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Quantified Gait Analysis in Children with Cerebral Palsy: A Retrospective Study of Spatiotemporal and Kinematic Characteristics

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Abstract | **Original Research Article**

***Purpose*:** Cerebral palsy (CP) is the leading cause of motor disability in children. Clinical visual gait analysis is limited due to the complexity of motor impairments associated with this condition. Quantified Gait Analysis (QGA), as an objective and reproducible tool, offers a better biomechanical understanding of gait abnormalities. This study aimed to identify gait characteristics in children with cerebral palsy. ***Methods*:** This retrospective observational study was conducted over six months (March–September 2023) at the Mohamed VI University Hospital in Marrakech. Seventeen ambulatory children with cerebral palsy (Gross Motor Function Classification System levels I–II), aged 4 to 18 years, were included. Each underwent 3D spatiotemporal and kinematic analysis using the Rizzoli protocol in the motion analysis laboratory. ***Results*:** The average walking speed was 0.71 m/s, with a cadence of 141.5 steps/min and an average step length of 0.44 m. Joint range of motion revealed notable abnormalities, including excessive hip flexion and limited knee extension. QGA helped objectify these impairments and inform targeted therapeutic strategies. ***Conclusion*:** QGA is a valuable tool for the functional assessment of children with CP. It enables the quantification of motor deficits, identification of deformities, and guidance in therapeutic decision-making, whether surgical, orthopedic, or rehabilitative.

Keywords: Cerebral palsy, Quantified Gait Analysis, Spatiotemporal Parameters, Kinematic Analysis, Pediatric Rehabilitation, Functional Assessment.

INTRODUCTION

Walking is a fundamental motor function essential for daily activities, autonomy, and social integration. It results from a complex and coordinated sequence of segmental movements involving almost the entire body—particularly the lower limbs—as well as osteoarticular, muscular, and both central and peripheral neurological structures [1, 2].

Cerebral palsy (CP) is defined as a group of permanent disorders affecting the development of movement and posture, leading to activity limitations. These are attributed to non-progressive lesions occurring in the developing brain of the fetus or infant [3, 4]. In addition to motor impairments, CP may be associated with sensory, cognitive, perceptual, and behavioral disturbances [4]. It is the most common cause of motor disability in children, with an estimated incidence of 2 to 3.5 per 1,000 live births [5].

Clinical gait assessment, often based on visual observation, remains subjective and limited—particularly when faced with the multiplanar gait disorders frequently observed in CP [1-6]. In this context, Quantified Gait Analysis (QGA) has emerged as a key tool in functional assessment. It allows for the synchronized acquisition of spatiotemporal, kinematic, kinetic, and electromyographic data during walking [2-7].

QGA enables a better understanding of motor disorders, helps identify the patho-biomechanical mechanisms underlying gait abnormalities, and supports the planning of therapeutic strategies— whether surgical, orthopedic, or rehabilitative [6–10].

Objective

The objective of this study is to identify gait characteristics in children with cerebral palsy through spatiotemporal and joint parameter analysis, carried out

at Mohamed VI University Hospital in Marrakech, to better guide their functional management.

MATERIALS AND METHODS

Type of Study

This was an observational, retrospective, cross-sectional study conducted over a six-month period, from March to September 2023.

Study Setting

The study was conducted at the Department of Physical Medicine and Rehabilitation of the Mohamed VI University Hospital in Marrakech, in collaboration with the Gait and Movement Analysis Laboratory at the hospital's Clinical Research Center.

Study Population

During the study period, 105 children with cerebral palsy were evaluated. Seventeen ambulatory children who met the inclusion criteria were selected.

Inclusion Criteria:

- Age between 4 and 18 years
- Clinical diagnosis of cerebral palsy
- GMFCS level I or II
- Ability to walk independently without assistive devices
- No prior orthopedic surgery related to CP
- Informed parental consent and child cooperation

Exclusion Criteria:

- Non-ambulatory children
- Severe intellectual disability or uncontrolled epilepsy

Data Collection

Data were collected using a structured data sheet, which included:

- Sociodemographic data (age, sex, socioeconomic status)
- Medical and obstetric history
- Anthropometric parameters (weight, height, BMI)
- Functional gait assessment (modified FAC, Fugl-Meyer score)
- Associated clinical data (pain, orthopedic deformities, aesthetic concerns)

Gait Analysis

QGA was performed at the hospital's motion analysis laboratory using a comprehensive setup that included:

- 6 optoelectronic cameras (Optitrack®)
- 2 force platforms (AMTI®)
- An 8-channel wireless EMG system (Delsys®)
- Motiv® and Visual3D® software for data processing

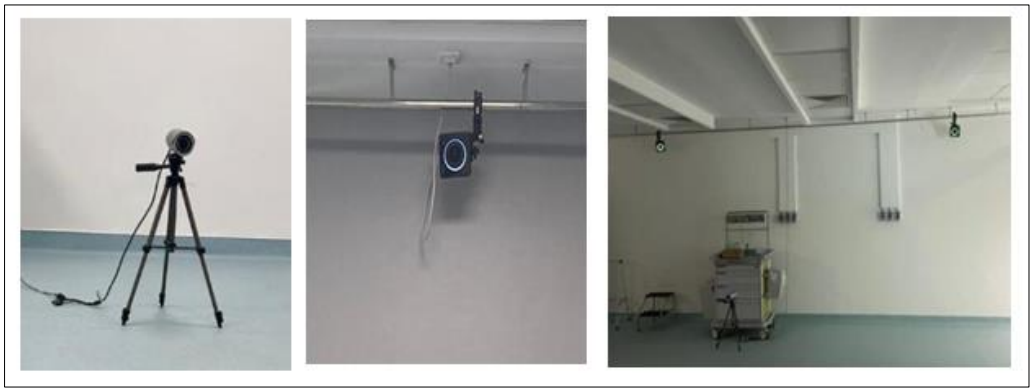

Figure 1: Gait and Movement Analysis Laboratory at the Marrakech University Hospital

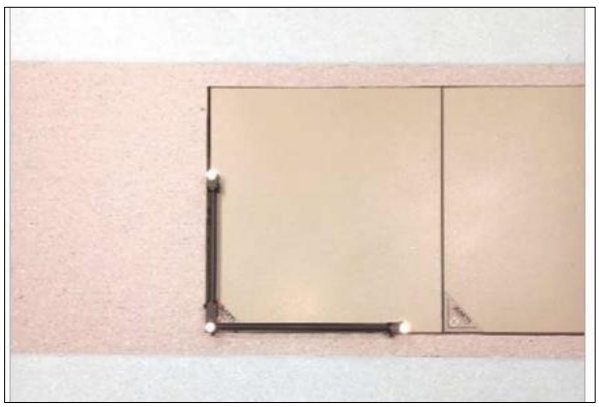

Figure 2: Force platform and calibration equipment

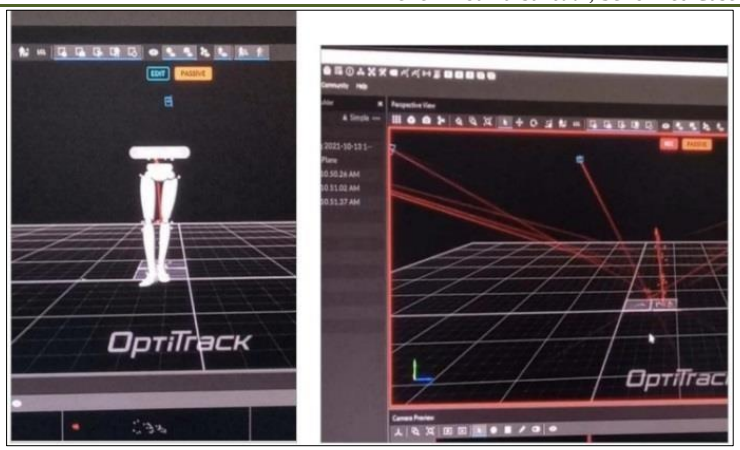

Figure 3: Interface of the 'Motiv' software for quantified gait analysis

Data acquisition followed the **Rizzoli Lower Body Protocol**, involving placement of reflective markers on specific anatomical landmarks to enable 3D modeling of lower limb motion.

Figure 4: Rizzoli lower body Protocol mode markers (11)

Measured Parameters Included:

- **Spatiotemporal variables:** cadence, stride length, walking speed, gait cycle duration, stance and swing phase durations
- **Joint kinematics (sagittal plane):** pelvis, hip, knee, and ankle movements

Statistical Analysis

Data were entered and analyzed using Google Forms and Microsoft Excel 2023. Results are expressed as mean ± standard deviation (SD).

Ethical Considerations

This study was conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from the parents or legal guardians of all participants. Confidentiality, anonymity, and respect for participants' privacy were strictly maintained.

RESULTS

Population Characteristics

Out of the 105 children with cerebral palsy evaluated during the study period, 17 met the inclusion criteria, representing 16.2% of the total.

- **Sex:** 10 boys (58.8%) and 7 girls (41.2%) — sex ratio M/F = 1.42
- **Mean age:** 10.41 years (range: 5 to 15 years)

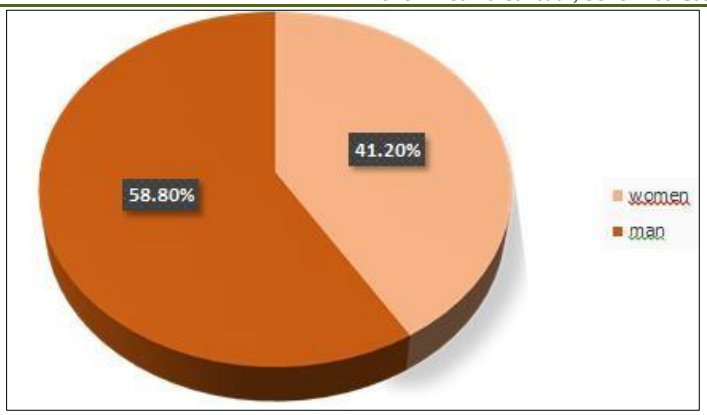

Figure 5: Distribution by gender

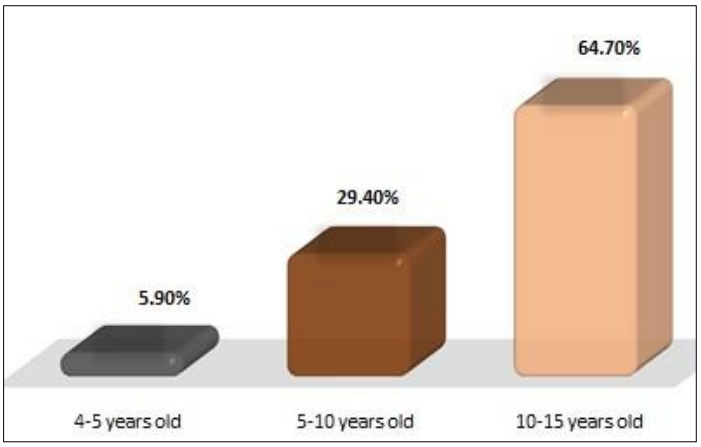

Figure 6: Distribution by age

Clinical Characteristics

- **Type of CP:** Hemiplegia in 10 children (58.8%), quadriplegia in 7 children (41.2%)
- **GMFCS Levels:** 56.2% were classified as level I, and 43.8% as level II

Functional Walking Assessment

- The new functional ambulation classification ≥ 7 in 41.2% of participants
- Fugl-Meyer score ≥ 5 in 100% of participants (52.9% scored 5; 47.1% scored 6)

Pain

- Pain was reported in 7 children (41.2%). Assessment was based on the Visual Analogue Scale (VAS) for communicating patients and parent-reported VAS for non-communicating patients.

Orthopedic Deformities

- Equinus or equinovarus foot: 47.1%
- Valgus foot: 23.5%
- Knee flexion contracture: 23.5%
- Hip deformity: 5.9%

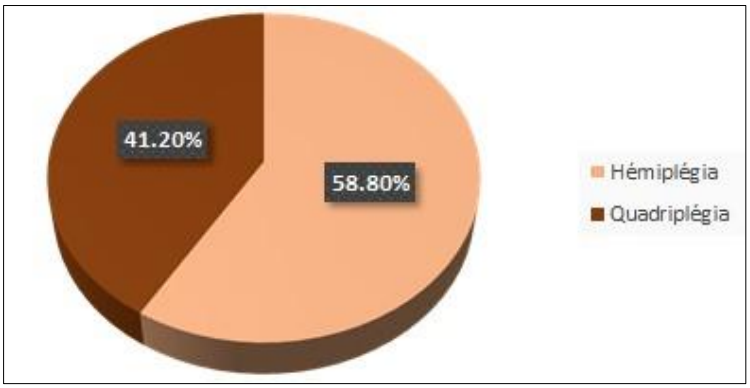

Figure 7: Distribution according to the type of cerebral palsy

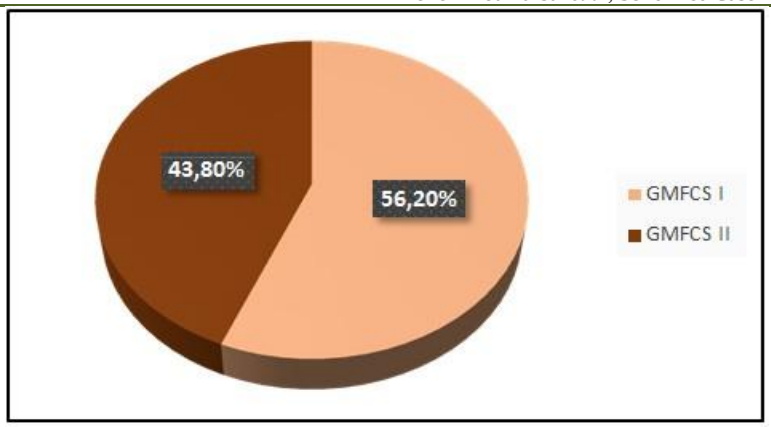

Figure 8: Distribution according to GMFCS

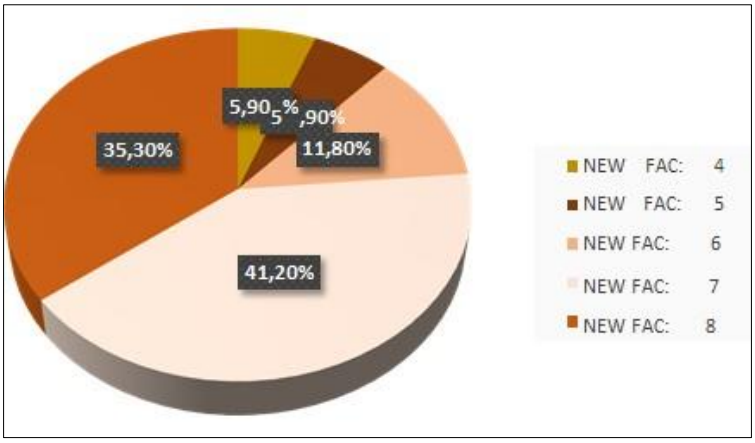

Figure 9: Distribution according to the new functional ambulation classification

Anthropometric Data

- Mean weight: 34.2 kg (range: 17–66 kg); 64.7% were underweight
- Mean height: 137.8 cm (range: 108–168 cm)
- Mean BMI: 17.4 kg/m²

Spatiotemporal Gait Analysis

Analysis was based on an average of 123 gait cycles per participant, leading to the following results

- **Average walking speed:** 0.71 m/s
- **Cadence:** 141.5 steps/min
- **Average step length:** 0.41 m (left), 0.45 m (right)
- **Average gait cycle duration:** 1.13 s (right: 1.08 s, left: 1.18 s)
- **Stance phase:** 56.1% (right), 53.8% (left)

The average walking speed was below normative values for the age group, suggesting functional limitations [4,69]. The elevated cadence may reflect compensatory mechanisms—particularly a reduction in step length—to maintain forward progression.

Table I: Spatio-temporal parameters

	Value	DS
Walking speed (m/s)	0.71	-
Left steps per minute (steps/min)	154.8	186.15
Right steps per minute (steps/min)	128	103.22
Left step length (m)	0.41	0.15
Right step length (m)	0.45	0.07
Left stance time (s)	0.63	0.38
Left stance time (s)	0.60	0.18
Right stance phase (%)	56.08%	-
Left stance phase (%)	53.76%	-
Left step time (s)	0.49	0.13
Right step time (s)	0.52	0.09
Gait cycle time (s)	1.13	-

Left gait cycle time (s)	1.18	0.50
Right gait cycle time (s)	1.08	0.38
Left swing time (s)	0.51	0.36
Right swing time (s)	0.46	0.23
Right swing phase (%)	43.26%	-
Left swing phase (%)	43.60%	-

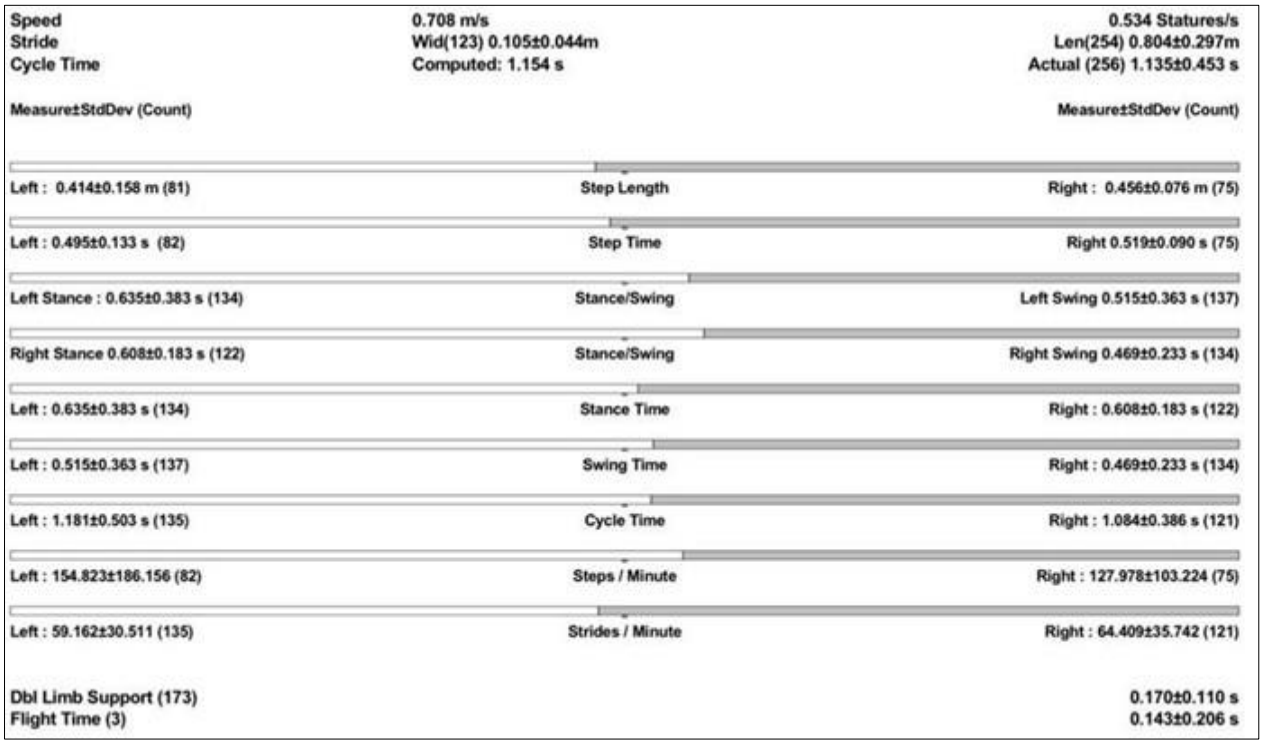

Figure 10: Graph of spatio-temporal parameters

Joint Kinematics (Sagittal Plane)

Pelvis:

Pelvic tilt ranged from 6.78° to 10.85° (left) and 8.66° to 10.89° (right), with mean amplitudes of 4.07° (left), 2.23° (right), and an overall mean of 3.15°. These values indicate slightly increased pelvic anteversion (Table II, Figure 11).

Table II: Degrees of antepulsion/retropulsion of the pelvis on the sagittal plane

	LEFT	DS	RIGHT	DS
Antepulsion	10.85°	8.21	10.89°	7.32
Retropulsion	6.78°	9.74	8.76°	8.27
Amplitude	4.07°	-	2.23°	-
Average of the 2 basins	3.15°	-	-	-

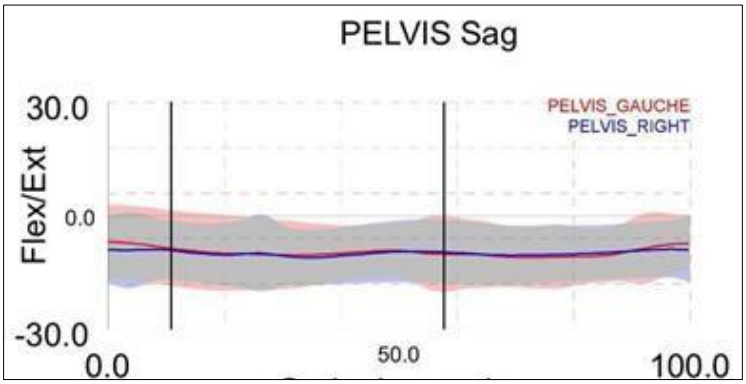

Figure 11: Graph of the degrees of pelvic antepulsion/retropulsion

Hip:

- Flexion ranged from ~4.45° (extension) to ~34.36° (flexion), with a mean amplitude of 29.47°
- Hip extension was limited, reflecting persistent flexion during pre-swing. (Table III, Figure 12)

Table III: Degrees of hip flexion/extension

	LEFT	DS	RIGHT	DS
Hip MIN (extension)	4.90°	13.21	4.45°	16.16
MAX hip (flexion)	33.94°	13.51	34.36°	12.69
Amplitude	29.04°	-	29.91°	-
Average of the 2 hips	29.47°	-	-	-

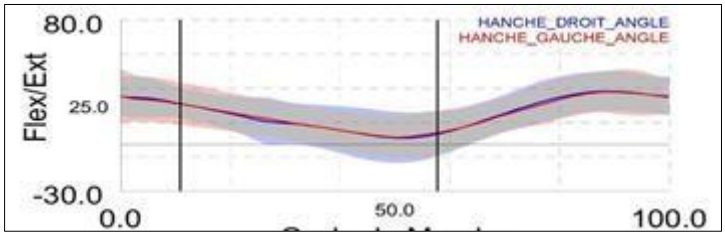

Figure 12: Hip flexion/extension degree graph

Knee:

- Mean extension: 18.70° (right), 24.41° (left)
- Mean flexion: 55.37° (right), 50.17° (left)
- Mean amplitude: 36.67° (right), 25.76° (left), with a combined average of 31.21°
- Full extension was not reached, and flexion range was reduced (Table IV, Figure 13)

Table IV: Degrees of knee flexion/extension

	LEFT	DS	RIGHT	DS
MIN knee (extension)	24.41°	12.83	18.70°	14.59
Knee MAX (flexion)	50.17°	16.77	55.37°	19.78
Amplitude	25.76°	-	36.67°	-
First peak of flexion	31.30°	9.22	30.01°	10.23
Second bending peak	50.17°	16.77	55.37°	19.78
Average of the 2 knees	31.21°	-	-	-

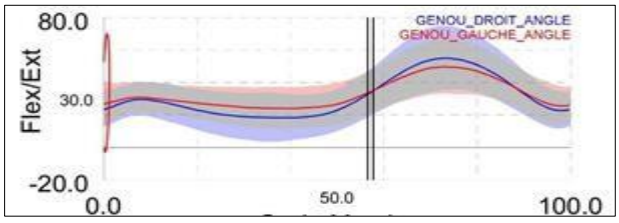

Figure 13: Graph of knee flexion/extension degrees

Ankle:

- Dorsiflexion/plantarflexion ranged from 0.49° to 17.21° (left) and 9.22° to 20.07° (right)
- Mean amplitude: 16.72° (left), 29.29° (right), with a mean of 23°
- High inter-individual variability rendered ankle data difficult to interpret (Table V, Figure 14)

Table V: Degrees of ankle flexion/extension

	LEFT	DS	RIGHT	DS
MIN ankle (Plantar flexion)	0.49°	52.64	9.22°	61.14
MAX Ankle (Back flexion)	17.21°	49.43	20.07°	59.02
Amplitude	16.72°	-	29.29°	-

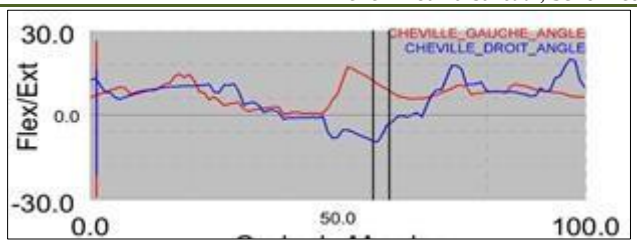

Figure 14: Graph of ankle flexion/extension degrees

The high variability of our patients makes the ankle joint kinematic data uninterpretable.

DISCUSSION

Cerebral palsy (CP) refers to a group of permanent disorders affecting movement and posture development, resulting in activity limitations due to non-progressive central neurological lesions occurring during fetal or early infant development [12]. CP is characterized by impaired selective motor control, abnormal co-activation of synergistic muscles [13], muscle weakness, spasticity, and secondary musculotendinous retractions (14).

Its prevalence is estimated at 2 to 3.5 per 1,000 live births [5]. In our study, a male predominance was observed, consistent with existing literature [15–18]. The mean age of participants (10.41 years) was higher than in other studies—such as Anna M. (5.8 years) [15], Kristina T. (5.4 years) [17], and Murat Celal S. (3.7 years) [18]. This may reflect delays in diagnosis and late referral to specialized care services.

Clinically, our patients were classified into hemiplegia (58.8%) and quadriplegia (41.2%). This aligns with Aviva Fattal V.'s study [19], where hemiplegia was most common (70.5%), while Hanene B [16], reported a predominance of quadriplegia, and Kristina T [17], and Murat Celal S [18], found diplegia to be the most prevalent.

Quantified Gait Analysis (QGA) combines synchronized acquisition of kinematic, kinetic, and EMG data during walking. Optoelectronic systems remain the gold standard for tracking 3D movement of anatomical markers [2]. This modeling enables calculation of joint motion in all three spatial planes.

In our cohort, walking speed was lower than values reported by A. Carriero (1.07 m/s) [21], and D. Patikas (1.11 m/s) [22], but closer to that of S. Armand (0.88 m/s) [20]. Cadence, however, was higher in our study (141.5 steps/min), which may reflect compensatory strategies such as shorter steps to maintain locomotion.

Table VI: Comparison of spatio-temporal parameters

	Our study	Study By A. Carriero (21)	Study By D. Patikas (22)	Study From S. Armand (20)
Speed(m/s)	0.71	1.07+/_0.31	1.11+/_0.15	0.88+/_0.05
Cadence (steps/min)	141.50	133.36 +/-17.70	124 +/_14	107.36 +/-3.45
Lengthof the step (m)	0.44	0.48 +/-0.12	1.08 +/-0.18	0.51 +/-0.02
Percentageof the phase support (%)	54.92%	BORN	60.3% +/-2.5	60.59% +/-2.04
Step time (s)	0.5	0.46 +/-0.06	0.97 +/-0.11	0.56 +/-0.03
Cycle time (s)	1.18	BORN	BORN	1.12+/_0.04

Joint Range of Motion (Sagittal Plane)

- **Pelvis:** Our mean amplitude (3.15°) was lower than A. Carriero's (6.27°) [21], indicating less pronounced anterior pelvic tilt.
- **Hip:** Our mean hip range (29.47°) was reduced compared to Patikas (42.5°) [22], Carriero (47.53°) [21], and Alfenso (36.66°) [23].
- **Knee:** The average knee ROM (31.21°) was also lower than in other studies—Carriero (51.69°), Alfenso (43.44°), and Patikas (37.5°).
- **Ankle:** Our average ankle ROM (18.37°) was difficult to interpret due to high inter-individual variability.
- These results reveal common findings in children with CP: reduced hip extension and persistent knee flexion, which impair gait fluidity. Such abnormalities are frequently associated with spasticity and musculotendinous shortening [6-14].

Table VII: Comparison of joint ranges on the sagittal plane

The joints	Our study	Study By A. Carriero (21)	Study From L. Alfenso (23)	Study By d. Patikas (22)
Basin	3.15°	6.27°	Born	Born
Hip	29.47°	47.53°	36.66°	42.5°
Knee	31.21°	51.69°	43.44°	37.5°
Ankle	18.37°	Born	40°	27.5°

Quantified Gait Analysis (QGA) has proven to be of great use in synthesizing and quantifying a patient's gait defects, thus enabling their identification. Through patho-biomechanical interpretation, treatments can therefore be selected more effectively [6-24].

Limitations of the Study

Several limitations should be highlighted:

- Reduced sample size(n=17), limiting statistical power;
- Retrospective study, without comparison before/after treatment;
- Clinical heterogeneity participants despite the selection criteria;
- Analysis limited to the sagittal plane, excluding frontal and transverse movements;
- Lack of EMG analysis, depriving the study of a fundamental neuromuscular component.

Despite these limitations, AQM has made it possible to finely objectify the motor disorders specific to each patient, to quantify joint deviations and to lay the foundations for individualized therapeutic reasoning. As highlighted in several studies [6-10], AQM effectively guides clinical decisions, whether it concerns multi-level surgery, botulinum toxin injection, choice of orthoses or rehabilitation protocols.

CONCLUSION

Quantified Gait Analysis (QGA) has proven to be a valuable tool for the functional assessment of children with cerebral palsy. By accurately quantifying spatiotemporal and kinematic parameters, it allows clinicians to objectify motor impairments, identify compensatory mechanisms, and support clinical decision-making.

Despite the small sample size, this study confirms the relevance of QGA as a key element in the personalized, multidisciplinary management of children with CP. It supports its routine use in pretherapeutic evaluations, especially in the context of orthopedic surgery, rehabilitation planning, and orthotic device prescription.

Further prospective studies on larger cohorts, incorporating three-dimensional analysis and electromyographic data, are needed to refine and strengthen clinical recommendations.

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