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Gait Parameters of Elite Kickboxing Athletes

Marta Niewczas [1], Łukasz Rydzik [2,*], Tadeusz Ambroży [2], Wojciech Wąsacz [2], Michał Spieszny [2], Jacek Perliński [3] and Norollah Javdaneh [4]

1 Institute of Physical Culture Studies, College of Medical Sciences, University of Rzeszów, 35-958 Rzeszów, Poland; martaniewczas@wp.pl
2 Institute of Sports Sciences, University of Physical Education, 31-571 Kraków, Poland; tadek@ambrozy.pl (T.A.); wojciech.wasacz@doctoral.awf.krakow.pl (W.W.); michal.spieszny@awf.krakow.pl (M.S.)
3 Faculty of Medical Sciences, Academy of Applied Medical and Social Sciences in Elblag, 82-300 Elbląg, Poland
4 Department of Biomechanics and Sports Injuries, Kharazmi University of Tehran, Tehran 14911-15719, Iran
* Correspondence: lukasz.rydzik@awf.krakow.pl

Abstract: Background: Correct movement techniques are crucial for enhancing athletic performance and minimizing the risk of injury. This is particularly true for kickboxing, in which a variety of forms of locomotion are employed. Despite its importance, gait and movement analysis in this sport is under-researched. The primary objective of this study is to understand gait patterns and limb symmetry between the dominant and non-dominant legs among professional kickboxers and to explore their correlation with the level of technical and tactical preparation. Methods: A cross-sectional observational study was conducted involving 20 elite kickboxers. Data collection employed the 3D Force Treadmill for gait parameters, as well as simulated sparring sessions to evaluate technical–tactical indices. Various gait parameters were analyzed, including the center of pressure (COP), gait phase, spatial and time parameters, as well as reaction force. Results: No significant bilateral differences were found in the majority of gait variables. Exceptions were in the medio-lateral component of the COP and force, where more deviation was observed in the non-dominant foot. The only noted significant correlation was between lateral symmetry and attack activity. Conclusions: This study allows us to indicate that kickboxers' training promotes symmetrical gait patterns. Targeted training interventions could further optimize these patterns. The significant relationship between lateral symmetry and attack activity suggests areas for future research and potential performance improvement. The results of this study contribute to athletes' self-monitoring and coaching strategies.

Keywords: center of pressure parameters; technical–tactical performance; kickboxing; technical and tactical training

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1. Introduction

The pursuit of excellence in competitive sports involves both the eradication of weaknesses and the continuous enhancement of strengths [1]. A cornerstone for achieving this high level of performance is optimal biomechanics, an interdisciplinary field that applies the principles of physics to study the mechanical aspects of biological systems, specifically how organisms move and interact with their environment [2,3]. Despite achieving mastery in their disciplines, even elite athletes have opportunities for incremental improvement in performance [4].

Biomechanics provides critical insights into both human structure and movement [5]. While physique and physiological capability are important, it is technique that often dictates success in competitive sports [5,6]. The movement technique itself can be crucial in the context of minimizing injuries and improving performance [7,8]. Understanding the laws of mechanics can greatly assist in optimizing the quality of an athlete's movement, thereby serving as a significant diagnostic tool for assessing the fitness level of an athlete's locomotor system [9,10].

Traditional gait analysis has been extensively used for observing and monitoring movement quality among athletes across a range of sports, from golf to tennis to athletics [11–14]. This type of analysis is focused on both the kinematic and dynamic properties of movements [10,15]. Although useful, gait analysis is generally associated with walking and running. Within the context of combat sports such as kickboxing, more comprehensive movement or motion analysis may offer additional insights [16,17].

Kickboxing is a physically demanding combat sport that requires both intricate technical skills and tactical mastery for success [18,19]. In kickboxing, performed within a ring, athletes employ their upper and lower limbs to deliver blows, often at full force and in a standing position [19,20]. Additionally, athletes are at risk of various kinds of injuries, both during training and fights. Understanding their gait technique can help identify potential weaknesses or imbalances that may increase the risk of injuries [21].

Given the sport's demands and specificities, mastering the fundamental forms of movement, i.e., stance and gait, are emphasized during early training [22].

For other combat sports with biomechanical demands similar to kickboxing, e.g., karate and Brazilian jiu-jitsu, factors such as sole thrust have been indicated to significantly and equally affect speed and stability [23,24]. This raises important questions for kickboxing, which is highly specialized and intense; not all adaptational changes may be advantageous, and some may even introduce risks of functional abnormalities as well as injuries [25,26].

Thus, there is a compelling need for comprehensive research to explore gait patterns and limb symmetry among elite kickboxers [27,28]. This research aims to fill that gap by investigating these biomechanical aspects in depth. The primary objective is to understand gait parameters and their symmetry between the dominant and non-dominant legs in professional kickboxers. Additionally, we aim to explore the correlation between these gait parameters as well as technical and tactical training indicators, such as attack efficiency, attack activity and the effectiveness of attack, in kickboxing [29–31]. This information will allow us to determine whether gait parameters directly affect an athlete's special skills.

All participants included in the study have had many years of sports experience. In our research, we adopted the hypothesis that, due to environmental factors in the form of long-term training and competition practice, as well as the asymmetrical stance of combat in kickboxing and the associated broad spectrum of movement, one should expect the occurrence of asymmetry in selected gait parameters.

2. Materials and Methods

2.1. Participants

A total of 20 male kickboxers were recruited for this study. All the subjects were characterized by an elite level, meaning they actively participated in master-class competitions—international, national and local—achieving significant sports results. Their ages ranged from 18 to 32 years, and they were across multiple weight classes: −71, −75, −81, −86, −91 and +91 kg. The mean demographic statistics for the participants are presented in Table 1.

Table 1. Anthropometric characteristic of the participants.

Variables	Number	Mean	Minimum	Maximum	1st Quartile	3rd Quartile	Std. Dev.
Age (year)	20	23.30	18.00	32.00	21.00	25.00	3.55
Weight (kg)	20	80.40	61.50	95.40	71.60	90.40	9.68
Height (cm)	20	179.99	170.10	188.40	177.00	182.60	4.41
Body Mass Index (kg/m^2)	20	25.26	20.50	33.00	22.90	27.53	3.56

The inclusion criterion for the study was that participants had to have at least 6 years of training experience, 4 years of which should be active competition experience. They should also have been free from any injury for at least 6 months prior to data collection. All participants provided informed consent in accordance with the 1964 Declaration of Helsinki. The study was approved by the ethics committee at the Regional Medical Board in Kraków (Approval No. 287/KBL/OIL/2020).

2.2. Sample Size Calculation

With a test power of 80% and a confidence level of 95%, the sample size was estimated to be 15 and was increased to 20 participants for this study.

2.3. Measurement Protocols

1. Warm-up and Adaptation

Before any measurements were taken, participants engaged in a 10–15 min warm-up program. They were then familiarized with walking on a treadmill to adapt to the procedure.

2. Gait Parameter Measurements

Participants were asked to walk on an instrumented treadmill (Gaitway 3D, Noraxon, Scottsdale, AZ, USA). This treadmill is integrated with MR3 software for detailed 3D gait analysis. Walking was performed at a predefined speed of 1.5 ± 0.01 m/s. "In this study, multiple gait parameters were captured using the treadmill's sensors at a 100 Hz sampling rate, including Length of Gait Line (mm), Single Support Line (mm), anterior/posterior Position (mm), Lateral Symmetry (mm), COPY (mm), COPx (mm), Stance Phase (%), Load Response (%), Single Support (%), Pre-swing (%), Swing Phase (%), Foot Rotation (degrees) for both left and right feet, Step Length (cm), Stride Length (cm), Step Width (cm), Velocity (km/h), Step Time (ms) for both left and right feet, Stride Time (ms), and Cadence (steps/min)".

3. Body Posture During Data Collection

Participants stood with each foot on the starting surface, with their body weight evenly distributed between both feet and their arms hanging by their sides. There were 3 practice trials before data collection.

4. Gait Velocity Measurement

A 20 m distance was set for measuring habitual gait velocity in a well-lit hallway. Gait velocity was controlled using a timer.

5. Analyzed Parameters

Parameters such as length of gait line, single support line, anterior/posterior position and lateral symmetry were included. Gait asymmetry parameters, i.e., step length, stride length, step width and foot angle, were also measured.

2.4. Simulated Sparring

Each athlete performed the same, standard set of exercises to prepare the body for exercise (warm-up). The warm-up comprised 5 min of jogging and 10 min of general warm-up exercises (conditioning) and stretching (flexibility). Then, immediately after this part, they participated in simulated sparring according to the K1 rules adopted by the World Association of Kickboxing Organizations (WAKO). Ten duels were conducted. Each subject had one 3-round sparring session lasting 2 min each, with a 1 min break between rounds. The fighters were arranged according to their weight categories. The fights took place in a ring, which was located in a neutral environment. The duels were supervised by a qualified, licensed referee of the Polish Kickboxing Association (PZKB). A GOPRO HERO10 camera on a specialized tripod was placed at a vantage point providing a full view of the ring, recording footage for a planned, retrospective analysis of the fight.

2.5. Measuring Indicators of Technical and Tactical Training

A technical–tactical analysis of the simulated sparring matches was carried out by 3 master-class PZKB coaches and 1 licensed PZKB referee. On special measuring sheets, the researchers recorded all offensive techniques, with a division into the effective (scored) and ineffective (missed, hit on block, guard) categories. The observational data were averaged and entered into an Excel (Microsoft) spreadsheet, where technical–tactical training indicators (attack activity, attack effectiveness, attack efficiency) were calculated using the following specialized formulas [32]:

Efficiency of attack (S_a)

$$\mathrm{Sa} = \frac{n}{N} \tag{1}$$

n—numbers of attacks awarded 1 pt.;
In K1 formula each fair hit is awarded 1 pt.;
N—number of bouts.
Effectiveness of attack (E_a)

$$\mathrm{Ea} = \frac{\text{number of efective attacks}}{\text{number of all attacks}} \times 100 \tag{2}$$

An effective attack is a technical action awarded a point.
Number of all attacks is the number of all offensive actions.
Activeness of attack (A_a)

$$\mathrm{Aa} = \frac{\text{number of all registered of fensive actions of a kickboxer}}{\text{number of bouts fought by a kickboxer}} \tag{3}$$

2.6. Statistical Analysis

The Statistical Package for Social Sciences (SPSS), version 19.0, was used for all statistical analyses. Data normality was assessed using the Shapiro–Wilk test. Descriptive statistics—including mean, median, minimum, maximum, and 95% confidence intervals, as well as the 1st and 3rd quartiles and standard deviation—were calculated for all variables. A paired *t*-test was used to examine the differences between the left and right sides. Pearson's correlation coefficient was employed to explore the relationships between variables. Specifically, correlations were assessed between indicators of technical and tactical preparation (i.e., activity, efficiency, effectiveness) and selected gait parameters: stance phase, load response, single support, pre-swing, swing phase and double stance. The level of statistical significance was set at $p < 0.05$.

3. Results

The results of the COP parameters (length of gait line, single support line, anterior/posterior position, lateral symmetry, and anterior–posterior and medio-lateral COP component) for the participants are shown in Table 2. No significant difference was observed in the length of gait line, the anterior–posterior component of the COP (center of pressure) and the single support line variables between the left (non-dominant limb) and right sides (dominant limb). For the medio-lateral component of the COP, there was a significant difference between the left and right feet, such that the deviation was greater in the case of the left foot.

Table 2. COP parameters of the participants.

Variables		N	Mean	Min	Max	SD	Diff. between R and L		
							Mean	***p***	**ES**
Length of gait line (mm)	L	20	215.62	103.48	249.70	47.76	4.47	0.82	0.094
	R	20	211.15	100.69	253.44	46.96			
Single support line (mm)	L	20	110.84	39.08	144.46	30.73	1.39	0.91	0.047
	R	20	109.44	41.25	138.28	28.65			
Anterior/posterior position (mm)		20	160.70	134.06	212.07	30.15		-	
Lateral symmetry (mm)		20	−0.32	−7.88	7.01	4.41		-	
COP_Y (mm) ¥	L	20	359.53	221.61	549.16	113.96	12.53	0.80	0.083
	R	20	349.99	214.06	547.53	115.35			
COPx (mm) ¥	L	20	163.64	121.36	191.88	23.29	15.86	0.00 *	5.81
	R	20	12.74	0	96.29	28.35			

L: left (non-dominant); R: right (dominant); SD: standard deviation; * statistically significant difference ($p < 0.05$); ¥ values are expressed as total maximum COP; COP_Y: anterior–posterior component of COP; COPx: medio-lateral component of COP; ES: effect size.

The results of the gait phase parameters (load response, single support, pre-swing, swing phase and double stance) for the participants are shown in Table 3. No significant differences were observed in the load response, single support, pre-swing or swing phase variables between the dominant and non-dominant limbs.

Table 3. Gait phase parameters of the participants.

Variables		Number	Mean	Minimum	Maximum	SD	Diff. between R and L		
							Mean	***p***	**ES**
Stance phase, %	L	20	61.46	58.45	62.90	1.16	0.51	0.35	0.39
	R	20	60.95	58.07	62.91	1.39			
Load response, %	L	20	11.13	8.34	12.55	1.31	0.16	0.76	−0.13
	R	20	11.30	8.15	13.25	1.26			
Single support, %	L	20	38.95	37.09	41.92	1.47	0.43	0.45	0.32
	R	20	38.52	37.11	41.58	1.17			
Pre-swing, %	R	20	11.38	8.19	13.25	1.31	0.24	0.66	0.19
	L	20	11.13	8.35	12.55	1.30			
Swing phase, %	L	20	38.53	37.10	41.55	1.16	0.51	0.35	−0.39
	R	20	39.04	37.09	41.93	1.39			
Double stance, %		20	22.47	16.52	25.80	2.50		-	

L: left (non-dominant); R: right (dominant); SD: standard deviation; CI: confidence interval; ES: effect size.

The results of the gait spatial parameters (velocity, step width, stride length, step length and foot rotation) for the participants are shown in Table 4. No significant differences were observed in the foot rotation and step length variables between the dominant and non-dominant limbs.

Table 4. Gait spatial parameters of the participants.

Variables		N	Mean	Minimum	Maximum	SD	Diff. between R and L		
							Mean	*p*	ES
Foot rotation (deg.)	L	20	6.65	1.59	10.03	2.53	0.73	0.55	−0.25
	R	20	7.39	3.28	13.25	3.18			
Step length (cm)	L	20	71.48	68.31	74.90	2.02	0.57	0.55	0.25
	R	20	70.90	66.35	75.40	2.51			
Stride length (cm)		20	142.33	136.39	150.30	4.32		-	
Step width (cm)		20	13.72	7.81	18.16	3.95		-	
Velocity (km/h)		20	5.47	5.45	5.49	0.01		-	

L: left (non-dominant); R: right (dominant); SD: standard deviation; cm: centimeter; deg.: degrees; CI: confidence interval; ES: effect size.

The results of the gait time parameters (step time, stride time and cadence) for the participants are shown in Table 5. No significant difference was observed in the case of the step time variable between the dominant and non-dominant limbs.

Table 5. Gait time parameters of the participants.

Variables		Number	Mean	Min	Max	SD	Diff, between R and L		
							Mean	*p*	ES
Step time (ms)	L	20	467.20	448.26	491.61	155.81	1.92	0.75	−0.013
	R	20	469.12	449.40	493.55	134.11			
Stride time (ms)		20	936.32	898.02	985.16	279.24		-	
Cadence (step/min)		20	128.41	121.83	134.20	3.93		-	

L: left (non-dominant); R: right (dominant); SD: standard deviation; ms: millisecond; CI: confidence interval; ES: effect size.

The results of the reaction force parameters (medio-lateral component of force, anterior–posterior component of force and vertical component of force) for the participants are shown in Table 6. No significant differences were observed in the vertical or anterior–posterior components of force variables between the left (non-dominant limb) and right sides (dominant limb). In the variable regarding the medio-lateral component of force, there was a significant difference between the left and right feet, such that this value was greater in the case of the left foot $p < 0.05$.

Table 6. Reaction force parameters of the participants.

Variables		Number	Mean	Min	Max	SD	Diff. between R and L		
							Mean	*p*	ES
F_Z (N) ¥	L	20	1181.12	911.69	1615.5	223.34	9.84	0.92	−0.041
	R	20	1191	896	1649	253.1			
F_Y(N) ¥	L	20	261.10	207.16	338.65	394.10	8.72	0.60	−0.031
	R	20	269.83	207.33	315.49	38.26			
F_X (N) ¥	L	20	207.13	126.21	258.83	47.77	69.98	0.002 *	2.06
	R	20	137.15	88.04	242.51	4.20			

L: left (non-dominant); R: right (dominant); SD: standard deviation; ¥ values are expressed as total maximum force; F_Z: vertical component of force; F_Y: anterior–posterior component of force; F_X: medio-lateral component of force; CI: confidence interval; ES: effect size; *-statistical significance

In Tables 7–10, the correlation values between the gait parameters and the technical–tactical training indicators, namely the activeness, effectiveness and efficiency of attack variables, are reported. In Table 7, the correlation indicators between the COP parameters and the technical–tactical efficiency are presented. For the lateral symmetry and attack activity variables, a significant, positive relationship with a high degree of correlation was found. In relation to the other variables, no relationships with signs of statistical significance were observed, and the strength of the correlations was at the level of weak and average.

Table 7. Relationship between COP parameters and attack activeness, effectiveness and efficiency.

Variables		Length of Gait Line (mm)		Single Support Line (mm)		Anterior/Posterior Position (mm)	Lateral Symmetry (mm)	COP_Y (mm)		COPx (mm)	
		L	R	L	R			L	R	L	R
Attack efficiency	r	0.35	0.43	0.29	0.32	−0.35	−0.11	−0.42	−0.48	−0.30	−0.21
	p	0.32	0.21	0.41	0.36	0.31	0.76	0.22	0.15	0.36	0.54
Attack activity	r	0.33	0.27	0.15	−0.07	−0.30	0.64 *	−0.06	−0.02	−0.48	−0.06
	p	0.35	0.43	0.67	0.84	0.38	0.046 *	0.85	0.93	0.16	0.86
Attack effectiveness	r	0.44	0.47	0.29	0.15	−0.43	0.38	−0.34	−0.35	−0.51	−0.19
	p	0.19	0.16	0.41	0.66	0.21	0.26	0.32	0.31	0.13	0.59

* Statistical significance. L: left (non-dominant); R: right (dominant); r: Pearson's linear correlation coefficient; COP_Y: anterior–posterior component of COP; COPx: medio-lateral component of COP.

Table 8. Relationship between gait spatial parameters and attack activeness, effectiveness and efficiency.

Variables		Foot Rotation (deg.)		Step Length (cm)		Stride Length (cm)	Step Width (cm)	Velocity (km/h)	Step Time (ms)		Stride Time (ms)	Cadence (step/min)
		L	R	L	R				L	R		
Attack efficiency	r	−0.22	−0.21	0.15	0.04	0.10	0.04	−0.13	0.055	0.19	0.12	−0.13
	p	0.53	0.54	0.66	0.90	0.77	0.90	0.71	0.88	0.59	0.73	0.71
Attack activity	r	0.34	0.22	0.30	0.34	0.34	−0.39	0.18	0.39	0.23	0.33	−0.36
	p	0.32	0.53	0.38	0.33	0.32	0.25	0.61	0.25	0.50	0.34	0.30
Attack effectiveness	r	0.12	0.03	0.26	0.22	0.26	−0.23	0.003	0.26	0.24	0.26	−0.29
	p	0.74	0.93	0.45	0.54	0.46	0.51	0.99	0.45	0.50	0.46	0.41

L: left (non-dominant); R: right (dominant); r: Pearson's linear correlation coefficient.

Table 9. Relationship between ground reaction force and attack activeness, effectiveness and efficiency.

Variables		F_Z (N)		F_Y(N)		F_X (N)	
		L	R	L	R	L	R
Attack efficiency	r	−0.42	−0.37	0.10	−0.37	0.23	0.09
	p	0.21	0.29	0.76	0.29	0.51	0.79
Attack activity	r	−0.15	−0.20	0.03	0.24	−0.17	0.24
	p	0.67	0.57	0.93	0.49	0.62	0.50
Attack effectiveness	r	−0.34	−0.35	−0.02	−0.06	0.06	0.21
	p	0.33	0.31	0.94	0.86	0.85	0.54

L: left (non-dominant); R: right (dominant); r: Pearson's linear correlation coefficient; F_Z: vertical component of force; F_Y: anterior–posterior component of force; F_X: medio-lateral component of force.

Table 10. Relationship between gait phase parameters and attack activeness, effectiveness and efficiency.

Variables		Stance Phase		Load Response		Single Support		Pre-Swing		Swing Phase		Double Stance
		L	R	L	R	L	R	L	R	L	R	
Attack efficiency	r	0.006	0.03	0.06	0.04	0.01	0.01	0.08	0.06	0.07	0.03	0.00
	p	0.98	0.92	0.86	0.90	0.97	0.97	0.82	0.86	0.98	0.92	0.99
Attack activity	r	0.52	0.47	0.37	0.61	−0.43	−0.51	0.58	0.37	−0.52	−0.47	0.50
	p	0.12	0.16	0.28	0.06	0.20	0.12	0.08	0.28	0.12	0.16	0.14
Attack effectiveness	r	0.35	0.35	0.30	0.39	−0.29	−0.34	0.34	0.31	−0.35	−0.35	0.35
	p	0.31	0.31	0.38	0.25	0.40	0.32	0.32	0.38	0.31	0.31	0.32

L: left (non-dominant); R: right (dominant); r: Pearson's linear correlation coefficient.

In Table 8, the correlation coefficient values between the gait spatial parameters and technical–tactical training are included. No clear relationships between the variables were found in this set.

In Table 9, data are contained regarding the results of analyses on the relationship between the ground reaction force and the technical–tactical indicators of kickboxing athletes. The analysis showed a lack of significant correlations between the variables.

The characteristics of the relationship between the gait phase parameters and the technical–tactical indicators are presented in Table 10. The analysis showed a lack of significant correlations between the variables. In the case of the relationship between the attack activity and load response of the dominant limb, as well as the pre-swing of the non-dominant limb, high-strength positive correlations were observed, although they were without statistical significance.

4. Discussion

The purpose of research was to examine gait parameters in kickboxing athletes at an elite level. In this study, the variables of the center of pressure (COP), gait phase, gait spatial, gait time and reaction force parameters were investigated in kickboxing athletes. Acquiring new information and developing positive attitudes towards the correct biomechanics of movement and a possible gait re-education among the kickboxer community can help optimize their training and competition activities, while reducing susceptibility to injuries. The literature on the subject shows that observing the gait style of an athlete, persistent practice aimed at improvement, and determining, if any, gait deformities, will increase their effectiveness of performance and also decrease injury risk [10,16]. In this study, no significant differences were observed in the length of gait line or anterior–posterior component of the COP or the single support line variables between the dominant and non-dominant sides. Also, no significant differences were noted in the load response, single support, pre-swing or swing phase, foot rotation or the step length, step time, or vertical or anterior components of the force variable between the dominant and non-dominant sides. Due to the lack of studies in this field among kickboxing athletes, a direct comparison is not possible. This limits our study to some extent but also creates scientific potential, revealing new horizons for research exploration.

In this study, the dominant limb of the participants was the right lower extremity. For the medio-lateral component of the COP (center of pressure) and the medio-lateral component of force variables, there was a significant difference between the dominant (right) and non-dominant limbs (left). In addition, there was a high association with signs of statistical significance regarding lateral symmetric quality with a higher attack activity (r = 0.64, p = 0.046). The load response of the right limb showed a similar trend, albeit without statistical significance. Inferring qualitatively, this may be a consequence of the targeted, specialized art of kickboxing. In many years of training practice, athletes, when delivering blows from an asymmetrical fighting position with their dominant limbs (right hand and leg), put a great deal of strain on the supporting limb (left leg) post-blow by twisting the whole body. As a result, the left foot (with the outer edge emphasized) experiences a very strong interaction with the ground. Specialized analyses of fights in kickboxing and boxing show the aspect of the number of blows inflicted with the dominant leg [3] and the quality of the dominant hand [33]. An increase in the value of displacement in the medio-lateral direction is a sign of balance and muscle weakness, as well as an increase in the risk of joint and muscle damage [34]. Balance is known to be an important factor in many sports such as kickboxing. Weakness in balance and postural control, when faced with disturbing factors, causes injuries such as instability or pain in the ankles and knees, knee osteoarthritis and acute ankle sprains [34]. Gait stability necessitates suitable mechanical interactions with the surrounding environment, especially while walking, where humans invariably encounter mechanical perturbations due to either motor control errors or environmental influences. Model simulations have shown that small anteroposterior perturbations are managed by the body's passive dynamics, while medio-lateral perturbations call for active stabilization, highlighting the critical role of frontal-plane motor control in maintaining gait stability [35,36]. Consequently, kickboxing athletes experiencing increased medio-lateral displacement may face a heightened risk of falls and enhanced deviation in the lower limb joints, particularly in the ankles. The stance phase in natural gait, characterized by the foot's contact with the ground and the associated ground reaction force (GRF), is pivotal to maintaining balance [37]. Prior studies have analyzed the direct correlation between an increase in GRF and an elevated risk of injury, emphasizing potential joint damage in cases of recurrent forces, especially during continuous weighting [38,39]. Improper dispersion of the impact forces on the ground can lead to misalignments in the lower limb, possibly reducing shock absorption and joint stability, thereby exacerbating stress on bones and joints in kickboxing athletes [40]. The understanding of the center of pressure's (COP) spatial relationship with the primary joints during normal gait is beneficial in deciphering an individual's pathomechanics. The COP, governed by the neural control of ankle muscles, shifts anteriorly with augmented activity of the plantar flexors and laterally with increased invertor muscle activity, serving as a reliable index for evaluating balance and functional analysis in clinical settings [41–44]. Moreover, its relation to foot pathology has proven useful in calculating torque around the foot's joint axis and evaluating the efficacy of rehabilitation devices, such as foot orthoses, during walking [45].

The center of pressure (COP) has been identified as a reliable indicator of neuromuscular response for maintaining balance. By comparing the trajectories of the COP for the right and left feet, we can gain insight into the sensorimotor control and function of an individual. The central nervous system's ability to integrate sensory information and activate the necessary postural muscles to maintain an upright stance is demonstrated by the respective COP trajectories for each foot and the congruence between both points of application [46]. Gaining an understanding of COP displacement between both feet across different age groups can help to identify postural issues, such as foot deformities caused by ill-fitting shoes or a lack of neuromuscular control due to a deficiency in the central nervous system [47].

In previous research, it has been suggested that the occurrence of asymmetry when maintaining balance may be the result of musculoskeletal dysfunction or lower extremity dominance. These conclusions were drawn by Ageberg [6], Lin [9] and Barone [48] comparing COP variables in static bilateral conditions. However, during single-leg testing, Hoffmann [49], Greve [50] and Cuğ et al. [51] did not observe any differences in postural balance between the dominant and non-dominant legs of young adults. Interestingly, Micarelli et al. [52] found more significant COP displacement in the right rather than left leg during quiet standing in a group of children aged 4–13 and 4–7 years old. In research on the development of postural control by Assaiante [53], it was found that the trunk serves as an important reference frame in the emergence of structured postural strategies. It has been suggested that, over time, shifting the center of mass over to the left increases the weight-bearing load of the left leg.

Gait analysis is a useful tool for assessing and comparing human movement patterns to gain insight into a variety of health-related factors. Spatio-temporal gait parameters are one form of data obtained through gait analysis that have been shown to be useful clinical measures that can detect 'negative' changes in individuals' gait patterns due to pathology or aging, and 'positive' changes due to rehabilitation or locomotor training [54–56]. In this study, the results of gait spatial parameters (velocity, step width, stride length, step length and foot rotation) for the participants showed that no significant differences in the foot rotation or step length variables between the left and right sides were noted. This authorizes the conclusion that the studied group of elite kickboxers presents a right-handed gait pattern, co-evolving with many years of training and running experience. Furthermore, this indicates the versatility of the applied training process with compensatory and corrective content.

Symmetry between the lower limbs is very important in performing sports movements [27,28]. In addition, it has been reported that the presence of symmetry between the dominant and non-dominant legs may prevent muscle imbalances and sports-related injuries [29,57]. Foot parameters and variables provide comprehensive information on symmetry between the feet [30,31], which may provide appropriate strategies for rehabilitation programs aimed at preventing lower limb imbalance and maintaining proper posture [58,59]. Since the right and left sides of the body are different, it may be thought that the foot parameters of the dominant leg can be different from the non-dominant one. In several studies, asymmetry has been reported in healthy subjects, which can be divided into three groups: children, young people and adults. Diop et al., by examining the kinematic parameters and reaction force in healthy children aged 4 to 10 years, showed that walking in these people is asymmetrical [60]. These findings on children were later confirmed in the work of Rosenbaum and Bosch by examining foot-loading parameters [61]. In this study, foot loading is asymmetric with the onset of independent walking and improved symmetry was shown with increasing age, dependent on the foot-loading parameters [61]. In the field of studies conducted among young people, Forczek and Staszkiewicz investigated asymmetry by examining kinematic parameters. An analysis of the results demonstrates no differences in the temporal or phasic variables of the movements of the right and left lower limbs. However, different profiles of angular changes in the sagittal plane were observed, measured bilaterally for the ankle joint [62]. Plotnik et al. showed that left–right anti-phase stepping is similar in normal and fast walking, but altered during slowed walking [63]. The gait of able-bodied subjects appears to be symmetric, while control and propulsion were recognized as two major roles of the extensors and flexors (global gait asymmetry). The symmetrical behavior of the lower limbs should be considered a consequence of local asymmetry, which indicates different levels of within- and between-muscle activities developed in each joint during gait cycles [64]. A research area concerning the analysis of variable and directional asymmetry in the bones of the lower limbs does exist. Asymmetries have been studied in the pelvic system, the femoral bone, the tibial bone, the fibular bone and the foot [65,66]. The studies covered various age groups [67,68]. Undoubtedly, asymmetry in bone structure is associated with the asymmetry of gait parameters [69,70]. Moreover, gait asymmetry can be linked to ontogenetic changes in bone remodeling. More than once, asymmetry of the body and bone structure was associated with the performed profession and the practiced sports discipline [71]. A literature analysis allows us to indicate that a greater asymmetry was noted in the structure of the upper limbs than the lower one, directly related to walking [72].

The presented gait pattern profile study in our own research and according to our opinion has not yet been used in the environment of combat sports, and certainly not with a personalized diagnosis for kickboxers. To the best of our knowledge, we were the first to describe a preliminary gait model for athletes representing this profession.

Limitations of the Study

Our study had some limitations; namely, we investigated selected gait parameters on a small sample. Therefore, it is recommended to extend the diagnosis to a larger population. In further studies, the kinetic and kinematic variables of other body parts should also be included in order to capture a multifaceted clinical context, and thus a detailed diagnosis, with an understanding of the condition regarding the study population. Additionally, due to the fact that the study was conducted on a small sample, exclusively consisting of men in young adulthood who are right-side dominant, further research should be conducted involving participants who are left-side dominant. Research should also be extended to populations representing different age groups, as an athlete's mechanics evolve with age. Further diagnosis should also be conducted involving female athletes. Moreover, the lack of a control group may hinder the generalizability of the results. Finally, future studies are recommended to compare the parameters (such as the angles of the lower limb joints' muscle torques) of kickboxing with other sports and to recognize the co-occurrence of the model gait pattern with training length and sport performance.

5. Conclusions

In the study, it was found that kickboxing training at an elite level during young adulthood does not significantly disrupt gait symmetry between the dominant and non-dominant legs. Contrary to concerns that such training may lead to imbalances, our research allows us to demonstrate that elite kickboxing actually contributes to maintaining a correct and balanced gait pattern. This balanced gait suggests that the lower limbs are properly loaded, reducing the likelihood of overuse injuries to the knees and hips. However, it is important to note that a specific asymmetry was observed in the medial–lateral components of the center of pressure (COP) and the force between the dominant and non-dominant feet. This asymmetry was most likely a result of specialized offensive techniques and fighting stances that are commonly employed in kickboxing, primarily focused on dominant limb use.

Practical Implications

The insights from this study have several practical applications. First of all, the findings offer a useful baseline for comparing and interpreting performance indicators in the field of combat sports, especially those based on mean values. This can be instrumental for coaches, therapists and researchers who aim to better understand an athlete's biomechanical profile. Secondly, the parameters and metrics used in our study can serve as diagnostic tools for assessing the musculoskeletal health of kickboxing athletes, enabling the planning of therapeutic interventions if they become necessary. Finally, these results can be used to individualize training programs. With a nuanced understanding of gait and force asymmetries, coaches and therapists can design training regimes that minimize the risk of developing musculoskeletal abnormalities. Therefore, this study amplifies the utility of gait profile analysis as an effective tool for optimizing the quality of coaching and therapeutic strategies in kickboxing.

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