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Gait Analysis in Child with Dystonic Cerebral Palsy Via Video Photogrammetry Using a Prototype of an Assistive Device

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***Abstract*— Children with cerebral palsy do not present normal posture and movement patterns, so it is required to improve them. This work aims to show the differences in the trunk and ankles kinematics during the gait cycle of children with dystonic cerebral palsy, GMFCS level IV, using an assistive device and without using it, and to demonstrate how certain systems of the assistive device contribute to the children's gait trajectory control. The assistive device is a walker-type prototype designed under physical therapists' requirements. Walking tests were performed using marker protocol on the assistive device to assess its anti-return and directional locking systems. Gait Analysis were carried out with the child under two conditions, the walk assisted by two individuals and the walk using the assistive device. Two marker protocols were established. Recorded information was analyzed using motion analysis software. The elevation of each ankle and the trend of trunk angle variation concerning the vertical in the sagittal plane are determined for gait cycles with and without the prototype's aid. The results showed that the subject could perform the walking with the assistive device by himself. The line of progression presented lesser lateral deviations and a homogeneous frontal stride when the assistive device was used than without it. The anterior trunk and pelvic tilt increased by 19° to 28° in comparison to the walk with the assistance of people.**

***Keywords*— Assistive device; gait analysis; cerebral palsy; orthosis; walker.**

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I. INTRODUCTION

Instrumented movement analysis provides an effective tool to describe the gait progression of children with cerebral palsy (CP). The information of gait analysis in children makes disease can help diagnose the disorder's level [1] and assess the efficacy of clinical interventions [2]. CP describes a group of developmental disorders of movement and posture, which cause limitation of physical activity [3]. CP is a neurodevelopmental condition that begins in early childhood and is almost always diagnosed at this stage, but persists throughout life and has a variable severity spectrum [4]. Spastic type CP is the most frequently identified, and the second most common type is the dyskinetic type, characterized by being highly disabling [5].

In Ecuador, until April 30, 2018, a total of 8262 people assessed with disabilities under the Predominant Diagnosis of Cerebral Palsy were reported in the registry of the National Directorate of Disabilities, and of this number, a total of 3464 (42%) people were between 5 and 15 years of age" [6]. The distribution of cases of CP reported in Ecuador according to the "International Classifier of Diseases of the World Health Organization ICD-11" is presented in Table 1. The population percentage from 0 to 15 years according to CID-11 diagnosis is shown in Fig. 1 [6]**.** There is a scarcity of solid information in Ecuador on the prevalence of CP, however, there are studies developed in other regions of the world that report that the prevalence of CP occurs commonly in two or three out of every 1000 live births and has multiple etiologies [7]–[9].

According to the Gross Motor Function Classification System (GMFCS), the classification indicates the degree of CP according to its severity in five levels. This classification assigns the first level 1 to "very mild condition in which the person can perform all activities with almost no restrictions except for very advanced motor skills," and the last assigned level is 5 "where the person is completely dependent on a third person in their activities" [8]. Effects in children with CP include motor disorders such as abnormal gait patterns and delayed onset of gait [3]. A statistical study in medicine indicates that children with CP have a higher rate of deterioration of their mental and physical functions and are at greater risk of developing secondary diseases [10].

TABLE I
DISTRIBUTION OF CASES OF CP IN ECUADOR ACCORDING TO ICD-11 [6]

ICD-11	Diagnosis ICD-11	General Population	Population (0-15 years)
8D20.10	Spastic quadriplegic CP	2536	1318
8D20.11	Spastic diplegic CP	446	242
8D20.12	Spastic Hemiplegic CP	623	248
8D21	Dyskinetic CP	227	121
8D22	Ataxic CP	303	119
8D2Y	Other specified CP	1089	653
8D2Z	CP, unspecified	3038	1808
	Total	**8262**	**4509**

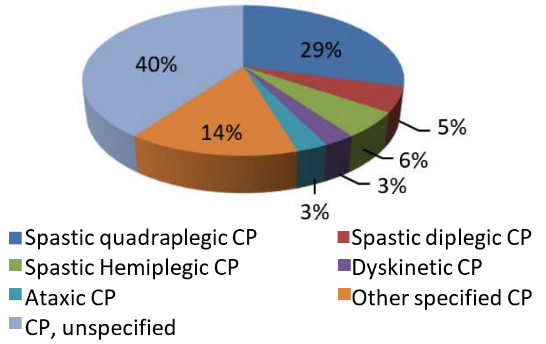

Fig. 1 Population percentage of between 0 to 15 years according to CID-11 diagnosis [6].

An investigation carried out in 2008 evaluated the ability to walk in a group of 451 children with different cases of CP. The results showed that 58.2% of the children with CP could "walk independently", 11.3% "walked using a handheld mobility device", and 30.6% had "no or limited walking ability" [11]. Walking in people with a neuromotor disability, such as CP, is abnormal. Therefore, in certain cases, such as weak muscle tone, exaggerated movements of the trunk tend to be performed. These gait conditions are due to alterations in muscle tone, motor control, balance, coordination, and other sensory disorders [12], [13].

The types of treatment for patients with CP depending on the patient's specific symptoms and range from physical therapy to the use of medications and surgery [9]. Early diagnosis and intervention of CP will optimize the infant's motor function, prevent secondary complications, and improve the caregiver's well-being [14].

However, physical treatment does not help to eliminate CP. Though, it controls its effects on the body, such as muscle hyperactivity, posture problems, altered muscle tone, difficulty in balance and walking, and muscle spasticity that leads to a decrease in muscle activity and increases sedentary lifestyle, among others [15]. Carrying out the physical treatment of children with CP requires adequate rehabilitation facilities, a program according to the patient's needs, prepared instructors, equipment, and assistive devices that can meet the requirements. Pediatric neurological physiotherapy includes treatments in which assistive devices are implemented as appropriate. Thus, the results can reach significant levels with physiotherapy at an early age and monitoring the patient's development. Consequently, an improvement in the living conditions and autonomy of the patients is achieved, and a comprehensive improvement of the patients is achieved using assistive devices [15].

Clinical gait analysis aims to determine the causes of a person walking in a particular way [16]. Previous studies indicate that clinical gait analysis is used to describe abnormal gait patterns in children with CP [12]. The experimental gait analysis procedure is performed to record and acquire data related to gait characteristics using a set of instruments to obtain precise and quantitative information [12], [13]. Spatiotemporal, kinematics, kinetics, and electromyography data are some types of information that are commonly assessed during gait analysis [13]. Clinical gait analyses are useful because they lead to a better understanding of the complex gait deviations present in CP patients. Thus, if gait deviations are known in a particular CP case, numerous treatment options can be applied to the patient.

A study involving 28 children with CP was developed to establish the natural variations in 2 gait analyses executed in each child with an average time lapse of 4.4 years without surgical intervention between the evaluations. The results showed a decrease in gait function of these children compared with another group of children that had had orthopedic intervention [17].

In the last years, sensors' data acquisition systems developed gait analysis in children with CP. A work presents gait parameters assessment by using a Kinect sensor-based system in a group of 11 subjects between 9 to 18 years old with GMFCS I to III to provide key information that can be used in rehabilitation [18]. Another study aims to establish the validity and reliability of Kinect sensor-based systems to perform walking tests in children with CP [19]. Gait analysis in about 18 children with CP (GMFCS I to III) has also been performed using 2D markerless protocol based on RGB-D sensor and validated with a marker-based photogrammetric system [20]. 3D gait analysis with a marker system was used to assess kinematic parameters by walking test of children with CP to determine the reliability of the results [21]. Gait analyses have also been used to support surgical recommendations and decision-king in patients with CP [13]. Performing gait analysis also allows determining walking speed in children with CP. The research was conducted with 15 children with CP (GMFCS I, II, III) to compare walking speed defined under laboratory conditions versus walking speed determined in real life. The authors concluded a heterogeneous behavior depending on each group of individuals' grade and type of CP[22].

These studies show the usefulness of gait analysis in the diagnosis, characterization of gait parameters, and treatment of patients with CP. However, to the authors' knowledge, gait analysis has been less investigated concerning the kinematics when using technical aids, assistive devices, or orthosis in children with CP. The limited studies are related to wearable ankle orthosis. For instance, an instrumented analysis of gait cycle on five people with CP to evaluate the influence of a wearable ankle exoskeleton was performed to determine its influence. Results showed improvement in the gait pattern by the use of the assistance device [23]. Another study with a robotic ankle exoskeleton for gait assistance in patients with CP was developed, and results demonstrated an improvement due to the use of the device [24]. A comparison study of gait parameters was done using a sort of orthotics in a child with spastic diplegic CP for rehabilitation after surgery to determine which one could be more suitable for the individual [25].

In the specific case of gait analysis on walkers, there is a a systematic review, which shows a lack of investigation on walkers used by dyskinetic CP children. Due to a low level of evidence, the study results should be considered carefully[26]. This work aims to show the differences in the trunk and ankles kinematics during the gait cycle of children with dystonic CP, GMFCS level IV, while walking assisted by two individuals and when walking by himself using an assistive device, walker typed, and to demonstrate how certain systems of the assistive device contribute to the children is gait trajectory control.

II. Materials and Method

A. Clinical Case

Dystonic, Dyskinetic, or Athetoid CP is paralysis in which the patient suffers from very rapid and sudden episodes of hypertonia and hypotonia, which means an increase and decrease in muscle tone. This rapid variation in muscle tone leads to incoordination and trouble walking and sitting [8]. The study subject is an 11-year-old boy diagnosed with dystonic CP, GMFCS grade 4, quadriplegia, and fluctuating muscle tone with low trunk tone. The child presents involuntary movements, lack of contraction, presence of archaic reflexes, and intends to start walking. The child requires the help of a third person to sit down, and his walk is extremely limited on his own.

He should always have the help of a caregiver, who is one of his relatives, for his mobilization and daily tasks. The caregiver moves and assists the child in his daily activities, including therapy sessions and exercises for his body joints. During the day, the child remains to lie down for a long time. This condition does not allow him to develop his motor skills or have optimal physical growth. The child needs to be carried by a third person to get around. He seldom walks with help, but the process is not ergonomic for the caregiver.

B. Anthropometry

Anthropometry is the study of the physical characteristics of a person. It is linked to ergonomics and safety in the production of machinery, equipment, and workspaces so that these are under the physical dimensions of people, customization of devices, and services. Table 2 shows the measurements of the height and weight of the user according to each year of measurement. This data has been provided by the child's therapist, who is following his rehabilitation treatment. Footprint markings measured anthropometric measurements of the child's stride length. The anthropometric measurements of the length of their limbs and the trunk, neck, head, among others, were measured following the WHO protocols. Anthropometric measurements were used for the adequate sizing of structural parts of the assistive device and for the calculation of work cycles.

TABLE II
Weight and Height of the Child in the Latest Years

Year	Height [cm]	Weight [kg]
2015	97	11,2
2016	100	13,4
2018	105	14,4

C. Assistive Device Prototype

The assistive device prototype was designed following a concurrent design process considering: (1) the requirements and needs of the physiotherapist and the patient and (2) the anthropometric measurements of the child. The prototype was designed with six functional systems: clamping system, damping system, anti-kickback system, brake system, directional locking system, folding system, and height variation system. The assistive device prototype developed is a walker-type mechanism shown in Fig. 2.

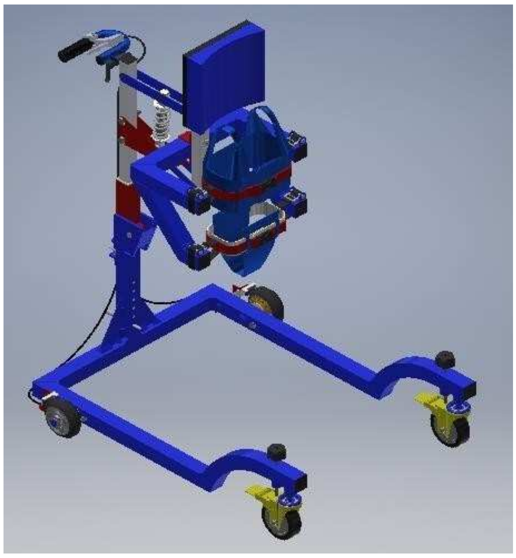

Fig. 2 Assistive device prototype, walker-type mechanism

D. Gait Analysis Test Protocol

The child's physiotherapist supervised the walking tests. Two groups of walking tests were performed with the child and the assistive device. The first walking test group was performed using a marker's protocol with two markers on the assistive device, as shown in Fig. 3. Walking tests using the assistive device with the anti-return and directional locking systems on and off were carried out in this stage. An aerial video camera captured the data, and it was analyzed using motion analysis software, which allowed obtaining the curves of the two-dimensional trajectories of the markers.

The second group of the walking test were also performed. Two conditions were analyzed: (1) the walk assisted by two people, and (2) the walk using the assistive device. Two protocols for the use of markers were established. The first is a protocol with 15 markers located on the child's body, as shown in Fig. 4. This marker's protocol was used in the two-people assisted walking test. The second protocol has 19 markers, six markers were located on the child's body, and the others were located on the assistive device as shown in Fig. 5 and was used in walking test with the assistive device. The information was collected using three video cameras and analysed using two motion analysis software. With the first software, the data of the trajectories of markers placed on the body of the child and the assistive device were debugged. With the second software, curves of the three-dimensional trajectories of the markers were obtained.

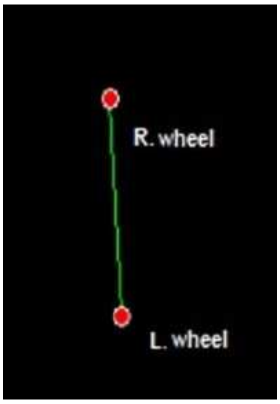

Fig. 3 Marker's protocol for walking tests with the assistive device with the anti-return and directional locking systems on and off (R: Right, L: Left)

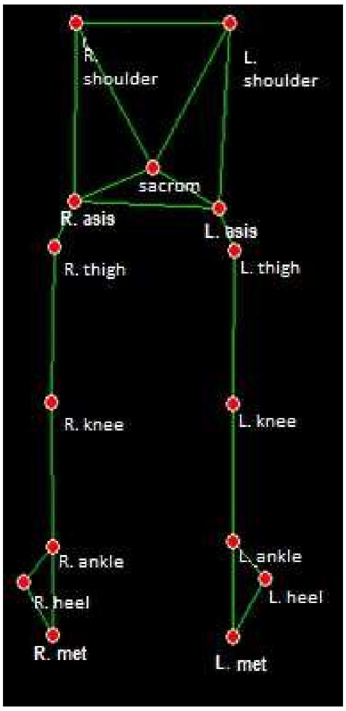

Fig. 4 Marker's protocol for walking test assisted by two people (R: Right, L: Left)

E. Kinematic Variables

1) Walking tests-Assistive device with anti-return and directional locking systems on and off: The two-dimensional trajectories given by the assistive device markers are the variables in the first group of walking tests.

2) Walking tests-Walking assisted by two people and walking using the assistive device: In the second group of walking tests, three-dimensional data is obtained for each ankle, shoulder, and sacral point (Fig. 4) using the assistive device in the gait cycle. Based on these points, variables, such as, elevation of each ankle and the inclination of the trunk with respect to the vertical in the sagittal plane, were defined for gait cycles in both ankles.

III. Results and Discussion

A. Results

1) Anthropometry: The anthropometric measurements of the child are indicated in Fig. 5.

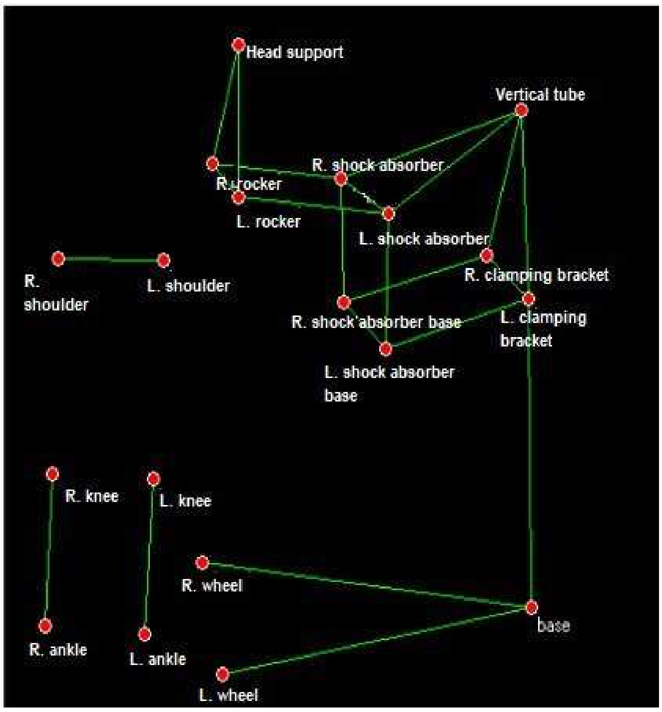

Fig. 5 Marker's protocol for walking test using the assistive device prototype (R: Right, L: Left)

2) Walking tests-Assistive device with anti-return and directional locking systems on and off: The trajectory of the assistive device during walking tests with the anti-reverse and directional locking systems activated is shown in Fig. 7. The trajectory of the assistive device with the anti-reverse system off is shown in Fig. 8. The trajectory of the device with the directional locking system off is shown in Fig. 9.

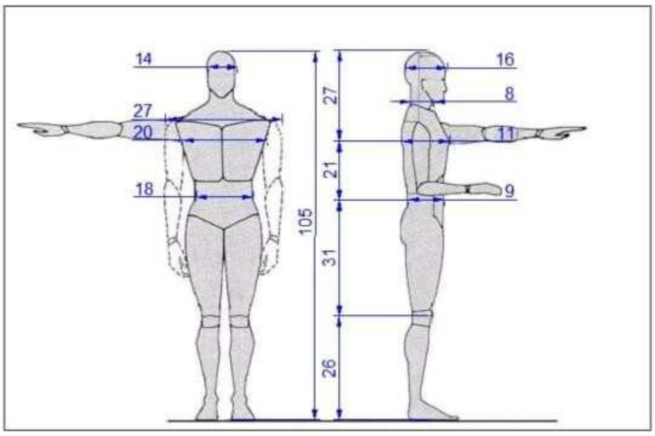

Fig. 6 Anthropometric measurements of the child. All measurements are in centimetres

3) Walking tests-Walking assisted by two people and walking using the assistive device: For the assisted by the two people walk, the trajectory of the ankle and some steps projected on the floor are shown in the Fig. 10 for the right one and in the Fig. 11 for the left one.

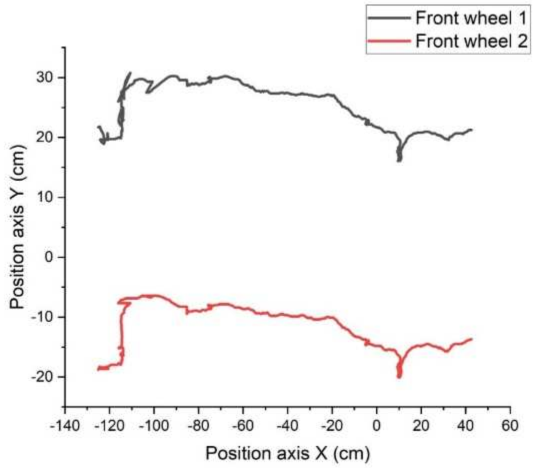

Fig. 7 X vs Y trajectory of the assistive device with the directional locking and anti-reverse systems activated

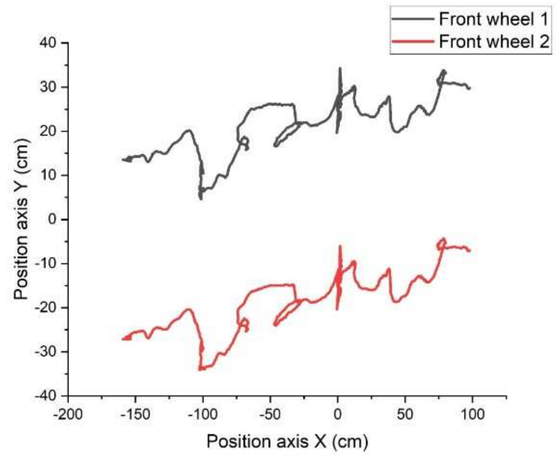

Fig. 8 X vs Y trajectory of the assistive device with the anti-reverse system deactivated

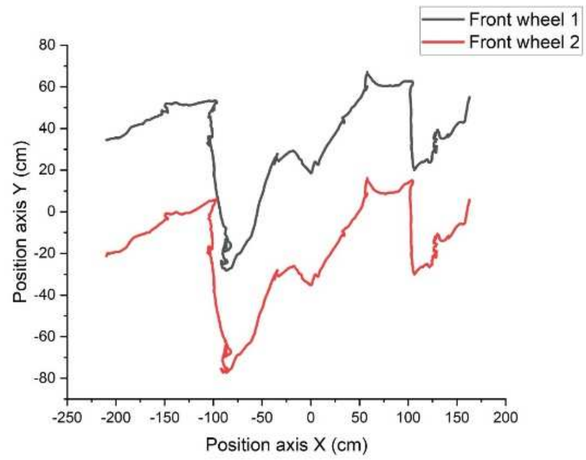

Fig. 9 X vs Y trajectory of the device with the directional locking system off

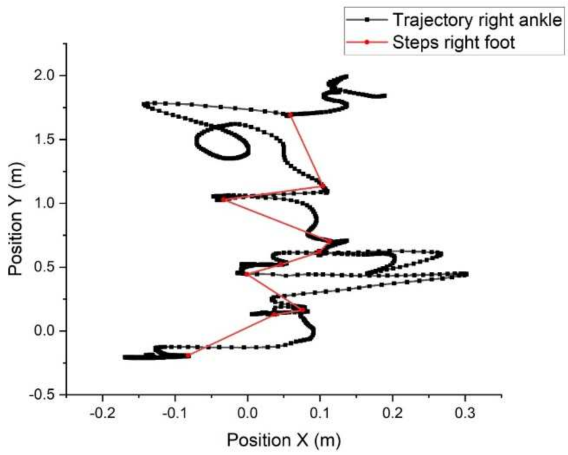

Fig. 10 Trajectory of the right ankle and some steps projected on the floor – Waking assisted by two people

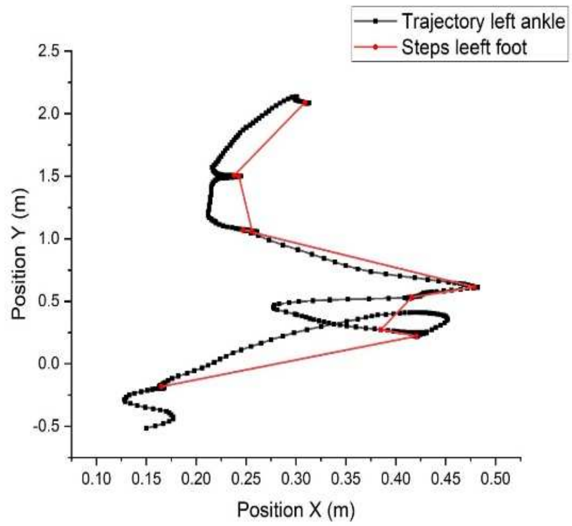

Fig. 11 Trajectory of the left ankle and some steps projected on the floor – Waking assisted by two people

For the assisted by the device walk, the trajectory of the ankle and some steps projected on the floor are shown in the Figures 12, 13, 14, 15 and 16 for the right one and in the Fig. 17 for the left one. The average right ankle position on the Y axis (height) vs the right foot step cycle during walking tests with and without the assistive device is shown in Fig. 18. The average left ankle position on the Y axis during a left foot step cycle with and without the assistive device is visualized in Fig. 19. The average angle of the trunk with respect to the vertical in the sagittal plane for a left walking cycle with and without the assistive device is shown in Fig. 20. The average angle of the trunk with respect to the vertical in the sagittal plane for a step cycle of right foot with and without the assistive device is shown in Fig. 21.

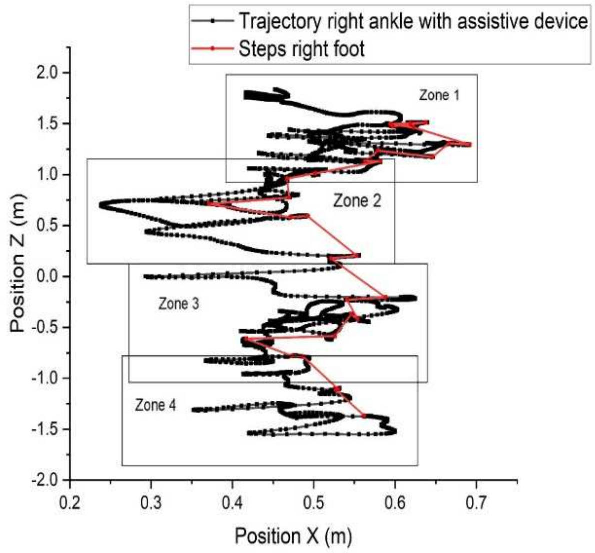

Fig. 12 Trajectory of the right ankle and some steps projected on the floor – Waking with the assistive device

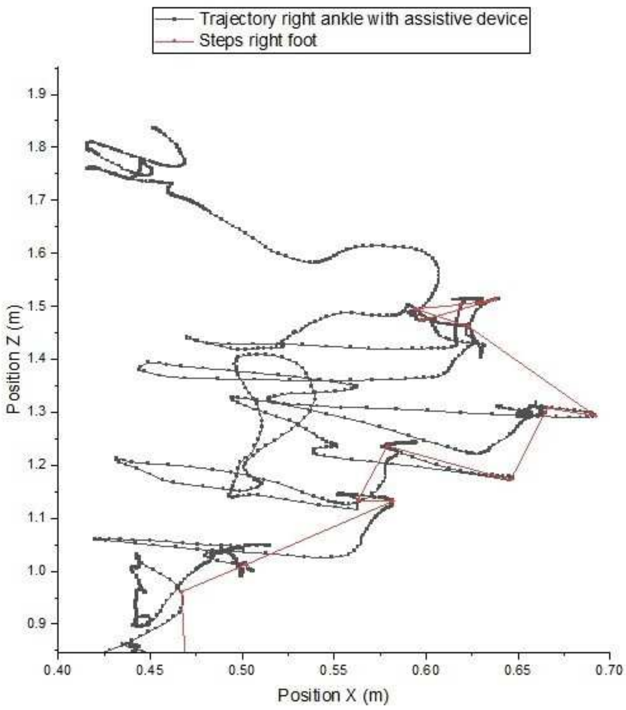

Fig. 13 Trajectory of the right ankle and some steps projected on the floor – Waking with the assistive device – Zone 1 amplified

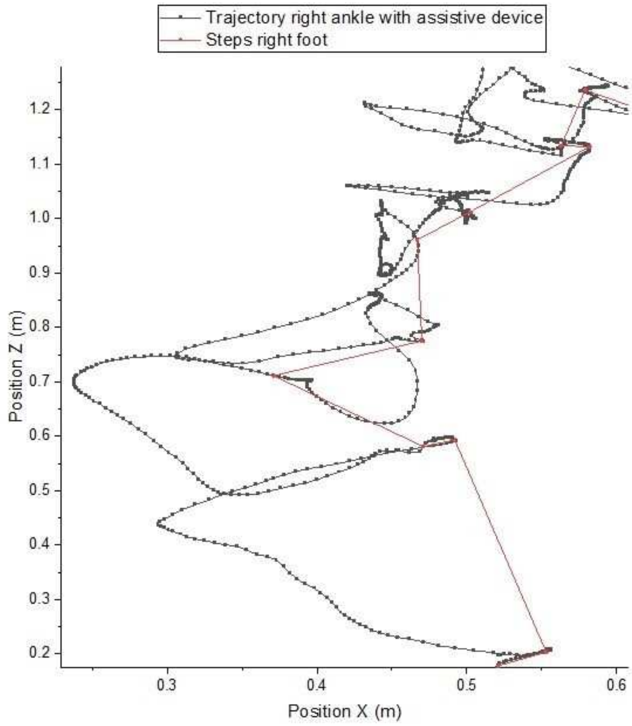

Fig. 14 Trajectory of the right ankle and some steps projected on the floor – Waking with the assistive device – Zone 2 amplified

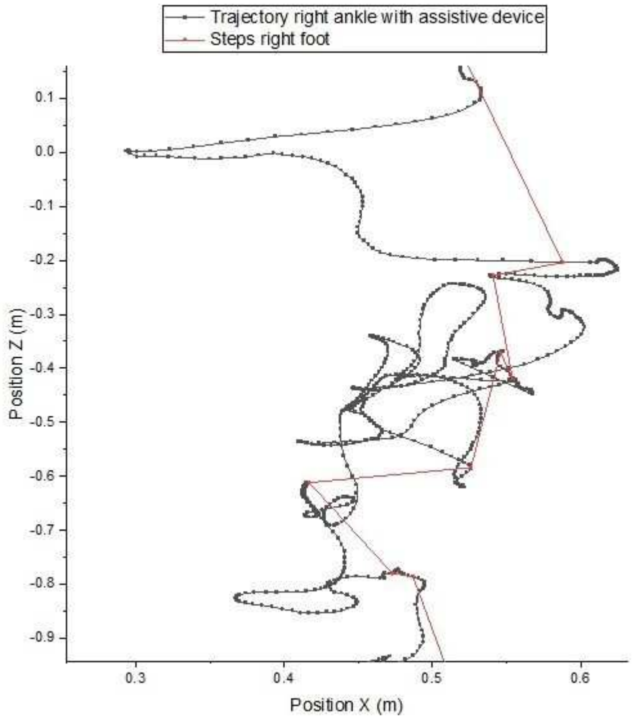

Fig. 15 Trajectory of the right ankle and some steps projected on the floor – Waking with the assistive device – Zone 3 amplified.

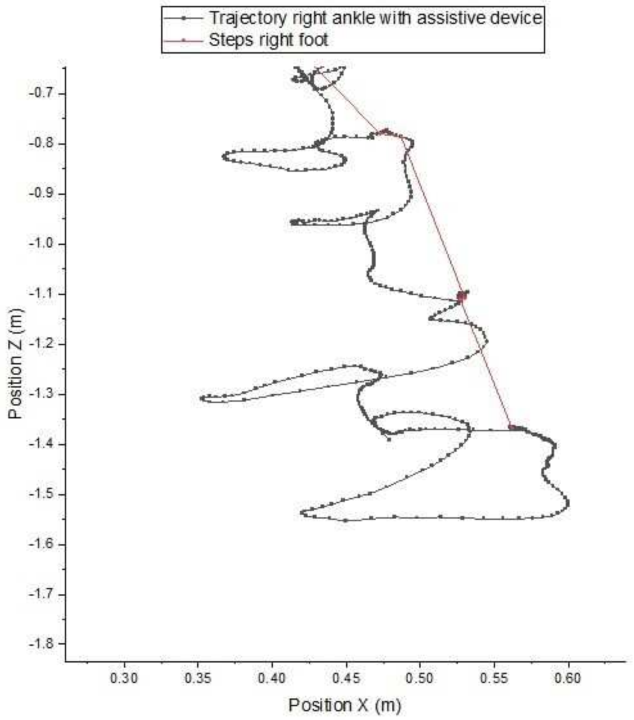

Fig. 16 Trajectory of the right ankle and some steps projected on the floor – Waking with the assistive device – Zone 4 amplified

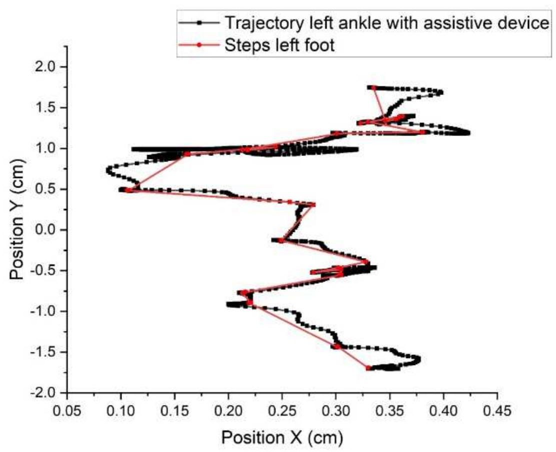

Fig. 17 Trajectory of the left ankle and some steps projected on the floor – Waking with the assistive device

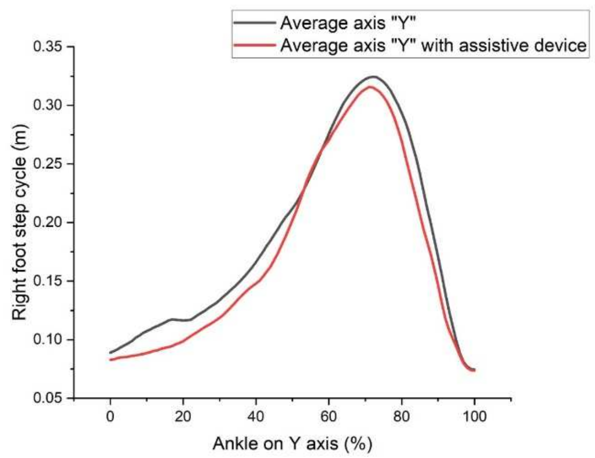

Fig. 18 Right ankle position in Y-axis (cm) vs. left foot step cycle (%)

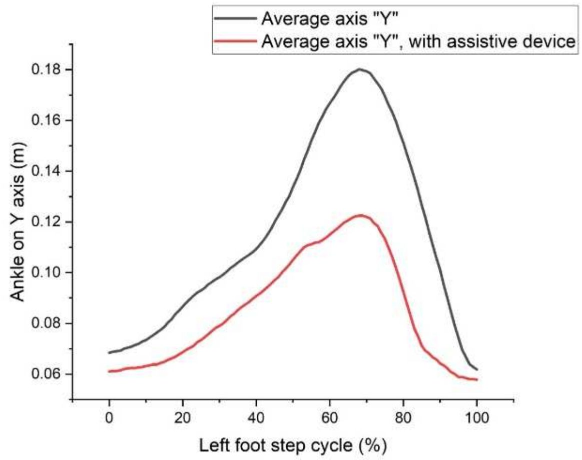

Fig. 19 Left ankle position in Y axis (cm) vs. left foot step cycle (%)

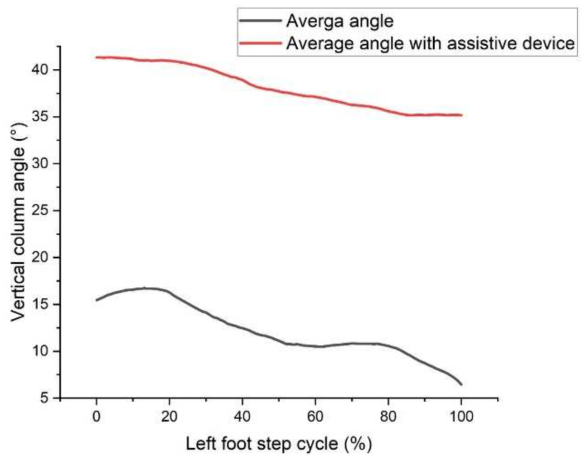

Fig. 20 Average angle between the trunk and the vertical in sagittal plane (degrees) vs. left foot step cycle (%)

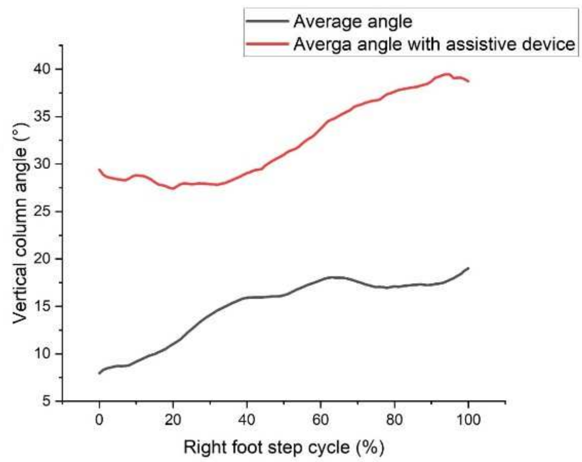

Fig. 21 Average angle between the trunk and the vertical in sagittal plane (degrees) vs. right foot step cycle (%)

B. Discussion

The trajectory of the front wheels of the assistive device when the anti-reverse and directional lock systems are activated is characterized by having a normal, continuous progression, without interruptions (Fig. 6), while the trajectory, when the anti-reverse and directional locking systems are deactivated, is not continuous (Fig.s 7 and 8). When the anti-reverse system is activated, the child does not present any backward motion during the walking (Fig. 6), while when the anti-reverse system has deactivated, the child with the assistive device shows several backward motions during the walking (Fig. 7). The most notable measured backward movement is approximately 20 cm. There are several peaks on Fig. 7 that indicate the child's movement stops in order to regain momentum.

When the directional locking system is off, the movement is highly variable in the Y-axis, although intended to be rectilinear (Fig. 8). Lateral displacements occur when the directional locking system is not activated, and they reach up to 46 cm (Fig. 8), but with directional block activated, the lateral displacement reaches up to only 14 cm (Fig. 6).

Without the use of the assistive device, the stride length varies between 10 cm and 55 cm, and the lateral displacement varies between 4 cm and 14 cm for the right ankle projection on the floor (Fig. 11). The stride length varies between 26 cm and 58 cm for the left ankle, and the lateral displacements between 1 cm and 25 cm for the right ankle projection on the floor (Fig. 17). With the use of the assistive device, the stride length reaches 38 cm, and the lateral displacement reaches 6 cm for the right ankle projection on the floor (Fig. 12 to 16). The stride length varies between 2 cm and 44 cm for the left ankle, and the lateral displacements reach 17 cm for the right ankle projection on the floor (Fig. 17).

The position of the right ankle is very similar with and without the assistive device in the step cycle of the right foot (Fig. 18). The right ankle reaches an average height of 31.5 cm with the assistive device and 32.4 cm without it (Fig. 18). In the case of the left foot, an average height of 12.2 cm is reached by the ankle with the assistive device and 18 cm without it (Fig. 19).

The average angle between the trunk and the vertical in the sagittal plane shows a decreasing trend in the step cycle of the left foot, with and without the assistive device (Fig. 20). The average angle that the trunk forms with the vertical without the assistive device presents a maximum of 15.45° and a minimum of 6.45°, while, with the assistive device, it corresponds to a maximum of 41.3° and a minimum of 35.16 ° (Fig. 20).

The average angle that the trunk forms with the vertical show an increasing trend in the step cycle of the right foot, with and without the assistive device (Fig. 21). The average angle that the trunk forms with the vertical without the assistive device presents a minimum of 7.96° and a maximum of 19°, while with the assistive device it presents a minimum of 28.2° and a maximum of 38.72° (Fig. 21).

IV. CONCLUSION

The device's anti-reverse and directional blocking systems allow the child to execute a gait only forward and with minimal lateral lags. In turn, both systems can be easily deactivated, providing versatility when performing the various therapeutic procedures. While walking with the assistive device, the user can carry out a homogeneous frontal stride by himself. In addition, the lateral displacements are lower, which makes the walking more directed and straight. At the same time, the inclination of the trunk increases between 19° to 28° in the sagittal plane compared to walking assisted by two people because when it maintains in a more upright position, it is unable to propel itself, and the assistive device.

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