The AGoRA V2 Unilateral Lower-limb Exoskeleton: Mechatronic Integration and Biomechanical Assessment

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***Abstract*— People who suffer from stroke have a higher difficulty performing gait activity, affecting their quality of life. New technologies have been developed to assist and rehabilitate the affected limbs. This paper presents the AGoRA V2 unilateral lower-limb exoskeleton and the assessment of physiological and spatiotemporal parameters of gait in 10 subjects who participated in a test. AGORA V2 combine a stiff structure for the Hip and Knee and the T-FLEX ankle exoskeleton (soft structure). The results showed a significant decrease in muscle activity compared to the condition without an exoskeleton. This decrease was 8% in Biceps Femoris (BF) muscle activity and 4% in Vastus Medialis (VM) muscle activity, generated by proper assistance of the devices thigh muscles. Tibialis Anterior (TA) and Lateral Gastrocnemius (LG) muscles and gait times did not show significant changes, which can be interpreted as a correct synchronisation of the devices with the person's gait. The results obtained can be used as a baseline for future studies with pathological patients.**

I. INTRODUCTION

Stroke is the rapid development of focal or global signs of compromised brain function, with symptoms lasting twenty-four hours or longer [1]. The impact of motor, cognitive and perceptual disorders of a person after a stroke contributes to the variation in functional autonomy, causing the person to be unable to perform activities of daily living (ADLs) [2].

Post-stroke rehabilitation is supported by the neuroplasticity mechanism where functional and motor recovery are re-learned through the assistance of the devices in the repeated gait activity [3]. To achieve this, robotic tools have been developed as external devices that aid the user, known as joint orthoses or exoskeletons.

One of the variations of these devices is recognised as unilateral exoskeletons, which assist people with hemiparesis or hemiplegia (partial or severe loss of strength of one side of the body) [4]. Some of them are stiff structures built with complex articulated structures that connect actuators to garments. Rigid exoskeletons transmit torques to the joint generated by the rotation of the actuator, with joints that can be mechanically limited [5]. Some limitations of these devices are kinematic compatibility [6], however, patients who demand major assistance or a variable control need a rigid powered device. In the ankle it has been found that rigid components restrict non-sagittal ankle motion [7]. Rigid ankle orthoses have no rotational or limited motion, therefore, articulated soft structures are used, which allow greater ankle rotational motion [8]. Compliant exoskeletons have different actuators (i.e. series elastic, variable stiffness and pneumatic actuators) with mechanical connections and transmission systems that run parallel to the user's limbs. These soft exoskeletons have promising adaptability, safety, efficiency and comfort [9]. For this reason, the combination of soft and stiff components are commonly used to achieve a more remarkable performance of both types [6].

The AGoRA V2 Unilateral Lower-limb exoskeleton is a rehabilitation and assistive device which contains the AGoRA exoskeleton and the T-FLEX orthosis. The AGoRA exoskeleton has three degrees of freedom (DOF), including two active DOFs in hip and knee joints along the sagittal plane and one passive DOF in the hip joint along the frontal plane. For the control of joint movements, actuators and sensors are used. This exoskeleton is considered a stiff structure [10]. On the other hand, T-FLEX is a robotic orthosis designed to assist and rehabilitate people with ankle dysfunctions such as foot drop. T-FLEX includes composite tendons made of elastic and rigid filaments which attach the frontal and posterior actuators to the foot-tip and the heel to induce the variable stiffness effect [11].

A previous study evaluated two control strategies in the AGoRA exoskeleton: transparency, and assistance. In the assistance mode, the torques for the knee joint generated in the pilot study were high-level torque profiles (20-30Nm) and can assist hip joint movements during the gait cycle. Besides, in transparency mode, the user's motion intention can be represented in angular velocities [12], [13]. An experimental characterisation was performed concerning T-FLEX to measure the device's capabilities and determine its configuration. The study evaluated two conditions, the tendons working independently and in conjunction with the stiff filaments. It was concluded that the best performance was obtained with the tendons acting alone, and the stiff

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filaments did not improve the device's performance [11]. In addition, T-FLEX has been used in a study with ten stroke patients. Each participant performed multiple 6-metre tests unassisted and with T-FLEX assistance. An improvement in the ankle kinematics was found, with significant changes of 70% in the range of motion of the lower joints of the subjects. Therefore, T-FLEX was found to generate a positive impact on the dorsiflexion movement [14].

In this sense, the main contribution of this work is the integration of the AGoRA exoskeleton and T-FLEX orthosis with the aim of improving quantitative and qualitative parameters using rigid components for greater power transmission in the hip and knee joints and soft components in the ankle joint that allows greater degrees of freedom in human locomotion. This assessment was conducted in ten healthy subjects on a treadmill for 6 minutes. Besides, it presents and analyses how the robotic devices acting together compensates the gait activity in healthy subjects in muscle activity and in gait cycle times such as stance and swing phase. Additionally, this work analyses the perception of healthy users while wearing the device with a questionnaire.

II. METHODOLOGY

A. Integrated Lower-limb exoskeleton

The mechanical structure of the new integrated device is similar to the AGoRA lower-limb exoskeleton regarding the kinematic chain and the actuators, presented in [10]. However, several features of the mechanical design and control strategies are modified to include the ankle-foot exoskeleton.

1) Mechanical Design: The main changes in the AGORA exoskeleton are related to the physical interfaces (see Figure 1) aiming at (1) the attachment of the ankle-foot orthosis T-FLEX and (2) distribute the forces of the powered side. To correctly perform the attached ankle-foot orthosis, the stiff structure of the T-FLEX is adapted to the stiff physical interface of the AGoRA exoskeleton. Likewise, the flexible structure of both exoskeleton are combined into two parts of foam (Polyurethane 70/30, Colombia), fabric and a layer of ECOFLEX 50 (Smooth-on, U.S.A). This new physical interface allows properly attaching the T-FLEX to the user's shank, and it also fixes the shank link of the AGoRA exoskeleton to the user.

Following, the forces are distributed using a vest that has installed and fastened the supports of the hip. The internal design provides different weight distributions divided into the shoulders and the abdominal area where the fixation system attaches the hip's fasteners.

2) Control strategy: The AGoRA exoskeleton comprises low-level (LL) control, mid-level control (ML), and high-level control (HL). The LL control is applied using a current controller at the hip and knee joints using hall effect sensors. The current controller comprises a PI controller where the gains applied in the hip controller are equal to P = 955671 μVA, I = 485188 μV/As. The gains used in the knee are equal to P = 937294 μV/A, I = 430053 μV/As. The ML control applies impedance control using a mass-spring-damper system that estimates a torque for angular position error compensation at each joint [15]. For the AGoRA exoskeleton, the hip elasticity constant is k = 60 Nm/rad and the constant damping is β = 10 Nms/rad. The knee elasticity constant is k = 39 Nm/rad and the constant damping is β = 8 Nms/rad. The HL control uses the gait phase detection module [15] that estimates a gait phase (Heel Strike (HS), Flat Foot (FF), Heel Off (HO), Swing Phase (SP)) for the non-actuated limb. In this way, the desired gait phase is estimated for the actuated limb using torque profiles in each joint [12]. The T-FLEX robotic orthosis comprises a LL control based on a PI controller using the motor's position. Each motor is coupled with a composite tendon changing the ankle joint's stiffness. This mechanism provides support to the dorsiflexion and plantarflexion movements. In this application, the estimated PI frontal motor gains are P = 4.37, and I = 19.53. The estimated PI posterior motor gains are P = 4.50, and I = 17.57. The HL control provides a gait phase in the non-actuated limb (HS, FF, HO, SP) [11] to define a desired gait phase for the actuated limb (see Figure 2).

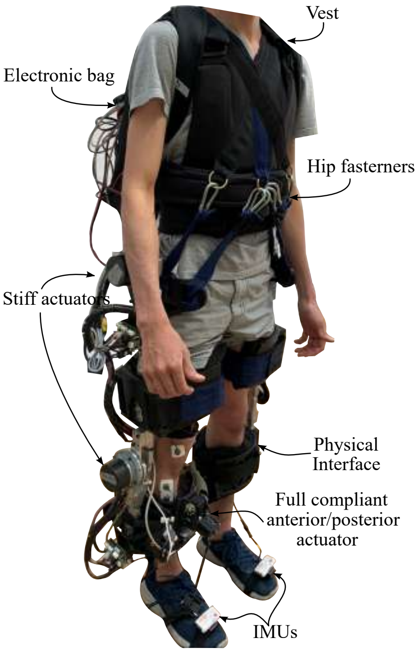

Fig. 1: The AGoRA V2 unilateral lower-limb exoskeleton assists hip and knee joints through stiff actuators and aids the ankle joint using a fully compliant actuator.

B. Subjects

The study included the voluntary participation of ten people (age: 24 ± 2 years old, weight: 75.6 ± 15.6 kg, height: 175 ± 4 cm) who met the inclusion criteria, which consisted of being healthy adults, within the height range of 170 to 185cm, and a weight of less than 110kg, which are the anthropometric measurements that adapt to the robotic device. Exclusion criteria included being intolerant to exercise, suffering from any pathology that would prevent the

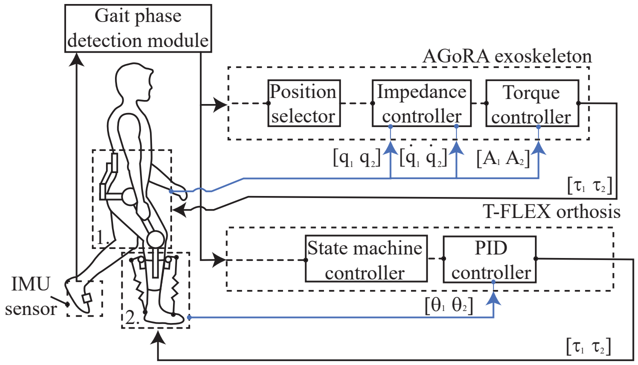

Fig. 2: Control scheme implemented in the AGoRA V2 exoskeleton. The gait phase detection module is provided as an input for the two devices. The AGoRA exoskeleton control system uses the angular position of the hip and knee joints (q_1, q_2), the angular velocity of the hip and knee joints ($\dot{q}_1$, $\dot{q}_2$), and the current applied to the actuation system for each joint (A_1, A_2). τ_1 and τ_2 are the torque generated for the hip and knee joints. The T-FLEX robotic orthosis senses the position of the two motors (θ_1, θ_2) for the implementation of a PID control supplemented with a state machine control. The orthosis outputs actuation system are estimated torques (τ_1, τ_2) for the anterior and posterior parts of the ankle joint.

use of a device, presence of wounds or ulcers, being under the influence of alcohol or drugs during the procedure, and suffering from a cognitive impairment that would prevent the participant from reading, understanding or signing the informed consent form.

C. Experimental protocol

The proposed protocol is divided into tests with and without devices according to what is found in the literature [16]. The gait evaluation study of the AGoRA V2 Lower-limb exoskeleton consisted of one session of 30 minutes for each of the subjects. In this assessment, four steps were performed:

*1) **EMG and IMU Instrumentation**:* The participant was instrumented with surface electrodes and an EMG acquisition module (Shimmer3 EMG Unit, Shimmer, USA). A sampling frequency of 1024 Hz was used for EMG signal acquisition. The following muscles were used to monitor muscle activity during the tests: Biceps Femoris (BF), Lateral Gastrocnemius (LG), Tibialis Anterior (TA), and Vastus Medialis (VM). The location of the electrodes and instrumentation method followed the SENIAM guidelines. These muscles are essential during normal human locomotion in the sagittal plane. BF and VM being the knee flexors/extensors, and LG and TA being the ankle plantar-dorsiflexors [17]. Besides, two Shimmer3 IMU (Shimmer3 IMU Unit, Shimmer) with a sampling frequency of 128Hz were located in both feet to divide the EMG signals in gait cycles and find the gait cycle parameters.

*2) **Maximal voluntary contraction (MVC)**:* To normalise the inter-subject measurements the MVC is performed. The participant executes a muscle contraction and maintains it for 5 seconds, followed by 10 seconds of relaxation. The MVC is averaged from three consecutive measurements.

*3) **Test without the exoskeletons**:* The participant performed the gait test on a treadmill for 6 minutes at a fixed speed of 1km/h without the intervention of the lower limb exoskeleton [16]. The speed is established according to the maximum speed of the AGoRA exoskeleton. In addition, in this test, training employing the IMU sensor is performed to personalise the assistance of the devices according to the gait of each subject.

*4) **Test with the AGoRA V2 Lower-limb Exoskeleton**:* In this test, the participant performed the gait test on a treadmill for the same time and speed as the previous test. The exoskeleton assist the gait by applying various forces to the hip/knee and ankle joints.

D. Data processing and acquisition

Data processing was performed offline using MATLAB software (MathWorks, 2018b, USA). For the EMG signals, a band-pass filter was used to remove noise, and a Butterworth filter with a cutoff frequency of 15 Hz was used to remove baseline drift usually associated with movement and to remove DC offset [18], [19]. The signal is rectified to obtain the linear envelope, and a moving average window of 200 ms is applied. Finally, the root-mean-square (RMS) was calculated and averaged for each gait cycle to have a value that refers to the signal's average power.

The gait cycle begins when a foot makes contact with the ground and ends when the same foot touches the ground again [20]. This cycle is usually divided into the swing and stance phases. The stance phase is where the foot is making contact with the ground and has a duration between 60-62%, and the swing phase is where the foot lifts off the ground and has a duration of 38-40% of the gait cycle [21]. Considering this, the angular velocity of the right foot is used by applying a moving average filter with a 30 ms window.

E. Statistical Analysis

The SPSS software (IBM SPSS Software, USA) was used for the statistical analysis of each of the conditions. First, a Shapiro-Wilk test is performed to know the normal distribution of data. Afterwards, the Wilcoxon test is used to find statistically significant differences among the muscular activity of the four muscles with and without the devices. On the other hand, the Paired Samples T-test is used to analyze gait cycle times such as stance and swing times.

F. Ethics Statement

The Research Ethics Committee of the Colombian School of Engineering Julio Garavito approved the protocol. All subjects have explained the procedure and purpose of the study and signed an informed consent form. The subject was allowed to leave the study at any time.

III. RESULTS

This section presents the results of ten healthy subjects in two conditions. The results are divided into: (1) Muscular activity and (2) Gait cycle times.

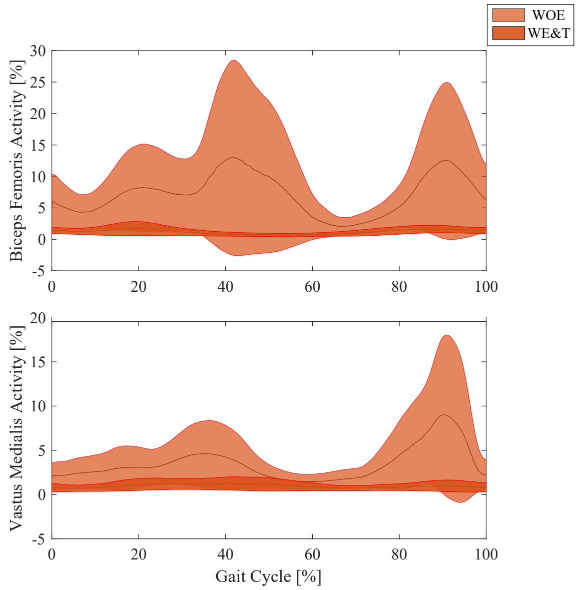

Fig. 3: Muscular activity behaviour of 10 subjects of Biceps Femoris (BF) and Vastus Medialis (VM) muscles in two conditions: (a) Without exoskeletons (WOE), and With Exoskeletons (WE&T).

A. *Muscular activity*

This part contains the muscular activity of 4 muscles: Biceps Femoris (BF), Lateral Gastrocnemius (LG), Tibialis Anterior (TA), and Vastus Medialis (VM) walking on a treadmill. Table I shows the mean and standard deviation of the RMS value across ten subjects in the test without the exoskeleton (WOE) and the test with the AGoRA and T-FLEX exoskeletons (WE&T). It can be observed that the BF and VM muscles decrease significantly with a p-value of 0.03 concerning the two conditions. Additionally, Figure 3 shows the mean muscular activity per gait cycle with a standard deviation of the ten subjects for the BF and VM muscles that showed significant differences between the two conditions.

TABLE I: Mean and standard deviation of the RMS value for: Biceps Femoris (BF), Lateral Gastrocnemius (LG), Tibialis Anterior (TA), and Vastus Medialis (VM) in two conditions: test without the exoskeleton (WOE) and test with exoskeletons (WE&T) with the respective p-value results. (*) indicate the normal distribution of samples.

MUSCLES	**WOE (%)**	**WE&T (%)**	**p-value**
BF	9.02 ± 18.06	1.49 ± 1.31*	0.03
LG	1.40 ± 0.91*	4.06 ± 6.51	0.33
TA	1.57 ± 0.94*	5.49 ± 8.47	0.51
VM	4.78 ± 7.89	1.22 ± 1.49	0.03

B. *Gait cycle times*

Table II presents the average stance and swing times in seconds for the ten subjects tested in the conditions without and with the exoskeletons. It can be seen that there are no significant differences when comparing these times in the two conditions.

TABLE II: Swing and stance times of the gait cycle for each condition without (WOE) and with exoskeletons (WE&T). (*) indicate the normal distribution of samples

PHASES	**WOE (s)**	**WE&T (s)**	**p-value**
SWING	0.40 ± 0.11*	0.36 ± 0.11*	0.43
STANCE	0.93 ± 0.19*	0.76 ± 0.31*	0.16

C. *QUEST*

The Quebec User Evaluation of Satisfaction with assistive Technology (QUEST) [22] survey evaluates user's satisfaction qualitatively. A scale of 1 to 5 is used where one is very unsatisfied, and five is very satisfied. The survey was performed at the end of the test. The items evaluated are presented in Table III.

TABLE III: QUEST survey responses after using the AGoRA V2 Exoskeleton.

QUEST item	**Level of Satisfaction**
Dimensions (size, height, length, width)	4.5 ± 0.7
Weight	3.1 ± 0.9
Adjustments (fixing, fastening)	3.7 ± 0.9
Safety (secure)	4.8 ± 0.4
Ease of use	4.1 ± 0.6
Comfort	3.5 ± 0.7
Effectiveness	4.3 ± 0.7
Device satisfaction	**4.0 ± 0.7**

IV. DISCUSSION

In this section, the results obtained in the study are discussed following the previous section order. According to muscle activity, statistical tests for the TA and LG muscles showed no significant differences; however, the BF muscle activity decreased by 8% and the VM muscle activity by 4% according to the mean values of the 10 subjects observed in Table I. The BF muscle is responsible for the initial swing advancement of the limb by the active flexion at the knee [23]. This phase produces a concentric contraction to control the knee flexion and facilitate foot clearance in the swing phase. Because of this, the lower limb exoskeleton contributes to the assistance of knee flexion in the swing phase, significantly reducing the RMS value of the activity of this muscle. This also explains the hip extension and that when performing forward flexion, the exoskeleton assumes part of the hip extensor moment. This is supported in a study involving ten people walking with the Lokomat exoskeleton where the assistance of the device reduced the amplitude of muscle activity in those muscles responsible for stability and propulsion, such as the BF, with a reduction of up to 15.1% [24]. Also, BF muscle activity was lower in a bi-articular knee-ankle-foot exoskeleton comparing with the powered-off situation, owing to the assistance of knee flexion and lowering the person's metabolic cost of walking.

In addition, another study shows that the reduction of the EMG for this muscle indicates the assistance of hip extension as mentioned above in the late swing phase [25]. This is shown in Figure 3, where there is a reduction in the BF muscle activity amplitude. The exoskeleton is observed to advance knee flexion where the peak is displaced from 40% to 20% of the gait cycle. It is observed that the deviations decrease between the two conditions, which indicates that the exoskeleton causes all subjects to walk regularly. Therefore, despite anticipating the person's knee flexion, it is observed that the users adapt to the assistance of the exoskeleton by not generating a muscular force opposed to the movement of the exoskeleton.

According to Chen et al., the VM muscle is the primary muscle during the knee's extension motion, mainly acting in the stance phase [26]. This indicates that the lower-limb exoskeleton assists the torque generated in the stance phase, decreasing mean muscle activity by 4%. This relates to a study evaluating the KAD exoskeleton where the VM is reduced when using the device, indicating assistance in this gait phase [27]. This can also be seen in Figure 3, where the reduction in the mean amplitude of VM muscle activity is observed, with values of less than 2%.

There are no significant differences in muscle activity in the LG and TA muscles while using the devices. In the videos presented, it is shown that the ankle flexion from the toe-off is slightly longer with the use of T-FLEX, which can be interpreted as a compensation strategy by increasing the flexion so the person does not drag the foot. However, this represented no significant differences in either condition, which can be interpreted as a correct synchronisation between the devices and the person's natural gait. It could be assumed that the device's weight (20 kg) affects this measurement as well. However, this is not observed in the extension or flexion of the limb, i.e. in the significant difference of the TA and LG muscles.

Therefore the exoskeleton strategy is correctly synchronised with the gait, so the person compensates the weight of the exoskeleton when it transmits the torques to the hip, knee and ankle joints. This is confirmed by Cenciarini et al. that to avoid muscle co-contractions, the torque generated by the joint assistance must be synchronous with the torque exerted by the limb, causing coordination between the person and the exoskeleton [28]. On the other hand, this is a positive effect because this synchronisation in a pathological user refers to proper muscle activation.

In exoskeletons featuring all 3 joints, it has been found that the use of the device reduces the muscle activity of the BF muscle and even reduces the metabolic cost [29], which in our study was reflected in the reduction of an additional muscle, which was the VM muscle. In exoskeletons that have a rigid ankle joint with hip and knee actuation [30], or just knee actuation [31] it has been observed that the activity of the TA muscle increases in healthy subjects, which represents the importance of a soft orthosis in the ankle joint to compensate the muscles responsible for the dorsi-plantarflexion of the ankle.

Regarding the stance and swing times, it can be observed that since there are no significant differences, it can be implied that the person's gait is not altered. Therefore, the exoskeletons control follows the person's natural gait, causing the phases of the gait cycle not to be altered. This indicates that despite adding a weight of 20 kg to the person, the training performed in the test without the devices works correctly by adjusting to the natural gait of the subjects.

The AGoRA V2 exoskeleton has a weight of 19.8kg (AGoRA = 17kg, T-FLEX=2.8kg). This exoskeleton has a bilateral structure and unilateral active hip, knee, and ankle joints. Bilateral hip and knee exoskeletons such as Ekso (23kg) and ReWalk (23.3kg) have been found in the literature [32], however, they lack ankle actuation. Some unilateral exoskeletons such as KNEXO [33] and PH-EXOS [34] weigh between 3.5kg to 4.5kg, however, they only focus on one joint and have unilateral structures. Therefore, the AGoRA V2 exoskeleton has a weight benefit when compared to exoskeletons with bilateral two-joint actuation. Additionally, commercial bilateral exoskeletons with 3 actuators can weigh twice the AGoRA V2 exoskeleton as REX with 38kg [35].

According to the videos, it is observed that people reduce the step length when using the exoskeletons. However; it does not show a reduction in times because no significant differences are found, possibly because of a decrease in angular velocity. This indicates that the person makes a shorter step and takes the same amount of time, making the step slower.

Finally, the QUEST results show that the parameters that obtained the lowest satisfaction index correspond to the system's weight with an average index of 3.1 and comfort with an average of 3.5. The users reported that the weight of the devices was correctly distributed with the vest. However, as the test increased, the weight increased on the user's shoulders. On the other hand, the dimensions, safety and effectiveness of the exoskeleton are positive parameters greater than 4.5. This is similar in a lower-limb exoskeleton Kinesis, which had the lowest QUEST scores in weight, fit and comfort with a value of 3, while safety, durability and efficacy were the best evaluated, indicating that users have a positive perception of the devices in assisting gait activity [36]. Besides, users report in these measurements that the exoskeleton assisted correctly and did not affect the dimensions in their natural gait on the treadmill.

V. CONCLUSIONS AND FUTURE WORKS

This study presented the results of 10 subjects who performed tests with and without the AGoRA V2 exoskeleton. A decrease in BF and VM muscle activity was presented due to the devices' proper assistance. However, there were no changes in the LG and TA muscles. Likewise, it can be concluded that when adding an external weight of 20 kg to the person does not significantly alter their muscular effort. In addition, the devices also do not alter the natural gait of the person by not affecting the stance and swing times of the gait cycle. These results can be taken as a baseline in healthy subjects for future studies with pathological subjects where the main advantage is the synchronisation of the devices with the person's gait and the decrease of muscle activity in the muscles responsible for stance (VM) and swing phase

(BF). These studies can focus on evaluating the device overground, using long-distance locomotion tests. In addition, a greater number of muscle groups can be assessed, and the performance of the devices' controller can be shown. Lastly, the satisfaction index when using the devices had a value of 4, where the comfort and weight of the system should be taken into account in future studies.

REFERENCES

[1] C. Chugh, "Acute ischemic stroke: Management approach," *Indian journal of critical care medicine: peer-reviewed, official publication of Indian Society of Critical Care Medicine*, vol. 23, no. Suppl 2, S140, 2019.

[2] M. Louisette, A. Thérèse, H. Réjean, *et al.*, "Impact of Motor, Cognitive, and Perceptual Disorders on Ability to Perform Activities of Daily Living After Stroke," *Stroke*, vol. 32, no. 11, pp. 2602–2608, 2001.

[3] R. S. Calabrò, A. Naro, M. Russo, *et al.*, "Shaping neuroplasticity by using powered exoskeletons in patients with stroke: a randomized clinical trial," *Journal of NeuroEngineering and Rehabilitation*, vol. 15, no. 1, p. 35, 2018, ISSN: 1743-0003.

[4] G. Cioni, G. Sgandurra, S. Muzzini, *et al.*, "Forms of Hemiplegia BT - The Spastic Forms of Cerebral Palsy: A Guide to the Assessment of Adaptive Functions," in A. Ferrari and G. Cioni, Eds., Milano: Springer Milan, 2010, pp. 331–356, ISBN: 978-88-470-1478-7.

[5] S. Yeem, J. Heo, H. Kim, *et al.*, "Technical Analysis of Exoskeleton Robot," *World Journal of Engineering and Technology*, vol. 7, pp. 68–79, 2019.

[6] S. Toxiri, M. B. Näf, M. Lazzaroni, *et al.*, "Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends," *IISE Transactions on Occupational Ergonomics and Human Factors*, vol. 7, no. 3-4, pp. 237–249, 2019, ISSN: 2472-5838.

[7] M. B. Yandell, J. R. Tacca, and K. E. Zelik, "Design of a low profile, unpowered ankle exoskeleton that fits under clothes: Overcoming practical barriers to widespread societal adoption," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 4, pp. 712–723, 2019.

[8] D. Adiputra, N. Nazmi, I. Bahiuddin, *et al.*, "A review on the control of the mechanical properties of ankle foot orthosis for gait assistance," in *Actuators*, Multidisciplinary Digital Publishing Institute, vol. 8, 2019, p. 10.

[9] M. d. C. Sanchez-Villamañan, J. Gonzalez-Vargas, D. Torricelli, *et al.*, "Compliant lower limb exoskeletons: a comprehensive review on mechanical design principles," *Journal of NeuroEngineering and Rehabilitation*, vol. 16, no. 1, p. 55, 2019, ISSN: 1743-0003.

[10] M. Sánchez-Manchola, D. Gómez-Vargas, D. Casas-Bocanegra, *et al.*, "Development of a Robotic Lower-Limb Exoskeleton for Gait Rehabilitation: AGoRA Exoskeleton," in *2018 IEEE ANDESCON*, 2018, pp. 1–6.

[11] D. Gomez-Vargas, F. Ballen-Moreno, C. Rodriguez-Guerrero, *et al.*, "Experimental characterization of the T-FLEX ankle exoskeleton for gait assistance," *Mechatronics*, vol. 78, p. 102 608, 2021, ISSN: 0957-4158.

[12] L. J. Arciniegas M, M. Múnera, and C. Cifuentes, "Human-in-the-Loop Control for AGoRA Unilateral Lower-Limb Exoskeleton," *Journal of Intelligent and Robotic Systems*, 2021.

[13] C. A. Cifuentes and M. Múnera, *Interfacing Humans and Robots for Gait Assistance and Rehabilitation*. Springer, 2022.

[14] D. Gomez-Vargas, F. Ballen-Moreno, P. Barria, *et al.*, *The Actuation System of the Ankle Exoskeleton T-FLEX: First Use Experimental Validation in People with Stroke*, 2021.

[15] M. D. Sánchez Manchola, M. J. Pinto Bernal, M. Munera, *et al.*, "Gait Phase Detection for Lower-Limb Exoskeletons using Foot Motion Data from a Single Inertial Measurement Unit in Hemiparetic Individuals.," eng, *Sensors (Basel, Switzerland)*, vol. 19, no. 13, 2019, ISSN: 1424-8220 (Electronic).

[16] K. Knaepen, P. Beyl, S. Duerinck, *et al.*, "Human–Robot Interaction: Kinematics and Muscle Activity Inside a Powered Compliant Knee Exoskeleton," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 6, pp. 1128–1137, 2014, ISSN: 1558-0210 VO - 22.

[17] B. Chen, B. Zi, Z. Wang, *et al.*, "Knee exoskeletons for gait rehabilitation and human performance augmentation: A state-of-the-art," *Mechanism and Machine Theory*, vol. 134, pp. 499–511, 2019.

[18] P. Konrad, "A practical introduction to kinesiological electromyography," in *The abc of emg*, 1st ed., 2005.

[19] N. Lotti, M. Xiloyannis, G. Durandau, *et al.*, "Adaptive Model-Based Myoelectric Control for a Soft Wearable Arm Exosuit: A New Generation of Wearable Robot Control," *IEEE Robotics & Automation Magazine*, vol. 27, no. 1, pp. 43–53, 2020, ISSN: 1558-223X VO - 27.

[20] L. M. Silva and N. Stergiou, "The basics of gait analysis," *Biomechanics and Gait Analysis*, vol. 164, p. 231, 2020.

[21] A. Nandy, S. Chakraborty, J. Chakraborty, *et al.*, "1 - Introduction," in A. Nandy, S. Chakraborty, J. Chakraborty, *et al.*, Eds., Academic Press, 2021, pp. 1–15, ISBN: 978-0-323-85245-6.

[22] L. Demers, R. Weiss-Lambrou, and B. Ska, "Quebec user evaluation of satisfaction with assistive technology versione 2.0," *The Institute for Matching Persons and Technology: Webster, NY*, 2000.

[23] J. Webster and B. Darter, "Principles of normal and pathologic gait," *Atlas of Orthoses and Assistive Devices, Elsevier*, pp. 49–62, 2019.

[24] K. van Kammen, A. M. Boonstra, L. H. van der Woude, *et al.*, "The combined effects of guidance force, bodyweight support and gait speed on muscle activity during able-bodied walking in the lokomat," *Clinical biomechanics*, vol. 36, pp. 65–73, 2016.

[25] K. Kondo, Y. Akiyama, S. Okamoto, *et al.*, "Effect of different gait phase-based assist patterns of a wearable robot on gait motion," in *2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR)*, IEEE, 2021, pp. 378–381.

[26] J. Chen, X. Mu, and F. Du, "Biomechanics analysis of human lower limb during walking for exoskeleton design," *Journal of Vibroengineering*, vol. 19, no. 7, pp. 5527–5539, 2017.

[27] P. T. Chinimilli, Z. Qiao, S. M. R. Sorkhabadi, *et al.*, "Automatic virtual impedance adaptation of a knee exoskeleton for personalized walking assistance," *Robotics and Autonomous Systems*, vol. 114, pp. 66–76, 2019.

[28] M. Cenciarini and A. Dollar, "Biomechanical considerations in the design of lower limb exoskeletons. june 29-july 1, 2011; eth zurich, science city, zurich, switzerland;[part of rehab week zurich 2011, june 27 to july 1, 2011](vol. 2011)," *Piscataway, NJ: IEEE*, 2011.

[29] P. Malcolm, S. Galle, W. Derave, *et al.*, "Bi-articular knee-ankle-foot exoskeleton produces higher metabolic cost reduction than weight-matched mono-articular exoskeleton," *Frontiers in neuroscience*, vol. 12, p. 69, 2018.

[30] J. F. Veneman, R. Kruidhof, E. E. Hekman, *et al.*, "Design and evaluation of the lopes exoskeleton robot for interactive gait rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379–386, 2007.

[31] D. Zanotto, T. Lenzi, P. Stegall, *et al.*, "Improving transparency of powered exoskeletons using force/torque sensors on the supporting cuffs," in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, IEEE, 2013, pp. 1–6.

[32] A. Rodrıguez-Fernández, J. Lobo-Prat, and J. M. Font-Llagunes, "Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments," *Journal of neuroengineering and rehabilitation*, vol. 18, no. 1, pp. 1–21, 2021.

[33] P. Beyl, V. Grosu, M. Van Damme, *et al.*, "Knexo: A knee exoskeleton to study design and control concepts for walking assistance," in *Dynamic Walking International Conference, July 18-21, 2011, Friedrich-Schiller University of Jena, Germany*, 2011.

[34] Q. Wu, X. Wang, F. Du, *et al.*, "Design and control of a powered hip exoskeleton for walking assistance," *International Journal of Advanced Robotic Systems*, vol. 12, no. 3, p. 18, 2015.

[35] G. Barbareschi, R. Richards, M. Thornton, *et al.*, "Statically vs dynamically balanced gait: Analysis of a robotic exoskeleton compared with a human," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, 2015, pp. 6728–6731.

[36] A. J. Del-Ama, Á. Gil-Agudo, E. Bravo-Esteban, *et al.*, "Hybrid therapy of walking with kinesis overground robot for persons with incomplete spinal cord injury: A feasibility study," *Robotics and Autonomous Systems*, vol. 73, pp. 44–58, 2015.