Walking Biomechanics in Para-Athletes with Cerebral Palsy: A Cross-Sectional Analysis of Spatiotemporal Parameters and Ground Reaction Forces in Indonesian Para-Athletes

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Abstract:

Introduction: Cerebral palsy (CP) is a neurological disorder that affects motor skills, postural control, and coordination of movements, which significantly affects walking performance. For Para-athletes with CP, this limitation reduces their quality of life and affects their performance and biomechanics, such as spatiotemporal and Ground Reaction Force (GRF). There have not been many studies that know how many para-athletes with CP are capable of when walking, so this research is essential to find out the biomechanics of para-athletes with CP at two parameters. **Objectives:** This study analyses spatiotemporal and GRF parameters while walking in para-athletes with CP. **Material & Methods:** This study is an observational study with a cross-sectional design, quantitative descriptive analysis, and non-probability sampling with a purposive approach. The outcomes consist of the spatiotemporal and GRF data recorded using the DIERS pedogait (DIERS International GmbH, Schlangenbad, Germany). Results: The results showed no difference between the CP right affected and CP left affected groups in spatiotemporal and GRF gait parameters (P> 0.05). **Conclusion:** This study showed no significant difference in all variables. Still, if we look at the mean and standard deviation, we can see a difference in spatiotemporal gait parameters and GRF between the para-athlete with CP. However, the findings suggest that para-athletes with CP hemiplegia walking on pedogait, which speeds 3.5 km/h for 6 s, regardless of the affected side, develop comparable compensatory mechanisms in their gait biomechanics. Further research should be done because many factors can change the gait habits of para-athletes.

Keywords: Para-athletes, Spatiotemporal, Ground Reaction Force, Cerebral Palsy, DIERS.

Introduction

Cerebral Palsy (CP) is a neurological disorder caused by brain damage during development, which affects motor skills, postural control, and coordination of movements (Benfer et al., 2018; Martín-de-la-hoz & Jiménez-antona, 2016; Mcintyre et al., 2022; Morgan et al., 2013)

This disorder has a significant impact on the ability to walk, which is an essential activity of mobility. For para-athletes with CP, this limitation not only reduces the quality of life but also affects the performance of para-athletes, both in competitions and daily activities (Khoirunnisa & Perdana, 2025; Kim et al., 2021; Olmos-g et al., 2021) Therefore, gait biomechanical analysis is essential to understand how CP affects gait patterns and identify strategies to improve the functional capacity and performance of para-athletes. There have not been many studies that know how much para-athletes with CP are capable of walking, especially in spatiotemporal parameters and Ground Reaction Force (GRF) (Chui & Lusardi, 2010; Frimenko et al., 2015; Haber et al., 2008; Hollman et al., 2011; Kawai et al., 2019; Laurentius et al., 2023) In biomechanical studies, the two most important parameters for evaluating gait are GRF and spatiotemporal parameters. These two parameters provide essential insights into the biomechanical mechanisms underlying para-athlete walking patterns with CP, including load distribution, stability, and movement efficiency (Aycardi et al., 2019; E & R, 2013; Kloeckner et al., 2023; Punitha & Sivashankari, 2025; Rahayu et al., 2019)

GRF is the Force generated by the surface in response to the Force exerted by the body when the foot comes into contact with the surface. GRF includes three main areas such as the sagittal plane (Vertical and Anterior-Posterior Forces), the Frontal Field (Medio-Lateral Forces), and the Transverse Field (Rotational Forces) (Houglum, 2016) It represents the strength of the body that supports the weight during the standing phase the anteroposterior component, which is related to forward thrust and inhibition during acceleration and deceleration of steps. Mediolateral components reflect lateral forces and body stability from side to side (Jiang et al., 2020; Martínez-pascual et al., 2023; Vega & Conejo, 2007) In para-athletes with CP, the distribution and pattern of GRF are often different from those of para-athletes without CP. Unbalanced load distribution, muscle spasms, and postural weakness result in inconsistent GRF patterns with high vertical component fluctuations, difficulty in adjusting forward thrusts, and possible lateral instability (Hasan et al., 2018; Kluitenberg et al., 2012; Mahran & Ghany, 2014; Theologis, 2013) This imbalance increases the risk of injury and limits the athlete's ability to move efficiently.

In addition to GRF, spatiotemporal parameters were also used to evaluate the walking patterns of para-athletes with CP. These parameters include the spatial and temporal aspects of the running cycle, such as Step length, which describes the distance between one step and the next. Walking speed is an indicator of overall biomechanical efficiency. Step duration, which indicates the time it takes to complete a step cycle. Step symmetry, which measures the similarity of the step pattern between the right and left foot. Cadence (step frequency), which describes the number of steps per minute. According to Iii et al. (2020) and Kettlety et al. (2023) individuals with hemiplegia often show shorter stride lengths, slower walking speeds, and longer stride durations and also the para-athletes with CP hemiplegia according to IFFCPF Team. (2015) showed step length is decreased on the affected side in relation to the unaffected side. There is a striking step asymmetrical, in which one leg exerts more effort than the other, which impacts energy efficiency and increases the risk of fatigue and injury. The lower cadence in para-athletes with CP also reflects limitations in motor control, which leads to less efficient walking. However, the IFFCPF Team's guideline statement lacks a strong evidence base on this topic and there is currently no research examining spatiotemporal and GRF in para-athletes with CP hemiplegia.

Therefore, analyzing spatiotemporal parameters and GRF in para-athletes with CP provides critical insights into their gait patterns and walking mechanics. An in-depth understanding of these biomechanical imbalances is essential for designing more effective training, rehabilitation, and preventive programs and training strategies to improve stability, efficiency, and performance in para-athletes. This study aims to analyze spatiotemporal parameters and gait GRF in para-athletes with CP to provide scientific data that supports the improvement of the quality of life and the ability of para-athletes to compete in sports.

Material & Methods

This study uses an observational approach with cross-sectional and quantitative descriptive analysis, as well as non-probability sampling with a purposive approach in Indonesian CP para-athletes. This method comprehensively examined spatiotemporal gait and GRF in cerebral palsy individuals in the Indonesian men's national team using the DIERS pedogait dynamic foot pressure measurement and gait analysis tool (DIERS International GmbH, Schlangenbad, Germany). To minimize the risk of bias in measurement, this study employed assessors who were trained and certified by DIERS Germany. Ethical approval was given by the Research Ethics Committee of the University of Muhammadiyah Surakarta with number 575/KEPK-FIK/X/2024. Participants were given informed consent and signed to participate in the study before collecting data.

Participants

A total of 9 male para-athletes with Cerebral Palsy Hemiplegia (4 with right-side hemiplegia, 5 with left-side hemiplegia) from the National Paralympic Committee Indonesia participated in the study. They were aged between 20 – 30 years and met the inclusion criteria: spasticity grade 2-3 on one side of the body (in the frontal plane), walking or running with limp/visible due to lower limb spasms, good functional ability on the opposite side of the body. Exclusion criteria included current injuries to the lower extremities as well as CP with athetosis and ataxia.

Protocol test

The measurement process involved subjects walking on the DIERS Pedogait at a speed of 3.5 km/h for 1 minute to adjust the steps, followed by a 6-second measurement period. Gait performance was assessed using the DIERS pedogait (DIERS International GmbH, Schlangenbad, Germany) which has been validated in several studies (Degenhardt et al., 2020; Liu et al., 2020; Schumann et al., 2021; Tabard-Fougère et al., 2017). This treadmill-based tool features an integrated measurement platform that is 1.0 m long with 5,376 sensors to precisely capture pressure values. The system operates at a reception frequency at 100 Hz, providing an accuracy frequency of 10 ms (Balci et al., 2024). The study measured spatiotemporal parameters including step length (left and right), step time (left and right), stride length, stride time, track width, cadence. Additionally, ground reaction force including total force, mean force, max force, and mean COP-X and COP-Y were also assessed.

Statistical analysis

Statistical analyses were performed using SPSS software to examine differences between experimental trials. All variables were tested for normal distribution using the one-sample Kolmogorov-Smirnov test. Statistical comparisons included paired samples t-tests to evaluate changes within groups and independent samples t-tests to assess differences between groups. Descriptive statistics are reported as means with standard deviations, and statistical significance was established at $p < 0.05$.

Results

This study involves several key processes. First, subjects were selected from para-athletes with cerebral palsy based on specific inclusion and exclusion criteria, resulting in 9 individuals who met the requirements. After selection, the subjects were educated about the procedures and their significance in this study, and informed consent was obtained from all subjects.

Table 1. Characteristics of baseline participants.

Variables	Mean ± SD		p-value
	CP Left Affected	CP Right Affected	
Sex	5 males	4 males	
Age	27 ± 2.1	22.3 ± 1	0.005
Weight	63.4 ± 11.8	54 ± 3.9	0.174
Height	168.4 ± 10.6	163.3 ± 9.7	0.477
Body Mass Index (BMI)	20.92 ± 2.1	22.18 ± 1.3	0.140

Abbreviation: Mean ± SD: mean ± standard deviation.

The baseline characteristics of participants reveal that the CP left affected group is significantly older than the CP right affected group (mean age 27 ± 2.1 vs. 22.3 ± 1.0 years, p = 0.005). No statistically significant differences were observed between the groups in weight (63.4 ± 11.8 vs. 54 ± 3.9 kg, p = 0.174), height (168.4 ± 10.6 vs. 163.3 ± 9.7 cm, p = 0.477), or BMI (20.92 ± 2.1 vs. 22.18 ± 1.3, p = 0.140). These findings suggest that the two groups are generally comparable in physical characteristics except for age.

Table 2. Statistical results in the group of variable parameters of spatiotemporal gait

Variables	Mean ± SD	p-value

	left	Right	
CP Left Affected			
Step length (cm)	37.8 ± 12.4	33 ± 8.7	0.12
Step time (ms)	472.6 ± 200.7	365.6 ± 167.3	0.416
CP Right Affected			
Step length (cm)	43 ± 10.2	38 ± 4.1	0.287
Step time (ms)	424.3 ± 48.4	378.2 ± 44.5	0.318

Abbreviation: Mean ± SD: mean ± standard deviation.

Table 2 displays the comparative analysis of spatiotemporal gait parameters between left and right sides in para-athletes with cerebral palsy (CP). In participants with left-affected CP, statistical analysis revealed no significantly longer step length on the affected side (37.8 cm) compared to the unaffected side (33 cm, p=0.12). While step time showed no statistical significance between sides (p=0.416), the left side demonstrated a longer duration (472.6 ms) compared to the right side (365.6 ms). For participants with right-affected CP, although no statistically significant differences were found in either step length (p=0.287) or step time (p=0.318), there was a tendency toward longer measurements on the left side, with step length measuring 43 cm versus 38 cm, and step time measuring 424.3 ms versus 378.2 ms.

Table 3. Statistical results between groups of variable parameters of spatiotemporal gait

Variable	Mean ± SD		p-value
	CP left affected	CP right affected	
Step length left (cm)	37.8 ± 12.4	43 ± 10.2	0.523

Step length right(cm)	33 ± 8.7	38 ± 4.1	0.327
Step time left (ms)	472.6 ± 200.7	424.3 ± 48.4	0.656
Step time right(ms)	365.6 ± 167.3	378.2 ± 44.5	0.889
Stride length (cm)	70.6 ± 20.7	81 ± 13.9	0.421
Stride time (ms)	838.4 ± 258.6	802.3 ± 52.1	0.794
Track Width (cm)	8.4 ± 4.9	10 ± 2.2	0.565
Cadence (step/min)	194 ± 73.1	172.5 ± 15.7	0.583

Abbreviation: Mean ± SD: mean ± standard deviation.

Analysis of spatiotemporal gait parameters between para-athletes with right-affected and left-affected CP (Table 3) revealed no statistically significant differences across all measured variables (p>0.05). The left-affected group demonstrated shorter step length (37.8 cm vs 43 cm, p=0.523) and stride length (70.6 cm vs 81 cm, p=0.421) compared to the right-affected group. Step time was longer in the left-affected group (472.6 ms vs 424.3 ms, p=0.656), while track width was narrower (8.4 cm vs 10 cm, p=0.565). Although cadence was higher in the left-affected group (194 steps/min vs 172.5 steps/min, p=0.583), the substantial within-group variability, as indicated by standard deviations, and non-significant p-values suggest that both groups exhibited similar gait characteristics overall.

Table 4. Statistical results in the group of variable parameters of ground reaction force on gait.

Variables	Mean ± SD		p-value
	left	Right	
CP Left Affected			

Total force (N)	126092.4 ± 11916.5	120316 ± 13921.5	0.201
Mean force (N)	429.6 ± 45.5	411.6 ± 69.3	0.256
Max force (N)	898 ± 94	892.6 ± 123.3	0.797
CP Right Affected			
Total force (N)	100164 ± 27974.4	100642 ± 26876.8	0.857
Mean force (N)	412.3 ± 24	416.5 ± 39.2	0.716
Max force (N)	907 ± 135.7	962 ± 81.7	0.372

Abbreviation: Mean ± SD: mean ± standard deviation.

Table 4 displays the comparative analysis of GRF parameters between left and right sides in para-athletes with cerebral palsy (CP). In participants with left-affected CP, statistical analysis revealed no significantly higher total force, mean force, and max force on the affected side (126092.4 N, 429 N, and 899 N) compared to the unaffected side (120316 N p=0.201, 411.6 N p=0.256 and 892.6 N p=0.797). For participants with right-affected CP, show statistical analysis revealed no significantly higher total force, mean force, and max force on the affected side (100642 N, 416.5 N, and 962 N) compared to the unaffected side (100164 N p=0.857, 412.3 N p=0.716, and 907 N p=0.372).

Table 5. Statistical results between groups of variable parameters ground reaction force on gait.

Variable	Mean (SD)		p-value
	CP left Affected	CP Right Affected	
Total force left (N)	126092.4 ± 11916.5	100164 ± 27974.4	0.1
Total force right (N)	120316 ± 13821.5	100642 ± 26876.8	0.195

Mean force left (N)	429.6 ± 45.5	412.25 ± 24.1	0.516
Mean force right (N)	411.6 ± 69.3	416.5 ± 39.2	0.904
Max force left (N)	898 ± 94	907 ± 135.7	0.909
Max force right (N)	892.6 ± 123.3	962 ± 81.7	0.368
mean COP-X	19.8 ± 3.1	19 ± 1	0.619
mean COP-Y	-37.2 ± 19.1	-16 ± 21.5	0.162

Abbreviation: Mean ± SD: mean ± standard deviation.

Table 5 shows the results of the comparison between group variables with the independent sample T-test. The statistical comparison of ground reaction force variables between CP left affected and CP right affected groups reveals no significant differences across all parameters (p > 0.05). The total force on the left side showed a higher meaning in the groups (126092.4 vs 100164 N), but the difference was not statistically significant (p = 0.1). Similarly, the total force on the right side was higher for the groups (120316 vs 100642 N), with a p-value of 0.195. Mean and maximum forces on both left and right sides, as well as the center of pressure (COP) X and Y values, also showed no significant differences between groups, with all p-values exceeding 0.162.

Discussion

The results showed no statistically significant difference within or between groups on spatiotemporal gait or GRF (P>0.05). However, there were observed in the mean and SD of the spatiotemporal parameter both within and between groups. When compared to healthy individuals from previous studies (Laurentius et al., 2023; Susilo et al., 2022), notable differences were seen in stride length. Healthy individuals had an average stride length of 132.6 cm, while para-athletes with right-sided CP hemiplegia averaged 81 cm, and those with left-sided CP hemiplegia averaged 70.6 cm.

Analysis of spatiotemporal parameters revealed distinct patterns between groups. Para-athletes in the right affected group showed reduced step length (38 cm vs 43 cm, p=0.287) and step time (378.2 ms vs 424.3 ms, p=0.318) on their affected side compared to their unaffected side, though these differences were not statistically significant. Conversely, those in the left affected group demonstrated a difference in step length (37.8 cm vs 33 cm, p=0.12), with the unaffected side showing shorter steps, although this difference was not statically different. While their step time was notably longer on the affected side (472.6 ms vs 365.6 ms), though this difference did not reach statistical significance (p=0.416). The findings for the left affected group contradict the IFFCPF Team' statement that individuals with hemiplegic typically shows reduced step length on the affected side compared to the unaffected side (IFFCPF Team, 2015). This study did not support the IFFCPF Team' statement. However, the observed difference requires further investigation in future research to determine whether the unexpected result are due to the walking habits of para-athletes, the effect of specialized training for para-athletes, or the 3.5 km/h walking speed used in the study protocol.

Analysis of the GRF parameters revealed no statistically significant differences between the CP left affected and the CP right affected in terms of force and pressure distribution on the legs. Regarding total force, the CP left affected group produced a higher total force in both legs compared to the CP right affected group, though this difference was not statistically significant ($p > 0.05$). For mean force, no significant difference was observed in the average force between the two groups for either on the left or right foot, suggesting similar force production, despite affecting different sides of the body. In terms of max force, the CP right affected group showed a slight increase in maximum force in the right leg compared to CP left affected group, but this difference is also not significant. In summary, there were no statically significant differences in force generation capabilities between the two groups across all measured GFR parameters.

The Center of Pressure (COP) indicates the pressure distribution under the foot. COP-X reflects the lateral shift (right or left), while COP-Y reflects anteroposterior shift (forward or backwards). Analysis revealed no significant difference in the mean COP-X value between the two groups, indicating similar lateral pressure distribution. However, for the COP-Y, there was a notable difference in mean and SD between the two groups (-37.2 vs -16). suggesting a variation in anteroposterior pressure distribution. Despite this observed difference, it did not reach a statistical difference. The standard deviation (SD) in COP-Y values also differed between the groups, further indicating variability in anteroposterior pressure distribution patterns.

These findings could be influenced by the duration and nature of individual training program, which may lead to changes in gait habits. Long-term exercise programs play a crucial role in developing motor behaviour through a complex process involving various interacting factors. Training and experience are essential for motor behaviour development, as they can form new habits in coordination, endurance, strength, and balance (Buurke, 2021; Choi & Bastian, 2007; Gomeñuka et al., 2014; Mcintyre et al., 2022; Morgan et al., 2013; Vashista et al., 2012; Yokoyama et al., 2018)

Recent studies have shown that ground-level gait training using ankle exoskeleton technology can be effective for individuals with CP. This approach has led to improvement in spatiotemporal outcomes and increased activation of the ankle plantar-flexor muscle during walking with the exoskeleton Additionally, there was an increase in the step repetition from the ankle plantar-flexor muscles and knee extensors during walking, both with or without the device. These results suggest that individuals with CP can quickly benefit from structured ground-level gait training with powered assistance ((Adolph & Franchak, 2018)Fang et al., 2023). Such finding indicates potential for improving performance and skills of para-athletes with CP through targeted gait training intervention.

Overall, these data suggest that despite some differences in certain variables, there were no significant or consistent differences within and between the two groups. This indicates that individuals with CP affecting either the left or right side may have similar biomechanical compensation mechanisms. Impairments on one side of the body do not significantly impact the ability to generate force or control pressure distribution during standing or walking. From a physiotherapy and rehabilitation perspective, these results suggest that rehabilitation approaches for patients with CP may not be highly differentiated based on which side of the body is affected.

The strength of this study was that it was measured with modern tools without the effect of radiation so that the data produced was accurate and safe for respondents. However, this study poses several limitations, there was no comparison in the measurement at one time to know the difference in spatiotemporal gait and GRF with healthy people or people with hemiplegia so that the magnitude of the difference between healthy individuals and people with hemiplegia would be measured and this study participant too small did not enough to reach statistical significance. Therefore, more conscientious research was recommended for future researchers, such as measuring the parameters of the walking cycle, changes in posture, and measurement of lower extremity kinematics in CP subjects and healthy individuals.

Conclusion

This investigation revealed that among spatiotemporal and ground reaction force parameters, Despite the absence of statistical significance in other parameters, notable differences in mean values and standard deviations were observed between groups for both spatiotemporal parameters and ground reaction forces. The findings suggest that para-athletes with CP hemiplegia walking on pedogait, which speeds 3.5 km/h for 6 s, regardless of the affected side, develop comparable compensatory mechanisms in their gait biomechanics. While rehabilitation approaches may not need to be substantially different based on the affected side, the results indicate that structured exercise programs could potentially enhance spatiotemporal parameters and ground reaction forces in para-athletes with CP, ultimately improving their gait performance.

Conflicts of interest

There is no conflict of interest to be stated.

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