2023 IEEE International Conference on Robotics and Automation (ICRA 2023)
May 29 - June 2, 2023. London, UK

Exploring Multimodal Gait Rehabilitation and Assistance through an Adaptable Robotic Platform

Sophia Otálora[1], Sergio D. Sierra M.[2], Felipe Ballén-Moreno[3,4],
Marcela Múnera[2,5] and Carlos A. Cifuentes[2,6] *Senior Member*, IEEE

***Abstract*— Lower-limb exoskeletons and smart walkers are robotic devices to assist patients in regaining their autonomy after a stroke. The integration of these devices enables gait rehabilitation and functional compensation, promoting natural overground walking. This article presents the Adaptable Robotic Platform for Gait Rehabilitation and Assistance (AGoRA V2 platform), which integrates the new AGoRA V2 Smart Walker and the AGoRA V2 unilateral lower-limb exoskeleton. It was evaluated with 14 healthy subjects using physiological and kinematic variables and a perception assessment. The study entailed four conditions: Without exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP). Results indicate a reduction in the muscle activity of the Rectus Femoris (18%) and Vastus Lateralis (15%), comparing WE&T and WP, as well as walking without any device (WOE) and using any robotic device (WE&T, WW, WP). Results suggest the importance of combining the exoskeleton with the robotic walker and the assistance of each device independently. Moreover, using the complete platform induces slower gait patterns than the walker, as the mean impulse force and linear velocity decrease by 42% and 44%, respectively. These results demonstrate that the platform contributes to safety, and improvements in gait parameters and muscular activity, indicating the system's potential to act as a modular device according to users' conditions and therapeutic goals.**

I. INTRODUCTION

Stroke is the leading cause of long-term disability [1] and remains the second leading cause of mortality globally [2]. About 80% of stroke survivors exhibit walking dysfunctions causing difficulties in performing activities of daily living [3]. Stroke causes hemiparesis, which refers to muscle weakness on one side of the body [4]. Such dysfunctions increase the risk of falling due to reduced muscle strength [5]. There are also emotional disorders that can interfere, with depression being a key factor affecting the person's quality of life [6].

The rehabilitation process of stroke survivors involves the recovery of gait, acquiring autonomy and improving their confidence [7]. This process can benefit from assistive devices that provide gait support, stability, and safety [8]. Among these devices, robotic exoskeletons and robotic walkers (SW) are commonly found [9]. Lower-limb exoskeletons are wearable devices that assist people who have lost their ability to walk. They improve the quality of rehabilitation exercises and accelerate the recovery process [10]. Robotic walkers allow higher levels of autonomy for people suffering from stability impairments. These devices provide physical support, sensory and cognitive assistance, and health monitoring using multiple sensors and actuators [11].

Combining these devices can provide better lower-limb rehabilitation, exploiting their advantages. For instance, exoskeletons that assist multiple joints can generate more significant metabolic savings than those assisting a single joint [12]–[14]. Nevertheless, the weight of these systems increases due to the number of actuators, which can lead to stability issues [15]. Thus, having a device that acts as a weight support system (e.g., an SW) ensures proper lateral balance and stability [16].

Some platforms allow the integration of multiple devices, using weight support on a treadmill or overground with walkers. For instance, Lokomat is a commercial solution to assist people with impaired walking, which uses a treadmill and a fixed weight support system [17]. EXPOS is a lower limb exoskeleton and a robotic walker that assists in walking, sitting and standing activities [18]. Lastly, the CP Walker provides support and balance using an exoskeleton linked to a walker in overground training [19]. Nevertheless, these platforms are usually tested as a complete system and do not provide modularity. The advantages aforementioned of lower-limb exoskeletons and SW could lead to the modularity needed for different types of assistance. Hemiparesis in stroke patients requires special training, as only one side is affected. It is also desirable from the clinical point of view that rehabilitation tools offer adaptability according to the impairment level of the patient [20].

To overcome these limitations, the AGoRA V2 Platform (See Fig. 1) is an adaptable and modular system that provides multimodal physical and cognitive support in post-stroke rehabilitation scenarios for patients with hemiparesis [21]. The platform consists of the AGoRA V2 Unilateral Lower-Limb exoskeleton (i.e., AGoRA exoskeleton and T-FLEX orthosis) and the AGoRA V2 Smart Walker.

Previous studies separately assessed the AGoRA exoskeleton [22], [23] and the T-FLEX orthosis [24], [25], as well as their combined performance [26]. Moreover, Sanchez et

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*This work was supported by the Colombian ministry of science, technology and innovation *Minciencias* (Grant No. 845-2020), and EPSRC FARSCOPE CDT.

[1] Graduate Program of Electrical Engineering, Federal University of Espirito Santo, Vitoria 29075-910, Brazil, sophia.gonzalez@edu.ufes.br

[2] Bristol Robotics Laboratory, University of the West of England, Bristol BS16 1QY, UK, {sergio.sierramarin, marcela.munera, carlos.cifuentes}@uwe.ac.uk

[3] Robotics & Multibody Mechanics (R&MM) Reasearch Group, Vrije Universiteit Brussel, 1050 Brussels, Belgium, felipe.ballen.moreno@vub.be

[4] Flanders Make, 1050, Brussels, Belgium.

[5] Biomedical Engineering Program, Colombian School of Engineering Julio Garavito, Bogotá D.C., Colombia,

[6] The School of Engineering, Science and Technology, Universidad del Rosario, Bogotá D.C., Colombia.

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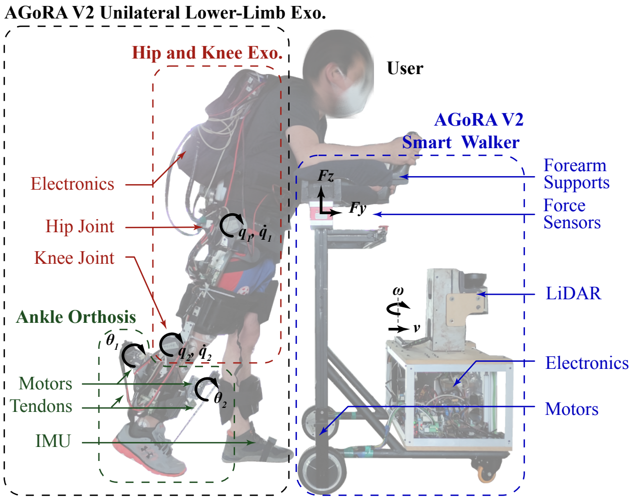


Fig. 1: AGoRA V2 Platform, consisting of the AGoRA V2 Smart Walker and the AGoRA V2 Unilateral Lower-Limb Exoskeleton. q_1, $\dot{q}_1$: angular position and velocity of the hip. q_2, $\dot{q}_2$: angular position and velocity of the knee. θ_1, θ_2: ankle motors' position. F_y, F_z: average impulse and vertical force at the handlebars. v, ω: linear and angular velocities of the walker.

al. and Arciniegas et al. explain that the AGoRA unilateral exoskeleton is suitable for stroke patients who suffer from hemiparesis [22], [23]. Regarding the integration of the exoskeleton, previous results showed physiological advantages in the reduction of muscle activity and improvements in the kinematic and spatiotemporal parameters of the users. On the other hand, a biomechanical evaluation of the AGoRA Smart walker mounted on a commercial robotic platform has demonstrated how users tend to compensate their kinematics, tilting their trunk and lower limbs to generate greater impulse forces on the device [27].

This article presents a modular platform with (1) the AGoRA V2 Unilateral Lower-Limb exoskeleton to assist hip, knee, and ankle joints; and (2) the newest version of the AGoRA Walker (AGoRA V2 Smart Walker), presented as a balance system that allows partial body-weight support and active propulsion. This work contributes to the state-of-the-art by evaluating the effect and performance of the robotic devices with 14 healthy users in 4 conditions. Besides, this work is relevant for future evaluations with pathological patients as a baseline of the performance of the devices working individually and in conjunction.

II. METHODOLOGY

A. AGoRA V2 Smart Walker

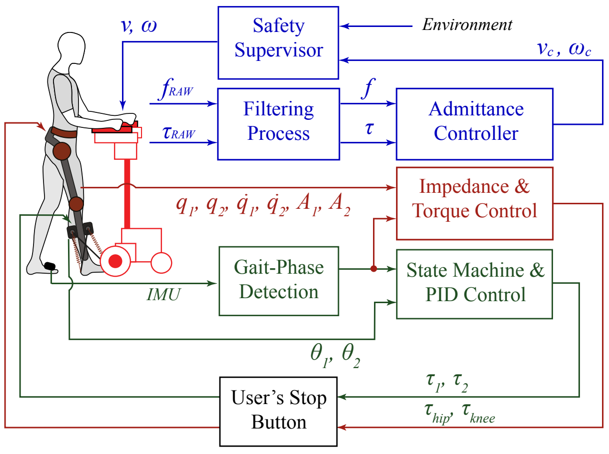
This work introduces the second version of the AGoRA Smart Walker. It entails a redesigned mechanical structure and a robust architecture of sensors and actuators seeking to provide partial body-weight support during overground walking (See Fig. 1). The first version was based on a commercial platform and could not provide body-weight support.

The device uses a differential drive configuration with two front caster wheels and two rear brushless DC hoverboard motors. Two kits of the DZRALTE-020L080 digital drive and the MC1XDZR02-QD board (A-M-C, USA) control the wheels. The drivers include an internal speed PID controller in a closed-loop configuration with the motors' hall effect sensors. The device equips one Li-Ion battery of 36V/4.4Ah and a Li-Po battery of 14.8V/5Ah. They provide autonomy of 6 - 8 hours of continuous use. Encoder (H1, US Digital, USA) placed at each motor estimate the device motion. An Inertial Measurement Unit (BNO055, Adafruit, USA) estimates the platform's orientation. Both sensors provide the platform's odometry. In addition, the device equips voltage sensors to alert when charging is required safely. 3D force sensors (MTA400, Futek, USA) at each forearm support estimate physical interactions with the user. Two front LiDARs (LMS111, SICK, Germany & Sweep V1, Scanse, USA) sense the environment, and one LiDAR (TIM551, SICK, Germany) at the front senses the user's legs. The device equips an onboard Raspberry Pi 4 8GB (Raspberry Pi Foundation, UK) running a Debian distribution compatible with the Robotic Operating System (ROS) framework. An external computer offloads heavy processing tasks and keeps experimental data.

B. AGoRA V2 Platform

This work exploits the assistance capabilities of a lower-limb exoskeleton and a robotic walker. To this end, the platform integrates the AGoRA V2 Smart Walker with the AGoRA V2 Unilateral Lower-limb Exoskeleton. The exoskeleton uses a rigid motorised structure with two active degrees of freedom in flexion/extension of the hip and knee joints. Also, it has a passive degree at the hip for abduction/adduction [23]. The ankle joint implements the concept of variable-stiffness actuation. It involves bio-inspired tendons using flexible and rigid elements and two servomotors to provide dorsi- and plantar-flexion assistance at the ankle [24]. The AGoRA V2 exoskeleton represents the conjunction between the hip and knee exoskeleton and the ankle orthosis, where its integration was previously assessed in another study [26].

Fig. 2 describes the control loops of the AGoRA V2 Platform. The ROS framework provides reliable communication protocols between the devices. On the one hand, the force sensors output the raw force and torque exerted by the user on the walker (i.e., f_{RAW} and τ_{RAW}). These signals are obtained from the impulse force signals F_y from both sensors [28]. Then they are filtered by two Fourier Linear Combiners to remove gait-related components as described in [29]. Two admittance controllers were used to emulate dynamic mass-damper systems and generate the reference linear and angular velocities (v_c, ω_c), using the force and torque signals [28]. Subsequently, an obstacle detection module uses the front LiDARs to detect hazardous situations. An algorithm estimates the distance to the closest object in a possible collision and modulates the velocity commands to prevent a collision [29]. This module is the safety supervisor and outputs the v, ω for the walker drivers.



Variables Description			
f	User's force	v	Walker linear speed
τ	User's torque	ω	Walker angular speed
v_C	Control linear speed	$\tau_{hip,\ knee}$	Executed torques on the exo
ω_C	Control angular speed	$\tau_{1,2}$	Executed torques on the ankle
$A_{1,2}$	Current at hip and knee	$q_{1,2}$	Angular position of hip and knee
$\theta_{1,2}$	Angles of ankle motors	$\dot{q}_{1,2}$	Angular velocity of hip and knee

Fig. 2: Internal control architectures of the multimodal AGoRA V2 Platform, consisting of the AGoRA V2 Unilateral Lower-limb Exoskeleton and the AGoRA V2 Smart Walker. The control variables are also depicted.

The exoskeleton involves two closed-loop control strategies driven by an IMU at the foot of the non-actuated limb. Employing the algorithm developed by *Sanchez-Manchola et al.* and the IMU signals, the gait phases are detected [30]. Regarding the hip and knee joints, an impedance controller uses the angular position and velocity of these joints ($q_{1,2}$ and $\dot{q}_{1,2}$), as well as the gait phases to estimate the required torques for the motors. A torque controller executes such commands and senses the electrical currents ($A_{1,2}$) for feedback purposes [23]. Regarding the ankle joint, a state machine determines the required angles at the variable stiffness actuators, and a PID controller executes them. The feedback loop of the PID controller uses the angular position of the ankle motors ($\theta_{1,2}$) [24]. For safety purposes, an emergency stop button provided to the user interrupts the power source of the complete platform.

C. Bio-mechanical Assessment

The following experimental procedure assesses the adaptable platform performance, the gait assistance capabilities and users' perception of the system.

1) Subjects: Fourteen healthy volunteers participated in the study (age: 22 ± 2 years old, height: 174 ± 4, and weight: 70 ± 7) with no condition in the upper or lower extremities that affects the gait pattern or prevents the participant from using the exoskeleton or the walker. Inclusion criteria were subjects with a height between 170 and 185cm and a weight of less than 110kg. In addition, the researchers obtained anthropometric measurements to ensure the devices' range (femur length: 49 ± 2, hip length: 31 ± 2, and tibia length: 42 ± 2).

2) Experimental protocol: This procedure lasted approximately 120 minutes. Initially, the participant is instrumented on the actuated leg with Shimmer3 (Shimmer3 EMG Unit, Shimmer) and electromyography (EMG) surface sensors at four relevant muscles in the gait activity: the Rectus Femoris (RF), Medial Gastrocnemius (MG), Tibialis Anterior (TA) and Vastus Lateralis (VL) according to SENIAM guidelines. In addition, the participant is instrumented with Inertial Measurement Units (IMU) at the tip of both feet (Shimmer3 IMU Unit, Shimmer) to analyse gait parameters and classify the EMG signals according to gait cycles. Afterwards, the EMG sensors record the maximum voluntary contraction (MVC) that the person can sustain through three measurements of 5 seconds of contraction and 10 seconds of rest. The MVC normalises the EMG signals for all subjects [31].

Following this, the participant performs the 10 Meter Walk Test (10MWT) overground in a straight line. The participants perform the 10MWT three consecutive times for experimental conditions of this study, (1) Evaluation without robotic devices (WOE), (2) Evaluation with AGoRA V2 Unilateral Lower-Limb Exoskeleton (WE&T), (3) Evaluation with AGoRA V2 Smart Walker (WW), and (4) Evaluation of the AGoRA V2 Platform (WP). Randomised order avoids the fatigue effects through the different conditions.

Finally, the participants fill out the perception questionnaire at the end of the evaluation stages. This questionnaire has different categories related to comfort, safety, assistance ability, ease of use, usefulness and satisfaction. The questionnaire is a simplified version of the QUEST 2.0 [32]. Also, the participants choose which form of the device provides better assistance.

3) Data processing and acquisition: Data processing in MATLAB (MathWorks, 2020a, USA) sampled EMG signals at a sampling frequency of 1024Hz. Also, the processing involved band-pass and Butterworth filters with a cutoff frequency of 15Hz to reduce noise [33]. The linear envelope is produced by rectifying the signal and applying a moving average filter with a window of 200ms.

Gait cycle extraction resulted in two phases: (1) the stance phase, where the foot is in contact with the ground, and (2) the swing phase, which is the time when the foot is in the air. The duration of these phases was 60% for the stance phase and 40% for the swing phase [34]. A complete gait cycle represents the time interval since a foot makes contact with the ground and ends when the same foot makes contact with the ground [34]. Processing for the IMU signals used a sampling frequency of 128Hz and a moving average filter with a window of 30ms. With the divided signals, the processing pipeline extracted the average root mean square (RMS) for each gait cycle, the stance and swing times, and the speed and cadence. The processing pipeline for the walker's data extracted the force exerted by the user, the vertical support force, and the executed linear velocity on the walker at a sampling frequency of 100Hz. This processing also obtained the average and maximum values for signals related to impulse force, vertical forces, and linear speeds for each participant.

4) Statistical Analysis: The SPSS software (IBM SPSS Software, USA) allowed statistical analysis of each condition. It involved a Shapiro-Wilk test for normality on all recorded variables. Also, this analysis performed the Friedman test to determine whether there were any statistically significant differences in muscle activity between the four evaluations with the devices. Furthermore, the Wilcoxon test was the alternative for non-parametric data distribution. On the other hand, the 1-WAY ANOVA determined differences among temporal gait parameters, and Tukey's post hoc test was performed in groups when the data followed a normal distribution. Regarding the variables from the walker, the one-tailed paired t-student test determined differences between the conditions that involved the walker (i.e., WW and WP). Finally, the Mann-Whitney U test is used for perception results.

5) Ethics Statement: The Research Ethics Committee of the Colombian School of Engineering Julio Garavito approved the experimental protocol. All participants received an explanation of the study and signed the informed consent form.

III. RESULTS

A. Control Architecture Illustration

To understand the control strategies in charge of providing gait assistance, Fig. 3 shows some of the signals involved in the architecture. The first signal, Force-Y, is the user's impulse force exerted on the walker by the upper limbs. The second signal is associated with the linear velocity executed on the walker, obtained from the admittance controller. The third graph describes the gait phases estimated online, where 0 is Toe Off, 1 is Heel Strike, 2 is Flat Foot, and 3 is Heel Off of the assisted and unassisted limb. The fourth graph displays the knee joint's desired and measured angular position. The fifth signal is the executed torque on the knee. The sixth graph displays the expected and measured angular position for the hip. The seventh signal is the executed torque on the hip. The eighth signal shows the ankle desired and measured angular position. The displayed signals were taken from a representative subject using all the AGoRA V2 Platform devices.

B. Kinematic Performance with the Smart Walker

Table I summarises the average and maximum values of the recorded variables from the AGoRA V2 Smart Walker. The table also describes the results of the t-student tests.

C. EMG activity

Table II shows the RMS value of the 14 subjects in the four conditions: Without exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP). Significant differences can be observed in the RF and VL muscles, comparing the four groups with a p-value under 0.01. In this sense, Fig. 4 shows the data distribution with the significant differences found with posthoc tests between the conditions with the devices in RF and VL muscles.

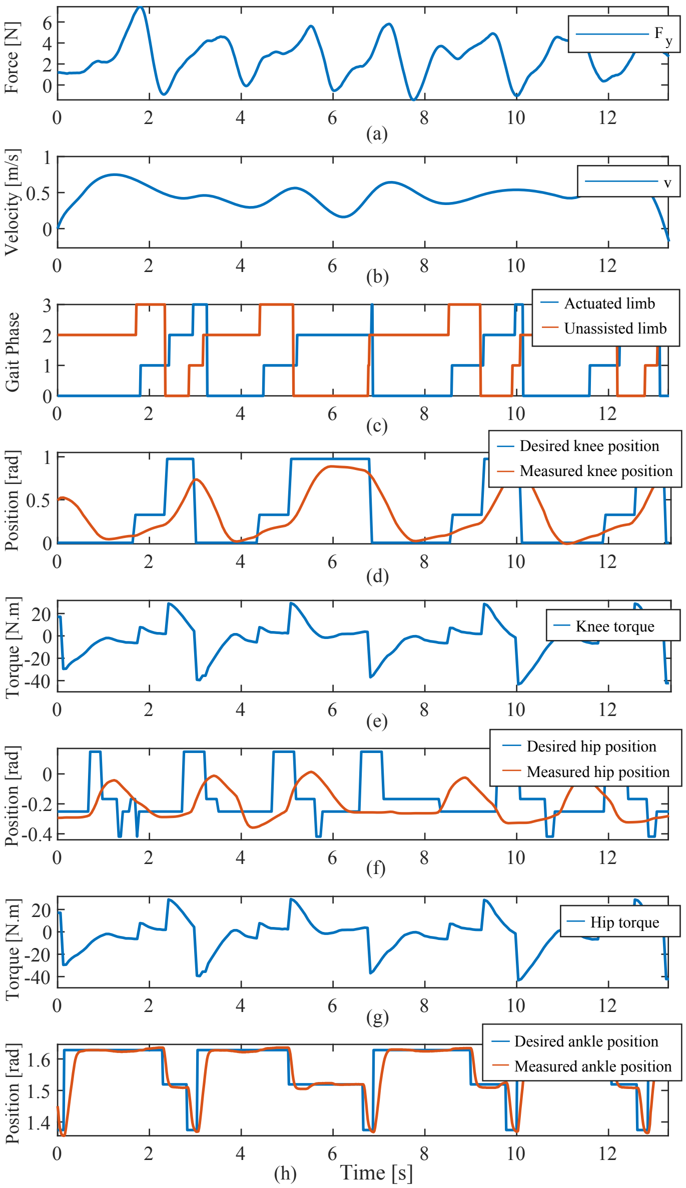


Fig. 3: Control signals of the AGoRA V2 Platform. (a) Impulse force of the user F_y (upper limbs). (b) Linear velocity of the walker v. (c) Gait phases at both limbs. (d) Desired and measured angular position at the knee. (e) Executed torque at the knee. (f) Desired and measured angular position at the hip. (g) Executed torque at the hip. (h) Desired and measured angle of the ankle.

D. Gait cycle parameters

Table III shows the swing and stance times of the gait cycle, the cadence, and the user's speed for the four conditions. The results show an increment in gait times and a reduction in cadence and speed when using any robotic device. Also, there are significant differences in the three parameters when comparing the four conditions. The posthoc test results indicated a significant difference for all pairwise comparisons (i.e., p-value $<$ 0.01), except for the tests between WE&T and WP for all gait parameters.

TABLE I: Physical interaction and kinematic indicators of the trials involving the AGoRA V2 Smart Walker control strategy. WW: Tests with the walker, WP: Tests with the walker and exoskeleton. (mean ± standard deviation)

Indicator	WW	WP	t-test
Mean Force-Y [N]	3.40 ± 0.58	1.96 ± 0.25	p<0.01
Max Force-Y [N]	7.41 ± 1.05	6.80 ± 0.98	0.03
Mean Force-Z [N]	6.26 ± 3.75	5.37 ± 3.86	0.12
Max. Force-Z [N]	11.87 ± 5.46	12.21 ± 6.14	0.37
Mean Velocity [m/s]	0.34 ± 0.06	0.19 ± 0.03	p<0.01
Max. Velocity [m/s]	0.74 ± 0.10	0.67 ± 0.01	0.03
Duration [s]	22.03 ± 5.07	38.04 ± 5.25	p<0.01

TABLE II: EMG RMS value for: Rectus Femoris (BF), Vastus Lateralis (VL), Tibialis Anterior (TA), and Medial Gastrocnemius (MG). Without exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP). (mean ± standard deviation)

Muscle	WOE (%)	WE&T (%)	WW (%)	WP (%)	p-value
RF	16.06±23.78	2.55±1.13	6.83±9.26	2.09±1.23	<0.01
VL	11.90±11.35	4.36±3.54	5.19±4.47	3.72±3.21	<0.01
TA	2.36±1.72	2.82±3.56	2.50±3.59	2.95±4.23	0.05
MG	16.4±19.6	11.7±15.1	12.9±13.8	12.6±23.6	0.21

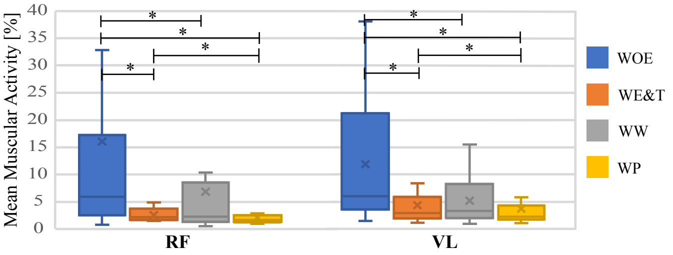


Fig. 4: Muscular activity for Rectus Femoris (RF) and Vastus Lateralis (VL). Without exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP).

TABLE III: Spatio-temporal parameters in four conditions: Without Exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP). SW: Swing phase, ST: stance phase (mean ± standard deviation)

Condition	SW (s)	ST (s)	Cadence (steps/min)	Speed (m/s)
WOE (%)	0.37 ± 0.04	0.85 ± 0.08	32.83 ± 4.17	0.76 ± 0.09
WE&T (%)	0.67 ± 0.12	1.71 ± 0.23	21.45 ± 3.55	0.28 ± 0.04
WW (%)	0.48 ± 0.06	1.31 ± 0.30	24.9 ± 4.05	0.45 ± 0.06
WP (%)	0.67 ± 0.12	1.80 ± 0.29	19.04 ± 3.56	0.27 ± 0.04
p-value	p<0.01	p<0.01	p<0.01	p<0.01

E. Perception questionnaire

The questionnaire used a 5-point Likert scale where ”1” meant ”*totally disagreed*”, and ”5” meant ”*totally agreed*”. The objective was to discuss the following variables: comfort, safety, assistance ability, ease of use, usefulness and satisfaction. Table IV shows the questionnaire items’ mean and standard deviation. Table V shows the results of the Mann-Whitney U test for pairwise comparisons. In addition, the participants answered an open-ended question to determine which robotic device provided better assistance, resulting in 50% for the complete platform and 50% for the walker.

IV. DISCUSSION

Fig. 3 shows the controllers’ response over time, e.g., the walker’s admittance controller takes the impulse force F_y of the user. The controller acts as a low-pass filter by rendering a smooth linear velocity on the device. Also, the gait phases for both assisted and unassisted limbs are estimated, finding that the exoskeleton properly uses them as input to support the knee, hip and ankle joints. The system tends not to reach the set point for both the hip and knee. This behaviour occurs mainly due to the short periods in each gait phase. However, the ankle joint equips faster motors that easily reach the set point, which could be useful for stroke patients suffering from foot drop conditions.

Regarding the results presented in Table I, the indicators related to the vertical force, the velocity, and task duration exhibited significant differences under the conditions With Walker (WW) and With Platform (WP). Particularly, using the complete platform induces slower gait patterns as the impulse force and linear velocity decrease. This can be seen as reductions in the average impulse force of 42% and thus in the average speed of 44%. This effect might be caused by the velocity constraints imposed by the exoskeleton. Such a slower pattern with partial body-weight support of the walker could guarantee a safer interaction, mainly in neurological patients.

In terms of muscle activity, it decreased in RF, and VL muscles, which are responsible for hip flexion [35] and knee extension, respectively. These reductions occur in two scenarios; without any device (WOE) and using any robotic device (WE&T, WW, WP) with decreases of 84% (WOE-WE&T), 58% (WOE-WW), and 87% (WOE-WP) for the RF muscle, and 63% (WOE-WE&T), 56% (WOE-WW), and 68% (WOE-WP) for the VL muscle. The muscle activation reduction occurs in both muscles when comparing WOE with WP. In addition, muscle activity is reduced between WE&T and WP, with percentages of 18% for RF and 15% for VL, indicating the importance of combining the exoskeleton with the robotic walker. Other studies have used the combination of an exoskeleton and a walker because it improves patient safety [36], [37]. In this case, muscle activity decreases because the user’s movements are attenuated due to its body weight support at the trunk level. Nevertheless, the walker used by Frizera et al. only provides weight support and has no active propulsion [36].

The comparison of muscle activity for TA and MG regarding WOE and WE&T showed no significant differences. Therefore, even though the users carry more weight, the exoskeleton provides support, and their muscle activity does not increase. Moreover, the ankle actuation generates an impact during the propulsion by assisting this joint in plantarflexion [38]. According to a previous study presented in [26], the integration of the AGoRA exoskeleton and the T-FLEX orthosis also presented no significant differences in the muscle groups responsible for ankle dorsi/plantar

TABLE IV: Questionnaire responses in three conditions: With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP) (mean ± standard deviation)

Item	WE&T (%)	WW (%)	WP (%)
Comfort	3.36 ± 1.08	4.50 ± 0.93	3.71 ± 0.99
Security	4.43 ± 0.93	4.79 ± 0.57	4.07 ± 1.07
Assistance ability	3.64 ± 0.84	4.21 ± 0.80	3.93 ± 1.14
Ease of use	4.14 ± 0.66	4.64 ± 0.84	4.29 ± 0.91
Usefulness	3.86 ± 0.77	4.14 ± 0.86	3.86 ± 0.95
Device performance	3.89 ± 0.41	4.46 ± 0.27	3.97 ± 0.21

TABLE V: Mann-Whitney U test of the questionnaire responses between the conditions using the robotic devices

Item	WE&T - WW	WE&T - WP	WW - WP
Comfort	0.01	0.34	0.02
Security	0.21	0.37	0.04
Assistance ability	0.08	0.38	0.61
Ease of use	0.02	0.41	0.15
Usefulness	0.36	0.94	0.45

flexion. In this sense, WE&T allows transparency in the lower muscles. Therefore, this would indicate in pathological patients appropriate assistance.

The WW contrast to WP also showed no significant differences because the user is leaning on the walker, which can be interpreted as the robotic walker bearing most of the overall weight (i.e., the user weight and the exoskeleton). In this sense, the system causes no muscular changes during walking with an assistive device of approximately 20kg, making the assistance of the exoskeleton transparent. However, when the WE&T is compared to WP, the muscle activity reduces by 18% for RF and 15% for VL muscles. Therefore, multiple assistive devices can generate more assistance when used in combination, which is also positively perceived by the user, and validated through the perception questionnaire.

It can be observed that cadence is directly related to the user's speed [39]. Therefore, given the limited speed of the exoskeleton, it decreases significantly in the conditions where it assists (WE&T and WP) and is higher in WOE and WW. This is also observed in the swing and stance phase times which do not change significantly between these conditions, given that the exoskeleton assists in both tests. However, it also implies a natural gait between the two conditions [40].

The speeds reported in the three conditions are slightly lower or similar to commercial lower-limb exoskeletons (Ekso - 0.24 m/s, Indego - 0.32 m/s, ReWalk - 0.33 m/s, WPAL - 0.24 m/s) [41]. Besides, the current speed ensures safety in using the robot for pathological patients. They have a slower speed than healthy subjects and, consequently, a shorter step length [42].

People chose WW and WP as the most helpful devices with 50%, which indicates that the weight support provided by this device for the exoskeleton is essential. There are differences in comfort, safety and ease of use when comparing the walker with the exoskeleton. Due to the addition of this device, healthy users prefer to use only the robotic walker, which is relevant for future studies to improve these features and the system's weight distribution. However, the device performance on the complete platform obtained a value of 4/5, indicating a positive overall perspective.

Stroke patients have a loss of balance, less propulsion at push-off, and less flexion at the hip and knee during the swing phase, which might lead to falls [43]. The AGoRA V2 Platform presents different modules evaluated separately and combined. According to this work's results, the device can be adapted to the patient's level of disability to have more control in the rehabilitation process. This allows the clinician to make decisions and configure the platform according to the therapeutic objectives of each patient. The AGoRA V2 Platform may overcome these limitations due to its contribution to gait parameters and reductions in muscle activity when using the complete platform. However, patients' capacity and disability must be evaluated to determine their tolerance to the exoskeleton and backpack weight in future studies.

V. CONCLUSIONS

This study presented an Adaptable Robotic Platform for Gait Rehabilitation (AGoRA). This platform involves the redesigned version of the AGoRA Walker (i.e., the AGoRA V2 Smart Walker) and the AGoRA V2 Unilateral Lower-limb Exoskeleton. This platform assessed 14 healthy subjects. At first, changes were observed by directly comparing the walker and the exoskeleton plus the walker, mainly due to velocity restrictions imposed by the exoskeleton.

Moreover, the muscular activity of the RF and VL showed significant differences, which are responsible for hip flexion and knee extension, respectively. Results showed that people tend to support their weight on the walker, which generates adequate weight support for the person using a unilateral exoskeleton that often experiences difficulty in stability and balance. In this sense, one of the main conclusions of this work is the ability of the AGoRA V2 Platform to address safe gait assistance. On the one hand, the exoskeleton provides actuation to the hip, knee and ankle joints. On the other hand, the walker provides partial weight support and active propulsion. Moreover, perception questionnaires evidenced positive users' safety, ease of use and usefulness of the walker as a complement to the exoskeleton. These features ensure independence and confidence in activities of daily living, especially for neurological patients.

Future works will focus on studies with pathological patients to evaluate the platform's performance on users with mobility and stability limitations, considering the previous results as a baseline. Regarding the performance of the devices, future studies will assess their use in stroke patients, including improvements in weight distribution, comfort, and the performance of the experimental protocol. In addition, users had a positive perception when using the devices in conjunction, which is a relevant factor in improving the design and structure of the devices in terms of reducing the complexity of donning and doffing the exoskeleton; provide a user interface to command the platform.

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