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. Four conditions were compared: 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). This suggests the importance of combining the exoskeleton with the robotic walker and the assistance of each device independently. Moreover, using the full platform induces slower gait patterns than the walker itself, as the mean impulse force and linear velocity decrease by 42% and 44%, respectively. These results demonstrate that the platform contributes to safe assistance, and improvements in gait parameters and muscle 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 the major 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 are reported to improve the quality of rehabilitation exercises and accelerate the recovery process [10]. Smart walkers allow higher levels of autonomy for people suffering from stability impairments. Using sensors and actuators, these devices provide physical support, sensory and cognitive assistance, and health monitoring [11].

The combination of these devices can provide better lower-limb rehabilitation, exploiting their individual 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].

There are platforms that 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 using a treadmill and a fixed weight support system [17]. EXPOS consists of a lower limb exoskeleton and a smart walker that assists walking, sitting and standing activities [18]. Lastly, the CP Walker is a platform that generates support and balance composed of 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 particular 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],

*This work was supported by the Colombian ministry of science, technology and innovation *Minciencias* (grant ID No. 845-2020)

[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, Bogota, Colombia.

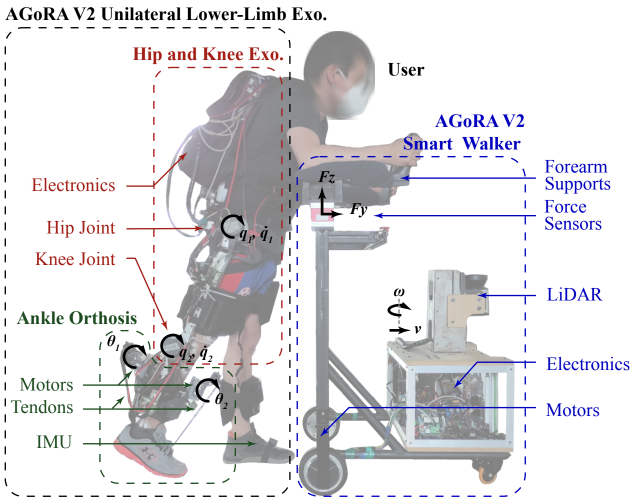


Fig. 1: AGoRA V2 Platform, consisting of the AGoRA V2 Smart Walker and the AGoRA V2 Unilateral Lower-Limb Exoskeleton. q_1, $\dot{q}_1$: angular position and velocity of the hip. q_2, $\dot{q}_2$: angular position and velocity of the knee. θ_1, θ_2: ankle motors' position. F_y, F_z: average impulse and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

as well as their combined performance [26]. Moreover, Sanchez et al. and Arciniegas et al. explain that the AGoRA unilateral exoskeleton is aimed at stroke patients who suffer from hemiparesis [22], [23]. Regarding the integration of the exoskeleton, physiological advantages were found in the reduction of muscle activity and improvements in the kinematic and spatio-temporal 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) that is 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 main 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 separately and in conjunction.

II. Methodology

A. AGoRA V2 Smart Walker

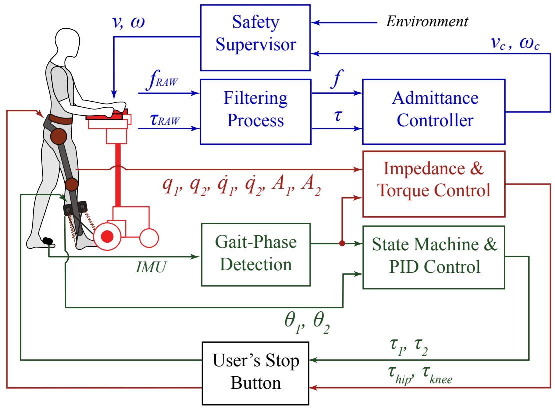
This work introduces the second version of this device, which consist of a redesigned mechanical structure and a robust architecture of sensors and actuators seeking to provide partial body-weight support during overground walking (See Fig. 1). The first version was based on a commercial platform and was not able to provide body-weight support.

The device uses a differential drive configuration with two front caster wheels and two rear brushless DC hoverboard motors. Each wheel is independently controlled by two kits of the DZRALTE-020L080 digital drive and the MC1XDZR02-QD board (A-M-C, USA). 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. To estimate the device motion, an encoder (H1, US Digital, USA) is placed at each motor. An Inertial Measurement Unit (BNO055, Adafruit, USA) estimates the platform's orientation. Both sensors are used to provide the platform's odometry. In addition, the device equips voltage sensors to alert when charging is required safely. To estimate physical interactions with the user, a pair of 3D force sensors (MTA400, Futek, USA) are placed at each forearm support. Two front LiDARs (LMS111, SICK, Germany & Sweep V1, Scanse, USA) are used to sense the environment, and one LiDAR (TIM551, SICK, Germany) is located in front of 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 is used to offload heavy processing tasks, as well as for experimental data storage.

B. AGoRA V2 Platform

This work exploits the assistance capabilities of a lower-limb exoskeleton and a robotic walker. To this end, the AGoRA V2 Smart Walker is integrated 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, and one passive degree at the hip for abduction/adduction [23]. The ankle joint is assisted under the concept of variable-stiffness actuation. It involves bio-inspired tendons made of 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 a hip and knee exoskeleton and an ankle orthosis where its integration was previously assessed in a study [26].

Fig. 2 describes the control loops of the AGoRA V2 Platform. The integration was done under the ROS framework, which 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 F_y from both sensors [28]. Then they are filtered by two Fourier Linear Combiner 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) from the users' force and torque [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 known as the safety supervisor and outputs the v, ω that are sent to 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 located 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 to be rendered on the motors. Thereafter, a torque controller executes such commands and senses the electrical current at the motors ($A_{1,2}$) 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 angular position of the ankle motors ($\theta_{1,2}$) is also estimated for the feedback loop of the PID controller [24]. For safety purposes, an emergency stop button provided to the user is capable of interrupting the power source of the full platform.

C. Biomechanical Assessment

The following experimental procedure was proposed to assess 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 $\pm$ 2 years old, height: 174 $\pm$ 4, and weight: 70 $\pm$ 7) with no condition in the upper or lower extremities that affects the normal 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 less than 110kg. In addition, anthropometric measurements were obtained to ensure the devices' functional range (femur length: 49 $\pm$ 2, hip length: 31 $\pm$ 2 and, tibia length: 42 $\pm$ 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 4 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 maximum voluntary contraction (MVC) that the person can sustain is performed through three measurements of 5 seconds of contraction and 10 seconds of rest. This is performed to normalise the EMG signals for all subjects [31].

Following this, the participant performs the 10 Meter Walk Test (10MWT), where they are asked to walk 10 meters overground in a straight line as they normally would, which they must perform 3 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). To avoid fatigue effects, the order of these stages is randomised.

Finally, the perception questionnaire is performed at the end of the evaluation stages. This questionnaire is divided into questions 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 are asked to choose which form of the device provides better assistance.

3) Data processing and acquisition: MATLAB software was used for data processing (MathWorks, 2020a, USA). First, EMG signals were acquired at a sampling frequency of 1024Hz; then, a band-pass filter and a Butterworth filter with a cutoff frequency of 15Hz were applied to reduce noise and artefact contamination [33]. The linear envelope is produced by rectifying the signal and applying a moving average filter with a window of 200ms.

The gait cycle is divided into two periods, the stance phase, where the foot is in contact with the ground, and the swing phase is the time when the foot is in the air. The duration of these phases is divided into 60% for the stance phase and 40% for the swing phase [34]. The signal gait cycles are divided by considering that one 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]. The IMU signals were acquired at a sampling frequency of 128Hz, and a moving average filter was applied with a window of 30ms. With the divided signals, the average root-mean-square (RMS) of each gait cycle is calculated, the stance and swing times are found, and the speed and cadence are calculated. The force exerted by the user, the vertical support force, and the executed linear velocity on the walker are recorded at a sampling frequency of 100Hz. The average and maximum values of the impulse force, vertical force, and linear velocity are estimated for each participant.

4) Statistical Analysis: The SPSS software (IBM SPSS Software, USA) was used for the statistical analysis of each condition. First, a Shapiro-Wilk test for normality is performed on all recorded variables. Afterwards, the Friedman test is performed to determine whether there are any statistically significant differences in muscle activity between the 4 evaluations with the devices. Then, the Wilcoxon test is performed when there is no normal data distribution. On the other hand, the 1-WAY ANOVA is performed to determine differences among temporal gait parameters, and the posthoc Tukey is performed in groups when the data follows a normal distribution. Regarding the variables from the walker, the one-tailed paired t-student test is applied to determine the existence of significant 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 protocol was approved by The Research Ethics Committee of the Colombian School of Engineering Julio Garavito. The study was explained to all participants, who signed the informed consent form.

III. RESULTS

A. Control Architecture Illustration

To understand the control strategies that are in charge of providing gait assistance, Fig. 3 shows some of the key signals involved in the architecture. The first signal, denoted as Force-Y, belongs to 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 hip joint's desired and measured angular position. 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 4 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 4 groups with a p-value under 0.01. In this sense, Fig. 4 shows the data distribution, together with the significant differences found with post-hoc tests between the conditions with the devices in RF and VL muscles.

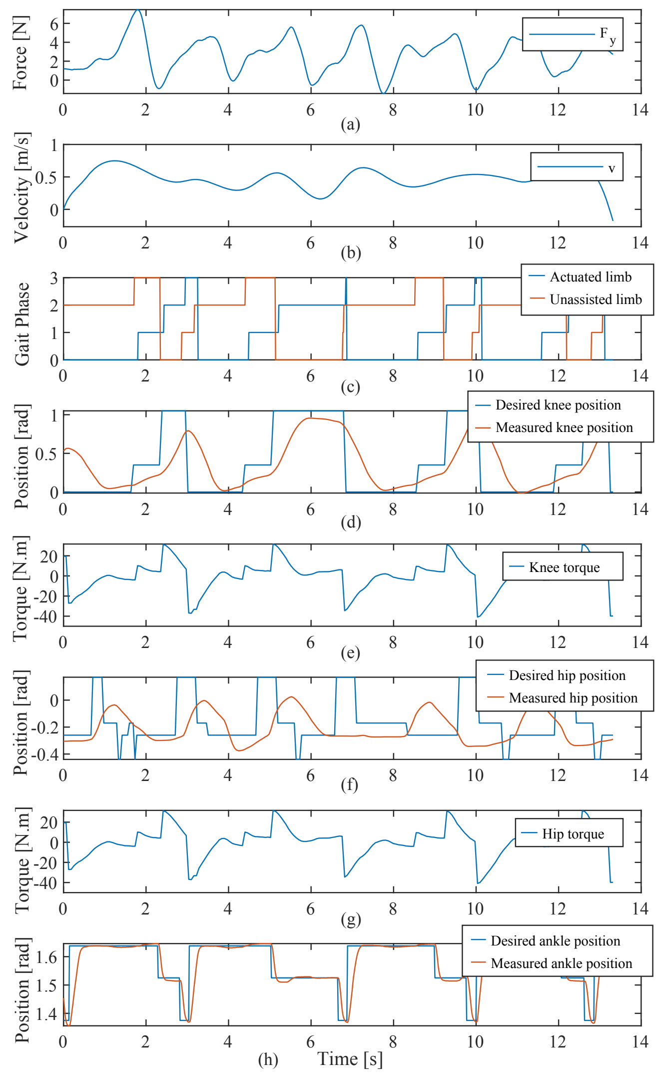


Fig. 3: Control signals of the AGoRA V2 Platform. (a) Impulse force of the user F_y (upper limbs). (b) Linear velocity of the walker v. (c) Gait phases at both limbs. (d) Desired and measured angular position at the knee. (e) Executed torque at the knee. (f) Desired and measured angular position at the 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 4 conditions. The results show an increase in gait times and a decrease in cadence and speed when using any robotic device. It is observed that there are significant differences in the 3 parameters when comparing the 4 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.

E. Perception questionnaire

Each question is ranked from 1 to 5 according to a Likert scale, where 1 has totally disagreed and 5 totally agreed. The objective is to discuss the following variables: comfort, safety, assistance ability, ease of use, usefulness and satisfaction. Table IV shows the mean and standard deviation

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

for each of the questionnaire items. Table V shows the results of the Mann-Whitney U test for pairwise comparisons. In addition, a question was asked to determine which robotic device provided greater assistance, resulting in 50% for the complete platform and 50% for the walker.

IV. DISCUSSION

According to Fig. 3, the controllers' response over time is observed. The admittance controller of the smart walker takes the impulse force F_y of the user and acts as a low-pass filter by rendering a smooth linear velocity on the device. 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. Both for the hip and knee, the system tends not to reach the set point. This occurs mainly due to the short periods in each gait phase. However, the ankle joint equips faster motors that easily reach the set point. This could constitute a key feature for stroke patients suffering from foot drop conditions.

Regarding the results presented in Table I, it is shown that 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 full platform induces slower gait patterns as the impulse force and linear velocity decrease. This is observed with 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. However, it should not be considered a drawback, considering that 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 reductions 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. These results show a greater muscle activation reduction occurs in both muscles when comparing WOE and 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]. It was observed that muscle activity decreases because the user's movements are attenuated due to its body weight support at the trunk level. However, the walker used by Frizera et al. only provides weight support and has no active propulsion [36].

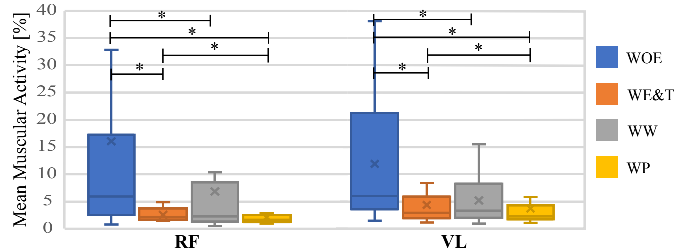


Fig. 4: Muscular activity for Rectus Femoris (RF) and Vastus Lateralis (VL). Without exoskeleton (WOE), With Exoskeleton (WE&T), With Walker (WW), and With Platform (WP).

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

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 plantar-flexion [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 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

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

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 than 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 lower 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 been found to have a loss of balance, less propulsion at push-off, and less flexion at the hip and knee during the swing phase, which can lead to falls [43]. The AGoRA V2 Platform presents different modules evaluated separately and combined. Through this biomechanical assessment, the device can be adapted according to the patient's stage 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 full 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 was assessed in 14 healthy subjects. At first, changes were observed by directly comparing the walker and the full platform, mainly due to velocity restrictions imposed by the exoskeleton.

Moreover, significant differences were found in the muscle activity of the RF and VL, which are responsible for hip flexion and knee extension, respectively. It is observed that people tend to support their weight to a greater extent 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 related to 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 are key features to 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. Considering the performance of the devices in healthy patients, their use in stroke patients can be evaluated in these studies, 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: reduce the complexity of donning and doffing of the exoskeleton; provide a user interface to command the platform.

REFERENCES

[1] E. J. Benjamin, M. J. Blaha, S. E. Chiuve, *et al.*, "Heart disease and stroke statistics—2017 update: A report from the american heart association," *circulation*, vol. 135, no. 10, e146–e603, 2017.

[2] G. Gillen and D. M. Nilsen, *Stroke Rehabilitation E-Book: A Function-Based Approach*. Elsevier Health Sciences, 2020.

[3] P. W. Duncan, R. Zorowitz, B. Bates, *et al.*, "Management of adult stroke rehabilitation care: A clinical practice guideline," *stroke*, vol. 36, no. 9, e100–e143, 2005.

[4] J. Cannan and H. Hu, "Upper body rehabilitation a survey," *Colchester CO4 3SQ, UK*, vol. 631, 2012.

[5] L. Jørgensen, T. Engstad, and B. K. Jacobsen, "Higher incidence of falls in long-term stroke survivors than in population controls: Depressive symptoms predict falls after stroke," *Stroke*, vol. 33, no. 2, pp. 542–547, 2002.

[6] A. Srivastava, A. B. Taly, A. Gupta, *et al.*, "Post-stroke depression: Prevalence and relationship with disability in chronic stroke survivors," *Annals of Indian Academy of Neurology*, vol. 13, no. 2, p. 123, 2010.

[7] R. S. Rasmussen, A. Østergaard, P. Kjær, *et al.*, "Stroke rehabilitation at home before and after discharge reduced disability and improved quality of life: A randomised controlled trial," *Clinical rehabilitation*, vol. 30, no. 3, pp. 225–236, 2016.

[8] C. Selves, G. Stoquart, and T. Lejeune, "Gait rehabilitation after stroke: Review of the evidence of predictors, clinical outcomes and timing for interventions," *Acta Neurologica Belgica*, vol. 120, no. 4, pp. 783–790, 2020.

[9] B. Kalita, J. Narayan, and S. K. Dwivedy, "Development of active lower limb robotic-based orthosis and exoskeleton devices: A systematic review," *International Journal of Social Robotics*, vol. 13, no. 4, pp. 775–793, 2021.

[10] P. Coenen, G. van Werven, M. P. van Nunen, *et al.*, "Robot-assisted walking versus overground walking in stroke patients: An evaluation of muscle activity," *Recovery of walking ability using a robotic device*, p. 19, 2013.

[11] W. M. Scheidegger, R. C. De Mello, M. F. Jimenez, *et al.*, "A novel multimodal cognitive interaction for walker-assisted rehabilitation therapies," in *2019 IEEE 16th international conference on rehabilitation robotics (ICORR)*, IEEE, 2019, pp. 905–910.

[12] B. T. Quinlivan, S. Lee, P. Malcolm, *et al.*, "Assistance magnitude versus metabolic cost reductions for a tethered multiarticular soft exosuit," *Science robotics*, vol. 2, no. 2, eaah4416, 2017.

[13] 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.

[14] N. A. Bianco, P. W. Franks, J. L. Hicks, *et al.*, "Coupled exoskeleton assistance simplifies control and maintains metabolic benefits: A simulation study," *PloS one*, vol. 17, no. 1, e0261318, 2022.

[15] M. F. Hamza, R. A. R. Ghazilla, B. B. Muhammad, *et al.*, "Balance and stability issues in lower extremity exoskeletons: A systematic review," *Biocybernetics and Biomedical Engineering*, vol. 40, no. 4, pp. 1666–1679, 2020.

[16] K.-R. Mun, S. B. Lim, Z. Guo, *et al.*, "Biomechanical effects of body weight support with a novel robotic walker for over-ground gait rehabilitation," *Medical & biological engineering & computing*, vol. 55, no. 2, pp. 315–326, 2017.

[17] N. Neckel, W. Wisman, and J. Hidler, "Limb alignment and kinematics inside a lokomat robotic orthosis," in *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, IEEE, 2006, pp. 2698–2701.

[18] K. Kong and D. Jeon, "Design and control of an exoskeleton for the elderly and patients," *IEEE/ASME Transactions on mechatronics*, vol. 11, no. 4, pp. 428–432, 2006.

[19] C. Bayon, O. Ramırez, J. I. Serrano, *et al.*, "Development and evaluation of a novel robotic platform for gait rehabilitation in patients with cerebral palsy: Cpwalker," *Robotics and autonomous systems*, vol. 91, pp. 101–114, 2017.

[20] J. M. Palomares-Pecho, G. F. M. Silva-Calpa, and A. B. Raposo, "End-user adaptable technologies for rehabilitation: A systematic literature review," *Universal Access in the Information Society*, vol. 20, no. 2, pp. 299–319, 2021.

[21] S. D. Sierra M, L. Arciniegas-Mayag, M. Bautista, *et al.*, "Introduction to robotics for gait assistance and rehabilitation," in *Interfacing Humans and Robots for Gait Assistance and Rehabilitation*, Springer, 2022, pp. 1–41.

[22] M. Sanchez-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*, IEEE, 2018, pp. 1–6.

[23] L. J. A. Mayag, M. Múnera, and C. A. Cifuentes, "Human-in-the-loop control for agora unilateral lower-limb exoskeleton," *Journal of Intelligent & Robotic Systems*, vol. 104, no. 1, pp. 1–19, 2022.

[24] 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.

[25] D. Gomez-Vargas, M. J. Pinto-Betnal, F. Ballén-Moreno, *et al.*, "Therapy with t-flex ankle-exoskeleton for motor recovery: A case study with a stroke survivor," in *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, IEEE, 2020, pp. 491–496.

[26] S. Otálora, F. Ballen-Moreno, L. Arciniegas-Mayag, *et al.*, "The agora v2 unilateral lower-limb exoskeleton: Mechatronic integration and biomechanical assessment," *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 7928–7933, 2022.

[27] S. Sierra, L. Arciniegas, F. Ballen-Moreno, *et al.*, "Adaptable robotic platform for gait rehabilitation and assistance: Design concepts and applications," *Exoskeleton Robots for Rehabilitation and Healthcare Devices*, pp. 67–93, 2020.

[28] S. D. S. M, M. Múnera, T. Provot, *et al.*, "Evaluation of physical interaction during walker-assisted gait with the agora walker: Strategies based on virtual mechanical stiffness," *Sensors*, vol. 21, p. 3242, 9 May 2021, ISSN: 1424-8220.

[29] S. D. S. M., M. Garzón, M. Múnera, *et al.*, "Human–robot–environment interaction interface for smart walker assisted gait: Agora walker," *Sensors*, vol. 19, p. 2897, 13 Jun. 2019, ISSN: 1424-8220.

[30] M. D. S. Manchola, M. J. P. P. 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," *Sensors*, vol. 19, p. 2988, 13 Jul. 2019, ISSN: 1424-8220.

[31] P. Konrad, "The abc of emg," *A practical introduction to kinesiological electromyography*, vol. 1, no. 2005, pp. 30–5, 2005.

[32] R. Wessels and L. D. Witte, "Reliability and validity of the dutch version of quest 2.0 with users of various types of assistive devices," *Disability and Rehabilitation*, vol. 25, no. 6, pp. 267–272, 2003.

[33] C. J. De Luca, L. D. Gilmore, M. Kuznetsov, *et al.*, "Filtering the surface emg signal: Movement artifact and baseline noise contamination," *Journal of biomechanics*, vol. 43, no. 8, pp. 1573–1579, 2010.

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

[35] M. B. Gerhardt, K. Logishetty, M. Meftab, *et al.*, "Arthroscopic and open anatomy of the hip," *Techniques in Hip Arthroscopy and Joint Preservation E-Book: Expert Consult*, p. 9, 2010.

[36] A. Frizera, R. Ceres, J. L. Pons, *et al.*, "The smart walkers as geriatric assistive device. the simbiosis purpose," in *Proceedings of the 6th International Conference of the International Society for Gerontechnology*, vol. 7, 2008, pp. 1–6.

[37] A. C. Villa-Parra, J. Lima, D. Delisle-Rodriguez, *et al.*, "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, 2020.

[38] L. Awad, H. Hsiao, and S. A. Binder-Macleod, "Central drive to the paretic ankle plantarflexors affects the relationship between propulsion and walking speed after stroke," *Journal of neurologic physical therapy: JNPT*, vol. 44, no. 1, p. 42, 2020.

[39] M. Volpini, V. Bartenbach, M. Pinotti, *et al.*, "Clinical evaluation of a low-cost robot for use in physiotherapy and gait training," *Journal of Rehabilitation and Assistive Technologies Engineering*, vol. 4, p. 2 055 668 316 688 410, 2017.

[40] F. A. Panizzolo, C. Bolgiani, L. Di Liddo, *et al.*, "Reducing the energy cost of walking in older adults using a passive hip flexion device," *Journal of neuroengineering and rehabilitation*, vol. 16, no. 1, pp. 1–9, 2019.

[41] K. Tan, S. Koyama, H. Sakurai, *et al.*, "Wearable robotic exoskeleton for gait reconstruction in patients with spinal cord injury: A literature review," *Journal of Orthopaedic Translation*, vol. 28, pp. 55–64, May 2021, ISSN: 2214031X.

[42] M. Pirpiris, A. Wilkinson, J. Rodda, *et al.*, "Walking speed in children and young adults with neuromuscular disease: Comparison between two assessment methods," *Journal of Pediatric Orthopaedics*, vol. 23, no. 3, pp. 302–307, 2003.

[43] B. Balaban and F. Tok, "Gait disturbances in patients with stroke," *Pm&r*, vol. 6, no. 7, pp. 635–642, 2014.