COB-2023-1514

HOW AN ACTIVE ORTHOSIS INTERFERES WITH THE MOVEMENT, MUSCLES RECRUITMENT AND ACTIVATIONS DURING KNEE FLEXION-EXTENSION

Denis Mosconi
Yecid Moreno
Adriano Siqueira
University of São Paulo, Mechanical Engineering Department, São Carlos, Brazil
Av. Trabalhador São-Carlense, 400, São Carlos-SP, 13566-590, Brazil
denis.mosconi@ifsp.edu.br, yecidmoreno@usp.br, siqueira@sc.usp.br

Abstract. The purpose of this work was to analyze the effects of a specific active knee orthosis on the human knee flexion-extension, with regard to the muscle recruitment and activations, movement and robot torques. To this, an experimental procedure was conducted with a subject performing knee flexion-extensions according to a predefined trajectory and wearing the orthosis in active-assistive mode, passive mode and also without orthosis. Measurements of position, torque and electromyography were performed. The results allowed to conclude that orthosis interferes with the patterns of movement and muscle recruitment, as well as increasing activation levels, in addition to the fact that such interferences are not always obvious. It was observed that the user does not always take advantage of the assistance provided by the orthosis. For future work, more experiments will be carried out with more people, in order to verify the repeatability of the results, as well as if there are new intercurrences not observed until then.

Keywords: Knee orthosis, exoskeleton, robotic therapy, human-orthosis interaction

1. INTRODUCTION

Rehabilitation of the lower limbs after trauma, stroke, spinal cord injury or surgery is extremely important and necessary to restore the motor autonomy of the patients, allowing them to perform the activities of daily living with maximum dexterity possible.

One of the most important articulation of the lower limbs is the knee, the largest and more complex synovial joint of the human body, fundamental for the lower limbs movements such as walking, jumping, squat-to-stand and climbing stairs. Such articulation is composed by two joints: the tibiofemoral joint and patellofemoral joint, and supports most of the body weight. Injuries that affects the knee can lead to great functional limitations and motor disability, being essential to resort to rehabilitation therapy to restore the motor skills of the joint as best as possible (McGinty *et al.*, 2000).

Knee flexion-extension is one of the movements performed during the rehabilitation therapy. It is an open kinetic chain movement that helps in regaining range of motion, strengthening, joint stability and motor coordination (Shelbourne *et al.*, 2007). At first, the movement can be performed with the patient in a seated position, being assisted by the therapist. Depending on the evolution of the clinical picture, some factors can be changed, such as the patient's position, assistance or not from the therapist and inclusion of obstacles, always satisfying the needs and the protocol followed.

A resource that can be utilized in knee rehabilitation are the robotic devices that have ability to repeat tasks accurately, potential to measure the progress of the rehabilitation, are flexible and contributes to the reduction of therapist workload, as well as time and costs of the treatment (Wilmart *et al.*, 2019).

However, when using robotic devices in rehabilitation, one must be concerned with the human-robot interaction, taking into account the effects of the device on the patient, with regard to the execution of movement, force production, motor coordination and safety, in order to ensure the effectiveness of the therapy and physical integrity of the people involved.

When designing and validating orthosis, as well as developing their controls, many researchers evaluated the human-robot interaction considering the movement, torques and electromyography (EMG) involved. For example, Nesler *et al.* (2022) assessed the influence of an active orthosis on the electromyography of a healthy male performing a voluntary movement of lifting and lowering. The author used three unilateral configurations of the orthosis: hip only, knee only, and hip-knee. The results proved that when compared to the movement performed bare the orthosis enabled considerable reductions in activation of the squat musculature, with major reductions with configurations that included the knee module.

Reduction in the quadriceps activation of able-bodied humans with bilateral active orthosis assistance during lifting-lowering, sit-to-stand, and stair climbing were verified by Zhu *et al.* (2021), when compared with the same movements performed without assistance from the orthosis (bare mode). With the orthosis in passive mode, the reductions in activations were less expressive, and in some cases there was even an increase in muscle activity.

A study conducted by Villa-Parra *et al.* (2020) evaluated, in terms of kinematics, kinetics, and muscle activity, the effects of an assistive control approach applied to an active knee orthosis plus a walker for gait rehabilitation. The researchers observed that the use of the orthosis-walker set caused a reduction in muscle activations and fatigability however changes in the gait pattern between the patients were identified.

The effects of a two degrees of freedom knee orthosis on the gait and sit-to-stand movements performed by patients with medial knee osteoarthritis were analyzed by Fesharaki *et al.* (2020). Compared to walking without the orthosis, reduction in knee range of motion and increase of walking speed were identified. Muscular activity was not measured.

Assessment of gait symmetry, muscular response, and torque interaction due to the assistance provided by an unilateral active knee orthosis in twelve healthy subjects was conducted by Lora-Millan *et al.* (2020). Results indicated that the assistance provided by the robot improved the gait symmetry of the users. It was also observed that users tended to respond to the robot assistance by generating torque in the same direction of the robot action instead of taking advantage of the assistance provided by the exoskeleton, which resulted in augmentation of the muscular activation in 22.7% of the cases.

An exploration of the biomechanical effects of using a powered unilateral knee exoskeleton during walking was conducted by Lee *et al.* (2020). The research was performed with twelve able-bodied subjects waking on incline and decline surfaces with the exoskeleton providing knee extension assistance during the early stance phase of the gait cycle. For both cases, the exoskeleton assistance reduced the muscle activation of the knee extensors on the assisted leg. However, only a half of the subject had metabolic cost reduction with assistance due to their compensatory behaviors from the unassisted leg.

The above studies demonstrate that there is no definitive answer to the question of the interaction between human and assistive robotic device for rehabilitation, since in certain cases there is a reduction in muscle activation while in others there is an increase. Even for cases in which there is a reduction in muscle activation in the assisted leg, there is the possibility of an increase in the biological cost due to compensatory behaviors. In addition, it is possible to verify that orthosis can cause alterations in the movement pattern. Thus, it is important to evaluate the effects of active orthosis on body alignment, muscle activity, interaction forces and movement pattern in order to plan a suitable rehabilitation program, develop effective interaction controls and ensure treatment efficacy and patient safety.

Thus, the objective of this work was to analyze the interaction between a human and a specific active-assistive knee orthosis during the execution of knee flexion and extension movements in a seated position. This study made it possible to understand how different levels of orthosis assistance influence muscle recruitment and activations, movement patterns and robot torques, providing conditions for the development of more effective interaction controls and rehabilitation protocols.

2. METHODOLOGY

To evaluate the human-orthosis interaction effects, an experiment was conducted with a healthy subject (male, 30 years old, 64.6 kg, 1.75 m tall) wearing an active knee orthosis in assistive mode and performing, in a seated position, movements of flexion and extension (F&E) with the right knee according to a sinusoidal trajectory with amplitude of $0°$ (flexion) to $70°$ (extension) and a period of 10 seconds, during 90 seconds (i.e. 9 repetitions). Both the reference and performed angular trajectories of the knee were displayed to the user on a computer screen.

The active orthosis that was used in the experiment is part of the ExoTAO robot developed by dos Santos *et al.* (2017b). The ExoTAO is a lower limb exoskeleton composed of a lightweight tubular structure connected by six free independent joints, resulting in a modular system. The links of the robot are of telescopic tubular type, allowing the exoskeleton to be adjustable for different anthropometries. This modular configuration of the exoskeleton allow it to be used by humans with body height between 1.65 and 1.90 m, as well as to be configured to treat one or more joints of the patient.

In this work only the right leg of the ExoTAO was used with only the knee joint being actuated (this joint is equipped with a rotary series elastic actuator developed by dos Santos *et al.* (2017a)). The robot structure was attached to the user with Velcro® straps and a custom shoe fixed on the exoskeleton. This configuration was used in order to guarantee stability and prevent the robot and user joints misalignment.

The orthosis was controlled by an impedance control whose law is determined by Equation (1), where τ_R is the robot torque, θ^d is the reference to be tracked by the user, θ is the knee angle, K_R is the robot virtual stiffness (that express the level of assistance from the orthosis to the user), B_R is the robot virtual damp and $\dot{\theta}$ is the knee angular velocity.

$$\tau_R = (\theta^d - \theta)K_R - B_R\dot{\theta} \tag{1}$$

Signals from three Xsens MTw Awinda Wireless Inertial Measurement Units (IMUs) were acquired at 100 Hz and processed using the ReRobApp from Moreno *et al.* (2022). These signals were used to determine the knee angular position. To this, two sensors were placed on the shank and one on the thigh. It was assumed that the knee positions of both the user and the robot are the same.
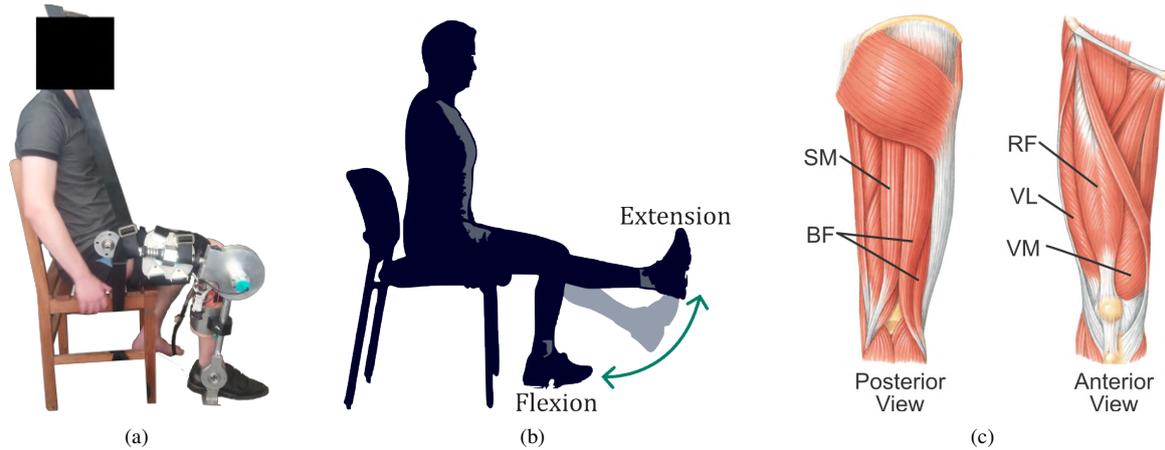
Figure 1. Active knee orthosis from ExoTAO used in this work (a), an illustration of the knee flexion-extension movement performed (b) and the leg muscles considered in the experimental procedure (c)

We used a Trigno Wireless EMG System (Delsys Inc., Natic, MA, USA) to perform a surface electromyography (sEMG) in order to determine the myoelectric activity of five muscles: the knee extensors rectus femoris (RM), vastus lateralis (VL), vastus medialis (VM) and the knee flexors biceps femoris (BF) and semitendinosus (ST). The placement of the electrodes and preparation of the skin (shaving, abrasion with sandpaper and cleaning with 70% alcohol) was performed according to the instructions provided by Biomedical Health and Research Program of the European Union. A maximum voluntary contraction (MVC) procedure with the user performing isometric contraction against manual resistance was conducted and used to normalize EMG data to %MVC. The EMG data were sampled at 2 kHz in a separate computer using the Delsys EMGworks Software and later processed using MATLAB (The MathWorks, Inc; Natick, MA, USA). First, to eliminate DC bias, the signal was high-pass filtered (20Hz) and its moving average (50 ms time window) was subtracted. Then, the corrected signal was rectified, low-pass filtered an normalized. The low-pass filter used is a second order butterworth with a cut-off frequency of 2 Hz. Finally the mean value was extracted from the processed signals of all movement repetitions and compared with the MVC mean.

Five tests were performed, as detailed bellow:

- **Bare (B):** In this case, the subject performed the movement without using the orthosis, that is, all the strength to perform the movement was provided exclusively by the individual's muscles.

- **Passive (P):** In this case, the orthosis was configured for passive mode, that is, with $K_R = 0$ in Equation (1). Thus, the torque produced by the orthosis is similar to that of a viscous friction element, and not as an active result for tracking the desired trajectory.

- **Active:** In this case the orthosis was configured in active mode, with K_R in Equation (1) assuming the values of 10, 20 and 30 N.m/rad. As the reference trajectory is the same both for the user and orthosis, it was expected that in creasing the virtual stiffness of the orthosis, the user would exert less force, participating less in the movement, presenting less muscle activations and leaving the orthosis with most of the responsibility for conducting the movement.

For every case in which the orthosis was configured as active, its behavior was determined as assistive, that is, helping the user to perform the movement. This was done assuming the same trajectory desired for both.

3. RESULTS AND DISCUSSION

The movements performed by the subject during the experiment are depicted in the Fig. 2. It is possible to verify that in all the movements there is a greater acceleration in the elevation of the leg, during the extension, since more than 50% of the movement was occupied by the flexion that was slower (the peak, where there is the inversion of the movement always occurs before the half of the cycle). This occurs even when the human is not wearing the orthosis, which qualifies as a characteristic of the subject. This initial acceleration results in an extension greater than that determined by the reference, which can be verified by analyzing the peaks of the position graphs.
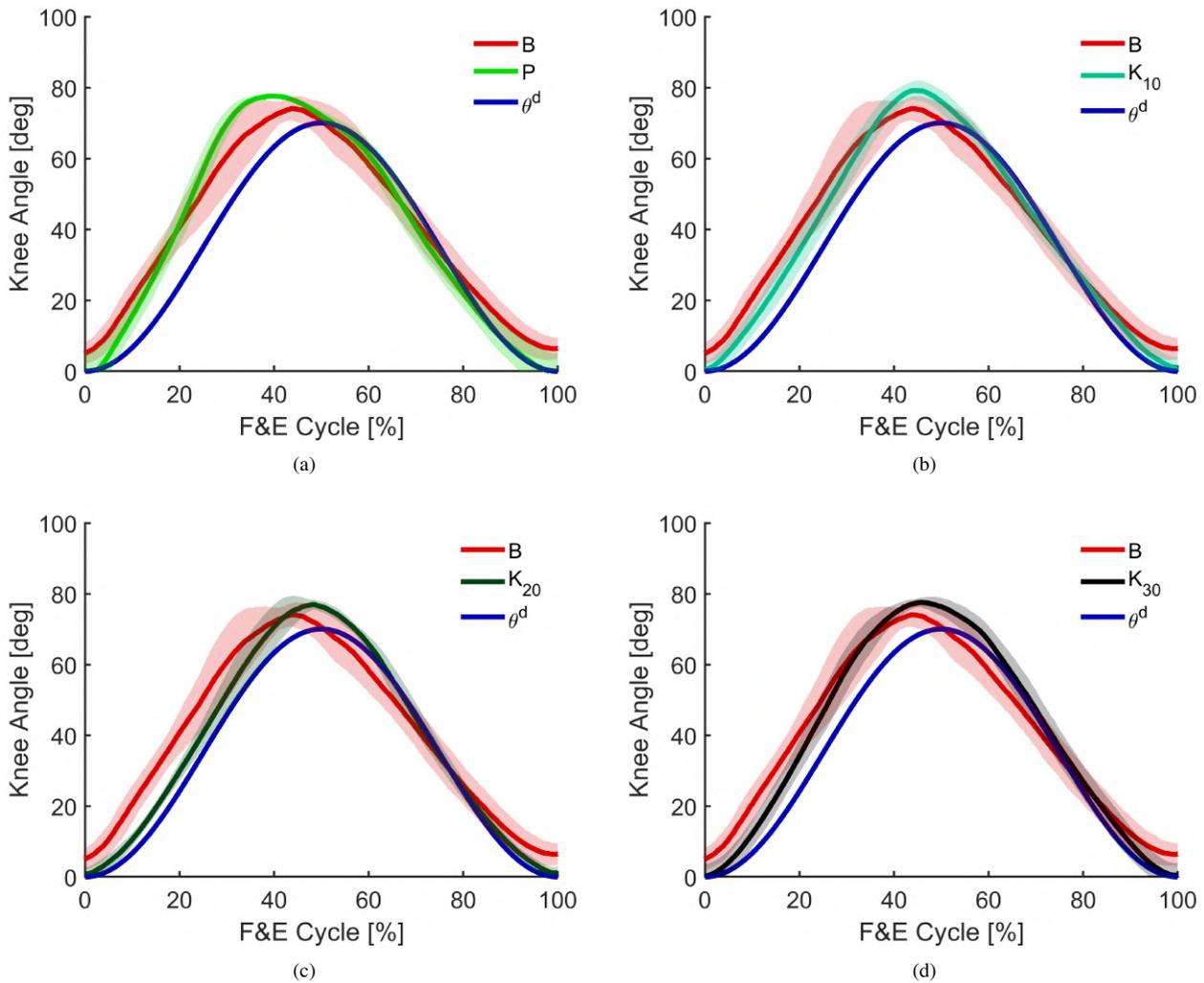
Figure 2. Knee angular position during F&E without orthosis (B), with orthosis in passive mode (P), with orthosis in active mode with stiffness values of 10, 20 and 30 (K_{10}, K_{20} and K_{30}, respectively), θ^d is the reference to be tracked
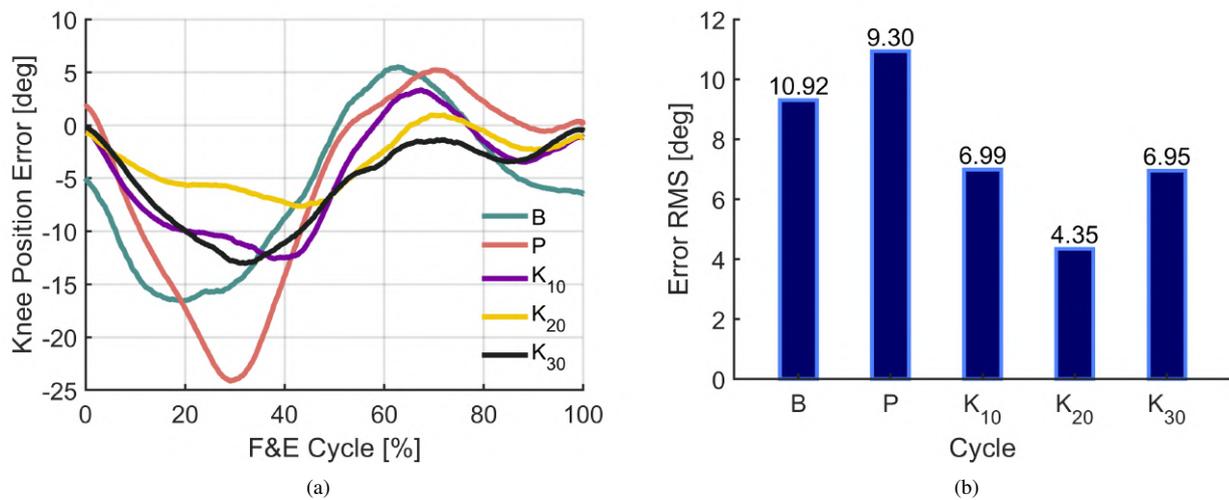

Figure 3. Knee angular errors in relation to the reference on time (a) and RMS (b)

The flexion movement takes up most of the cycle since it starts at an extension point above that established by the reference, but it is more controlled and with greater accuracy in relation to the reference. During flexion there is the aid of gravity, which means that the effort of the flexors are always smaller than those of the extensors.

When using the orthosis in passive mode, it is possible to verify that the ascent acceleration was even greater, which is evidenced by the increase in muscle activation of the extensors, especially of the vastus medialis (Fig. 4a).

Using the orthosis in active mode with $K = 10$, the extension approaches the reference, showing an improvement in relation to the movement with passive orthosis, resulting in a decrease in muscle activations. However, in relation to the movement without orthosis, the peak reached is even greater. Analyzing the torque applied by the orthosis (Fig. 5a), it is possible to verify that in the first 20% of the cycle, the orthosis applies a torque in the opposite direction of movement, in order to resist the exacerbated acceleration of the user in extension. Thus, as Lora-Millan *et al.* (2020) observed in their work, here too the user is not taking advantage of the assistance provided by the orthosis.

With the orthosis active and $K = 20$, the movement closest to the reference was obtained, among all those measured, although the orthosis also needs to resist the user's extension acceleration in the initial moments. In this case, muscle activations were also reduced, except for the BF which contributed to a slightly greater acceleration at the beginning of flexion (proved by the fact that the orthosis used a positive torque at this moment).

For $K = 30$, the deviations of the movement away from the reference increased in relation to $K = 20$, reaching values similar to that obtained for $K = 10$, however with a smoother transition peak, which indicates a reduced jerk. In addition, the peak occurred closer to 50% of the cycle, but even so, the extension movement was faster than desired. The maximum torque applied by the orthosis occurred in approximately 70% of the movement, when the user made a best use of his assistance, a fact that contributed to the best tracking of the flexion trajectory among all observed movements.

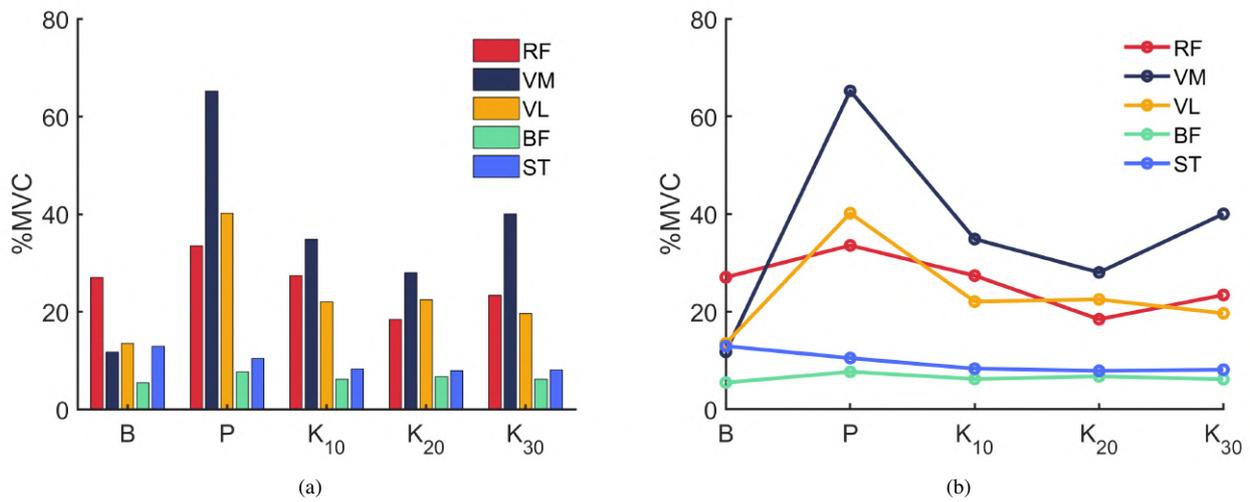(a)   (b)

Figure 4. Mean values for the muscles activation in %MVC

Variations in the muscle recruitment pattern were also observed: with the orthosis, the VM was always recruited more than the RF, contrary to what was observed in bare mode. Also with the orthosis, in some cases the RF was recruited more than the VL ($K = 10$ and $K = 30$) while in others it was less (P and $K = 20$). As for the flexors, the pattern remained constant, varying only their activation levels. Table 1 presents numeric values of the mean muscles activations in %MVC together to the standard deviation. Figure 4 presents the mean values of the muscle activations related to %MVC, with this figure it is possible to compare the myoelectric activity between the muscles, for each mode (Fig. 4a), as well as the variation that each muscle suffers when varying the mode of operation (Fig. 4b).

In general, the use of the orthosis did not reduce the mean muscle activation compared to the bare user. Furthermore, a higher assistance value did not lead to movement closer to the desired one, and it did not reduce activations as expected. Little impact was observed in relation to the flexor muscles, since for the movement used in the experiment, such muscles have the natural help of gravity.

Table 1. Mean muscle activations ($\pm$SD) comparisons

	Bare	Passive	$K = 10$	$K = 20$	$K = 30$
RF	27.0 (1.6)	33.6 (2.5)	27.4 (1.7)	18.4 (1.1)	23.4 (1.6)
VM	11.8 (1.8)	65.2 (0.8)	34.9 (2.7)	28.0 (1.3)	40.0 (2.5)
VL	13.5 (2.2)	40.2 (2.3)	22.1 (2.8)	22.5 (2.4)	19.6 (1.7)
BF	5.5 (2.4)	7.7 (1.2)	6.2 (2.5)	6.7 (2.7)	6.2 (2.1)
ST	12.9 (1.9)	10.5 (2.4)	8.3 (1.7)	7.9 (1.8)	8.1 (2.4)

The experiment was carried out considering the subject's dominant leg (right). A next experiment will be conducted

considering the non-dominant leg. The observations allowed us to conclude that the use of the orthosis from ExoTAO interferes both in the execution of the movement and in the muscle activations and recruitment. However, this is a pilot work that shed light on a certain issue. Experiments with more people will be carried out in order to verify if such occurrences persist or vary.
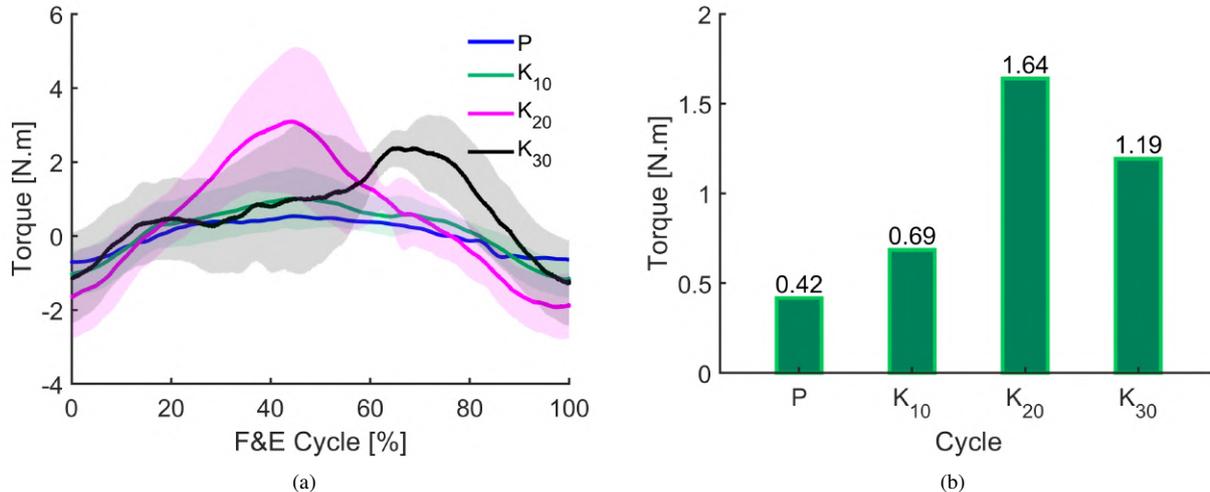

Figure 5. Torques applied by the orthosis on time (Positive torque contributes to extension, while negative torque contributes to flexion) (a) and RMS (b)

Considering all the results obtained, it is possible to verify that there is a tendency on the part of the user to promote greater acceleration in extension than in flexion, which results in an asymmetrical movement. Even with the aid of the orthosis, the asymmetry persisted, although reduced in some moments ($K = 20$). Thus, for future projects of controllers related to this user, this movement asymmetry must be considered, so that the control is effective, meeting the requirements of the rehabilitation protocol and taking into account the characteristics of the user.

Furthermore, it is verified that the orthosis not only influences muscle activation levels, but also the muscle recruitment pattern, as already mentioned. In bare mode, it can be seen that the rectus femoris (RF) is more activated than the vastus medialis (VM) and vastus lateralis (VL), while when using the orthosis this pattern is reversed (Fig. 4a).

Finally, despite the hypothesis that by increasing the level of assistance from the orthosis (i.e. the value of K), muscle activations should decrease and the movement performed should be as close as possible to the reference, the experiment did not show this, refuting this hypothesis, since the smallest muscle activations, the greatest participation of the orthosis and the smallest error in following the path occurred for $K = 20$ and not $K = 30$.

4. CONCLUSIONS

The major conclusion of this study is that the use of the ExoTAO orthosis interferes with the movement and muscle recruitment, as well as activation levels, and this interference is not always obvious (e.g. increasing the level of assistance does not always result in a reduction in muscle activations or better tracking of the desired trajectory, as is normally expected when using assistive devices).

One possibility to make the interaction more effective and logical is perhaps to improve the orthosis controller, considering the use of controllers that take into account muscle activations being capable of identifying the user intention of movement.

For future work, more experiments will be performed with more people, to verify the repeatability of the results and if there are new intercurrences not observed until then.

5. ACKNOWLEDGMENTS

6. REFERENCES

Biomedical Health and Research Program of the European Union, ???? "SENIAM - Surface ElectroMyoGraphy for the

Non-Invasive Assessment of Muscles". URL `http://www.seniam.org/`.

dos Santos, W.M., Caurin, G.A.P. and Siqueira, A.A.G., 2017a. "Design and control of an active knee orthosis driven by a rotary series elastic actuator". *Control Engineering Practice*, Vol. 58, pp. 307–318.

dos Santos, W.M., Nogueira, S.L., de Oliveira, G.C., Pena, G.G. and Siqueira, A.A.G., 2017b. "Design and evaluation of a modular lower limb exoskeleton for rehabilitation". In *2017 International Conference on Rehabilitation Robotics (ICORR)*. IEEE, London, England, Vol. 2017, pp. 447–451. doi:10.1109/icorr.2017.8009288.

Fesharaki, S.A., Farahmand, F., Saeedi, H., Raeissadat, S.A., Abdollahy, E., Ahmadi, A. and Maroufi, N., 2020. "The effects of knee orthosis with two degrees of freedom joint design on gait and sit-to-stand task in patients with medial knee osteoarthritis". *Sultan Qaboos University Medical Journal [SQUMJ]*, Vol. 20, No. 4, pp. e324–331. doi: 10.18295/squmj.2020.20.04.008.

Lee, D., Kwak, E.C., McLain, B.J., Kang, I. and Young, A.J., 2020. "Effects of assistance during early stance phase using a robotic knee orthosis on energetics, muscle activity, and joint mechanics during incline and decline walking". *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 28, No. 4, pp. 914–923. doi: 10.1109/tnsre.2020.2972323.

Lora-Millan, J.S., Moreno, J.C. and Rocon, E., 2020. "Assessment of gait symmetry, torque interaction and muscular response due to the unilateral assistance provided by an active knee orthosis in healthy subjects". In *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*. IEEE. doi: 10.1109/biorob49111.2020.9224414.

McGinty, G., Irrgang, J.J. and Pezzullo, D., 2000. "Biomechanical considerations for rehabilitation of the knee". *Clinical Biomechanics*, Vol. 15, No. 3, pp. 160–166. ISSN 0268-0033. doi:https://doi.org/10.1016/S0268-0033(99)00061-3.

Moreno, J.Y., Escalante, F.M., Boaventura, T., Terra, M.H. and Siqueira, A.A., 2022. "ReRobApp: A modular and open-source software framework for robotic rehabilitation and human-robot interaction". In *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*. IEEE. doi: 10.1109/biorob52689.2022.9925470.

Nesler, C., Thomas, G., Divekar, N., Rouse, E.J. and Gregg, R.D., 2022. "Enhancing voluntary motion with modular, backdrivable, powered hip and knee orthoses". *IEEE Robotics and Automation Letters*, Vol. 7, No. 3, pp. 6155–6162. doi:10.1109/lra.2022.3145580.

Shelbourne, K.D., Biggs, A. and Gray, T., 2007. "Deconditioned knee: The effectiveness of a rehabilitation program that restores normal knee motion to improve symptoms and function". *N Am J Sports Phys Ther*, Vol. 2, No. 2, pp. 81–89.

Villa-Parra, A.C., Lima, J., Delisle-Rodriguez, D., Vargas-Valencia, L., Frizera-Neto, A. and Bastos, T., 2020. "Assessment of an assistive control approach applied in an active knee orthosis plus walker for post-stroke gait rehabilitation". *Sensors*, Vol. 20, No. 9, p. 2452. doi:10.3390/s20092452.

Wilmart, R., Garone, E. and Innocenti, B., 2019. "The use of robotics devices in knee rehabilitation: a critical review". *Muscle Ligaments and Tendons Journal*, Vol. 09, No. 01, p. 21. doi:10.32098/mltj.01.2019.07.

Zhu, H., Nesler, C., Divekar, N., Peddinti, V. and Gregg, R.D., 2021. "Design principles for compact, backdrivable actuation in partial-assist powered knee orthoses". *IEEE/ASME Transactions on Mechatronics*, Vol. 26, No. 6, pp. 3104–3115. doi:10.1109/tmech.2021.3053226.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.