially in this region of bending angles, it is important to provide a significant amount of support to the exoskeleton user. The Laevo FLEX and Laevo V2.5 rapidly build up the support torque when slightly bending or leaning forward (see Figure 5a-f). This means that the user will experience 'direct' or 'fast' support and that each bending motion is supported effectively. Although the Laevo FLEX provides direct support, walking while wearing the Laevo FLEX is unobstructed because of its unique patented walk-differential mechanism.

To prevent obstruction in deep bending angles and to ensure safety, the amount of support should be constant or decreasing for large bending angles (90°to 120°). This can be seen in the torque curves of the Laevo FLEX (Figure 5a-e) and the Laevo V2.5 (Figure 5f).

5 Conclusion

An important characteristic of passive exoskeletons is the torque-angle curve, because it describes the amount of support that is provided to the user in different postures. The amount of support determines to what degree risks of LBP are reduced, which is the main purpose of the exoskeleton. Promoting the availability of torque-angle curve of passive exoskeletons further enables simple, objective and straightforward comparison.

This white paper should function as a first step to make the torque-angle curve of passive exoskeletons publicly available.

6 Contact

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

	Max. exerted torque	Max. support torque	Max. hysteresis	Returned energy
FLEX 100%	60Nm	52Nm	28%	46J
FLEX 85%	53Nm	45Nm	30%	41J
FLEX 70%	49Nm	41Nm	34%	36J
FLEX 55%	37Nm	29Nm	31%	27J
FLEX 40%	30Nm	22Nm	33%	20J
V2.5	38Nm	30Nm	51%	17J

Table 1: Summary of torque characteristics of the Laevo FLEX (100%, 85%, 70%, 55% and 40%) and Laevo V2.5 for a bending angle range of 0-110°. The actual support torque *exerted* by the exoskeletons is slightly higher than the *measured* support torque, since the exoskeleton 'supports' the weight of its own upper part. The hysteresis is a metric to evaluate the efficiency of the exoskeleton. The returned energy describes the amount of energy that is returned to the user by the exoskeleton over the complete range of motion.

References

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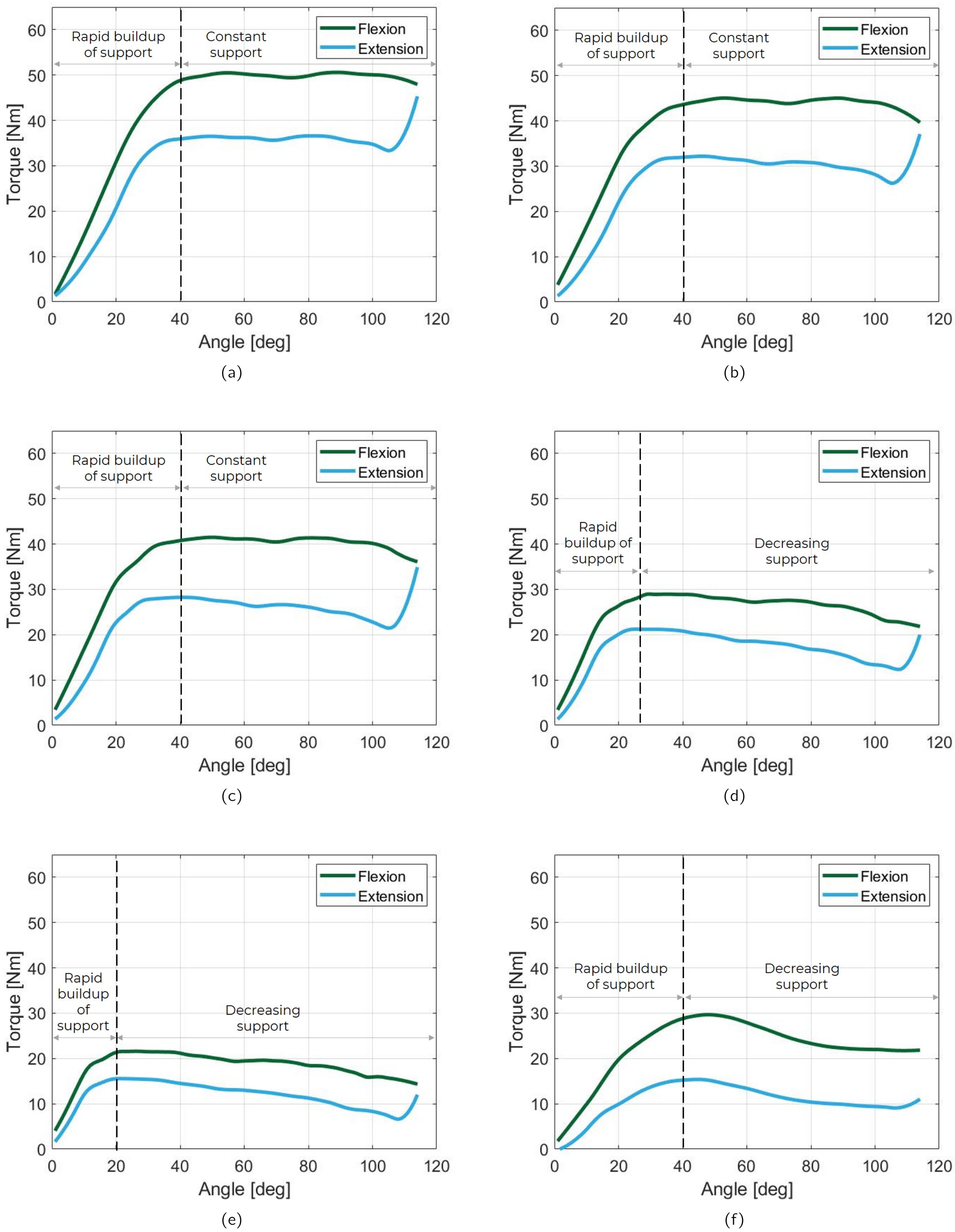

Figure 5: Torque-angle curves of (a) Laevo FLEX 100%, (b) Laevo FLEX 85%, (c) Laevo FLEX 70%, (d) Laevo FLEX 55% (e) Laevo FLEX 40% and (f) Laevo V2.5, with a rapid buildup of support torque for small bending angles and constant or decreasing support torque for large bending angles.

7 Appendix A: comparison

7.1 Considerations

As an extension of this study, the torque curves of the Ottobock Paexo Back, Muscle Suit GS Back, Ergosanté HAPO posture harness and Auxivo Liftsuit (high, medium and low pretension in elastic bands) are measured using the described measurement setup. The measurement setup is designed to resemble the human body, but improvements can still be made. Because of this, some exoskeletons fit better on the measurement setup than others. For example, the measurement setup has no closed connection between lower back and buttocks, which is sub-optimal for the measurement of soft exoskeletons.
The torque curve of the Ottobock Paexo Back can be altered by adjusting a specific setting on the exoskeleton. The torque curves of all exoskeletons can be influenced by the position of the exoskeleton on the human body, for example by tightening certain belts. These effects are not taken into account in this study.
Shifting of the exoskeleton interfaces on the measurement machine (and on the human body) affects the effectiveness of the exoskeleton. This may be the cause of the extension curve dropping below zero torque for the Muscle Suit GS Back, the Ergosanté HAPO posture harness and the Auxivo Liftsuit with low pretension in the elastic bands (see Figure 6). Practically, a torque curve below zero indicates that the exoskeleton does not provide support in this region, thus effecting the *returned energy* in Table 2. The degree of shifting of the exoskeleton interfaces dependents on the body shape, type of clothing and movements of the user.
Some exoskeletons tend to pull on the shoulders, contributing to compression forces in the spine of the user. This may affect the effectiveness of the exoskeleton, since compression forces are considered to be a risk factor for lower back injuries. The forces exerted by the exoskeleton along the body cannot be measured with the current measurement setup.

7.2 Results

In Figure 6, the measured torque curves of the (a) Ottobock Paexo Back, (b) the Muscle Suit GS Back, (c) the Ergosanté HAPO posture harness and (d, e, f) the Auxivo Liftsuit (high, medium and low pretension in elastic bands) are shown. All bending motions start at a bending angle between 0°and 30°. Therefore, especially in this region of bending angles, it is important to provide a significant amount of support to the exoskeleton user. Compared to the Laevo exoskeletons (Figure 5), the torque curves of the Ottobock Paexo Back, the Muscle Suit GS Back, the Ergosanté HAPO posture harness and the Auxivo Liftsuit (Figure 6) show a less rapid buildup of the support in this region.
In case of the Muscle Suit GS Back, Ergosanté HAPO posture harness and the Auxivo Liftsuit, the torque keeps increasing for large bending angles. This can be uncomfortable during deep bends and in some cases obstruct deep bends.
The energy that is returned by the exoskeleton to the user (*returned energy*) (see Table 2) is an important metric to measure the effectiveness of the exoskeleton and is equal to the area below the extension curve. In general, the more energy that is returned to the user, the more the user is supported. For all the measured exoskeletons with a comparable maximum support torque, the returned energy is considerably less compared to the Laevo exoskeletons.

7.3 Conclusion

More research needs to be performed to improve the accuracy of the measurement of the torque curves. The ultimate goal would be to develop a general standard that describes how the torque curve of any exoskeleton should be measured and displayed.
The results of this study show that there are large differences between the torque curves of the measured lower back exoskeletons. However, there are many more aspects that need to be considered in the selection of the right exoskeleton (e.g. weight, compactness, comfort, ability to sit while wearing the exoskeleton, etc). For example, the Laevo V2 provides less support compared to the Laevo FLEX, but is more compact and therefore more suitable environments where room for manoeuvre is limited. To select the right exoskeleton for your application, environment and users, it is crucial to identify your success factors.

	Max. exerted torque	Max. support torque	Max. hysteresis	Returned energy
FLEX 100%	60Nm	52Nm	28%	46J
FLEX 85%	53Nm	45Nm	30%	41J
FLEX 70%	49Nm	41Nm	34%	36J
Paexo Back	56Nm	49Nm	30%	31J
FLEX 55%	37Nm	29Nm	31%	27J
Auxivo high	51Nm	51Nm	47%	26J
FLEX 40%	30Nm	22Nm	33%	20J
Auxivo med.	36Nm	36Nm	42%	19J
V2.5	38Nm	30Nm	51%	17J
HAPO	51Nm	51Nm	48%	16J
GS Back	60Nm	54Nm	50%	15J
Auxivo low	24Nm	24Nm	45%	11J

Table 2: Summary of torque characteristics of the Laevo FLEX (100%, 85%, 70%, 55%, 40%), the Laevo V2.5, Ottobock Paexo Back, Muscle Suit GS Back, Ergosanté HAPO posture harness and Auxivo Liftsuit (high, medium and low pretension in elastic bands) for a bending angle range of 0-90°. The actual support torque *exerted* by the exoskeletons can be slightly higher than the *measured* support torque, since the exoskeleton 'supports' the weight of its own upper part. The hysteresis is a metric to evaluate the efficiency of the exoskeleton. The returned energy describes the amount of energy that is returned to the user by the exoskeleton.

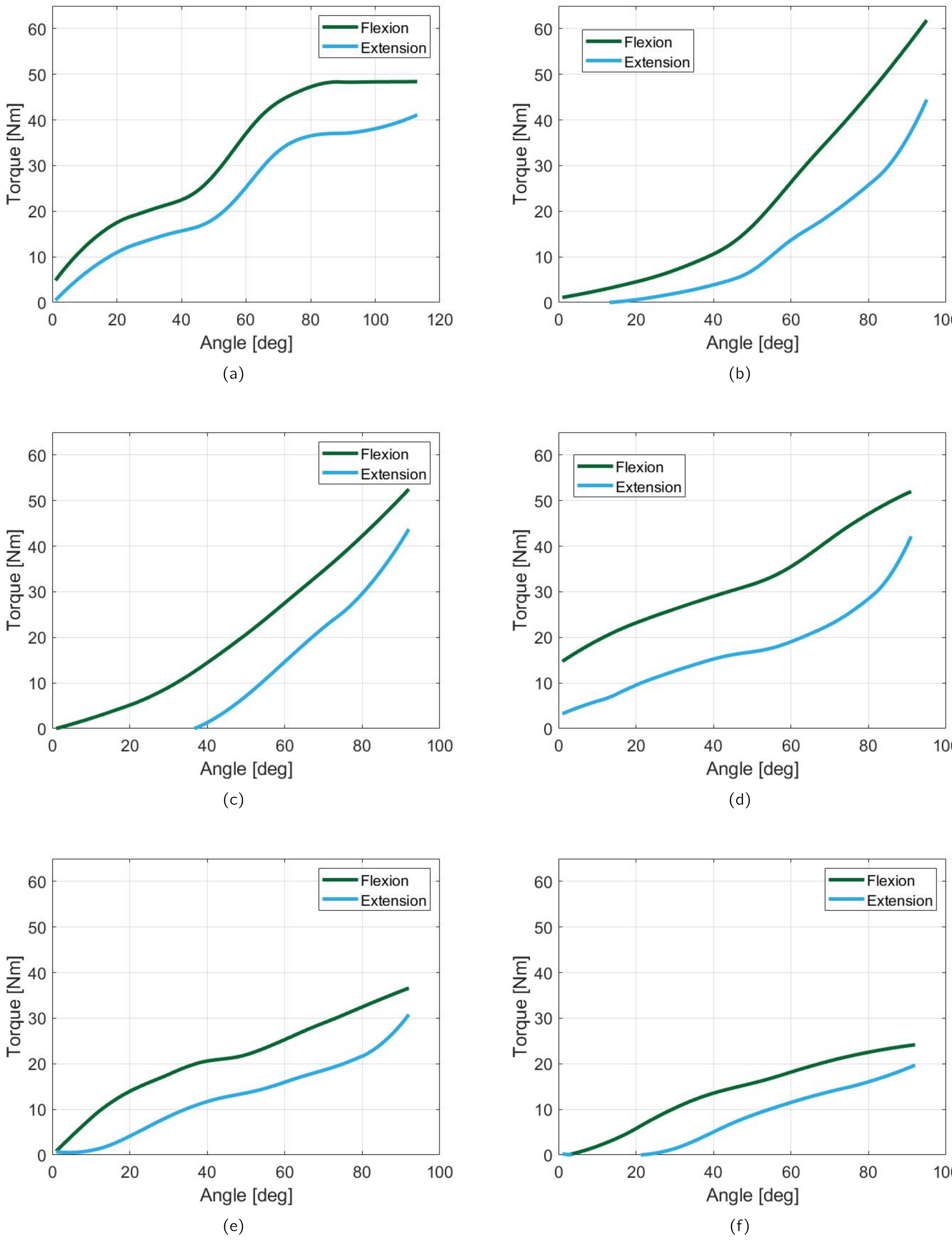

Figure 6: Torque-angle curves of (a) Ottobock Paexo Back, (b) Muscle Suit GS Back, (c) Ergosanté HAPO posture harness, (d) Auxivo Liftsuit high pretension in elastic bands (e) Auxivo Liftsuit medium pretension in elastic bands and (f) Auxivo Liftsuit low pretension in elastic bands.
Please be aware that the measurement setup is designed the be representative for the human body, but some exoskeletons fit better than others. This can influence the results of the torque curve measurement.