actuators

Article

Changes of Ankle Motion and Ground Reaction Force Using Elastic Neutral AFO in Neurological Patients with Inverted Foot During Gait

Du-Jin Park [1] and Young-In Hwang [2,*]

[1] Department of Physical Therapy, College of Health Sciences, Catholic University of Pusan, Busan 46252, Republic of Korea
[2] Department of Physical Therapy, Smart Healthcare Convergence Research Center, Research Institute for Basic Sciences, College of Life and Health Sciences, Hoseo University, Asan 31499, Republic of Korea
* Correspondence: young123@hoseo.edu

Abstract: Many stroke patients develop ankle deformities due to neurological or non-neurological factors, resulting in abnormal gait patterns. While Ankle-Foot Orthoses (AFOs) are commonly used to address these issues, few are specifically designed for ankle varus. The Elastic Neutral Ankle-Foot Orthosis (EN-AFO) was developed for this purpose. This study aimed to analyze changes in kinematic and kinetic gait data in stroke patients with ankle varus, comparing those walking with and without EN-AFO in both AFO and No-AFO groups. Initially, 30 stroke patients with ankle varus were screened; after exclusions, 17 were included in the final analysis. In the No-AFO group, EN-AFO significantly improved maximal ankle inversion on the affected side during the swing phase (from 4.63 ± 13.26 to 10.56 ± 11.40, p = 0.025). Similarly, in the AFO group, EN-AFO led to a significant improvement in maximal ankle inversion on the less-affected side during the swing phase (from 7.95 ± 10.11 to 12.01 ± 8.64, p = 0.021). Additionally, ground reaction forces on the affected side of the AFO group significantly increased at both the forefoot (from 182.76 ± 61.45 to 211.55 ± 70.57, p = 0.038) and hindfoot (from 210.67 ± 107.88 to 231.85 ± 105.38, p = 0.038) with EN-AFO. Conversely, maximal and minimal thoracic axial rotation on the affected side improved significantly in the No-AFO group compared to the AFO group with EN-AFO, during both the stance and swing phases (stance phase: max improvement from −1.13 ± 1.80 to 4.83 ± 8.05, min improvement from −1.06 ± 2.45 to 5.89 ± 7.56; swing phase: max improvement from −1.33 ± 2.13 to 5.49 ± 7.82, min improvement from −1.24 ± 2.43 to 5.95 ± 7.12; max p = 0.034, min p = 0.016 during stance; max p = 0.027, min p = 0.012 during swing). Furthermore, both maximal and minimal thoracic axial rotation on the less-affected side during the swing phase improved significantly in the No-AFO group (max improvement from −2.09 ± 4.18 to 6.04 ± 6.90, min improvement from −0.47 ± 2.13 to 8.18 ± 10.45; max p = 0.027, min p = 0.012) compared with the AFO group. These findings suggest that EN-AFO may effectively improve gait in stroke patients with ankle varus in the No-AFO group.

Keywords: ankle; ankle-foot orthosis; gait; ground reaction force; neurologic foot deformities; neurologic rehabilitation

check for updates

Citation: Park, D.-J.; Hwang, Y.-I. Changes of Ankle Motion and Ground Reaction Force Using Elastic Neutral AFO in Neurological Patients with Inverted Foot During Gait. *Actuators* **2024**, *13*, 526. https://doi.org/10.3390/act13120526

Academic Editors: Mahdy Eslamy, Geetika Aggarwal and Jinoop Arackal Narayanan

Received: 31 October 2024
Revised: 18 December 2024
Accepted: 18 December 2024
Published: 20 December 2024

1. Introduction

Many stroke patients experience reduced ankle joint mobility and deformities due to neurological or non-neurological factors [1–3]. Additionally, ankle and foot deformities frequently occur following a stroke [4]. In particular, varus deformity of the ankle and foot in stroke patients primarily arises from the co-activation of the tibialis anterior muscle, which functions as an ankle dorsiflexor, and the tibialis posterior muscle, which acts as an ankle plantarflexor. The severity of varus deformity is determined by the degree of spasticity and the weakness of these muscles [5]. Moreover, these ankle joint problems result in a functional leg length discrepancy [6], causing increased weight bearing on the non-paretic limb [7]. Furthermore, when varus of the foot due to spasticity occurs, the toes flex, and the lateral aspect of the foot contacts the ground, making ambulation more difficult without an orthotic device [8]. In such cases, the heel does not strike the ground first, leading to a shortened stance phase and a relatively prolonged swing phase on the affected side. Instead, the forefoot or the entire plantar surface strikes the ground first, resulting in an abnormal gait pattern characterized by reduced walking speed [9,10].

Stroke patients often use Ankle-Foot Orthoses (AFOs) to improve abnormal gait patterns and maintain independent mobility [11]. AFOs are known for providing mediolateral stability during the stance phase and facilitating and assisting ankle movement during the swing phase [12]. However, some researchers have argued that the prolonged use of AFOs may lead to dependency on the mechanical device, potentially causing muscle weakness, such as in the ankle dorsiflexors, which may, in turn, delay functional recovery [13]. Several previous studies on the gait of stroke patients using AFOs have reported an increase in ankle dorsiflexion at initial contact [14–16] and during the stance phase [15,17,18]. However, other studies have also observed a reduction in ankle plantarflexor power during push-off when AFOs are applied to stroke patients [19,20]. While AFOs provide mediolateral stability, they may also restrict ankle movement during the push-off phase.

An Elastic Neutral AFO (EN-AFO), which assists movement without restricting ankle motion, was developed by Hwang and Park (2021) to address the limitations of conventional AFOs [10]. In previous studies, a comparison of gait before and after wearing EN-AFO in patients with ankle varus demonstrated that wearing the EN-AFO could correct ankle varus during gait [10]. However, since that study did not compare conventional AFOs with EN-AFOs, it remains unclear which orthotic device is more effective during gait. This study, therefore, aims to compare kinematic and kinetic data during gait when EN-AFOs are applied to two groups: one group already using AFOs due to severe ankle varus and another group with ankle varus who walk without AFOs. The hypotheses of this study are as follows:

1. Wearing EN-AFOs on the paretic side will significantly reduce the ankle varus angle in both the AFO and No-AFO groups during walking in stroke patients with foot inversion.
2. Kinematic data will show greater improvement with EN-AFO in the No-AFO group compared to the AFO group during walking in stroke patients with foot inversion.

2. Methods

2.1. Participants

Thirty stroke patients with a varus deformity of the foot were recruited for screening from S, C, and J Hospitals in the Republic of Korea. Six patients (epilepsy: 1, equinovarus: 5) were excluded from the study. All participants voluntarily agreed to take part in the study. The inclusion criteria were as follows: (a) a diagnosis of hemiplegia due to cerebral hemorrhage or infarction, (b) the presence of a rearfoot varus deformity, (c) the ability to follow simple instructions, and (d) the ability to walk independently or with the use of an ambulatory aid. The exclusion criteria were (a) a history or current orthopedic issues affecting the foot, (b) bilateral leg problems, (c) a score of 3 or higher on the Modified Ashworth Scale, and (d) the presence of an equinus deformity. Of the 24 participants, 12 were assigned to the AFO group, consisting of those who walked with AFOs, and 12 were assigned to the No-AFO group, consisting of those who walked without AFOs. The general characteristics of the participants are presented in Tables 1 and 2. The flow chart was shown in Figure 1. This study was conducted with the approval of the Hoseo University Institutional Review Board (1041231-190624-HR-092-06).

Table 1. Characteristics of participants of AFO and No-AFO groups.

Characteristics	AFO Group (n = 9)	No-AFO Group (n = 8)
Age (yrs)	61.6 ± 13.0	63.9 ± 9.8
Height (cm)	166.9 ± 7.1	163.9 ± 7.2
Weight (kg)	63.8 ± 13.3	62.1 ± 11.4
Onset (months)	60.4 ± 24.7	48.9 ± 27.8
Sex	Male: 4 (44.5%)	Male: 5 (62.5%)
	Female: 5 (55.5%)	Female: 3 (37.5%)
Affected side	Right: 4 (44.5%)	Right: 3 (37.5%)
	Left: 5 (55.5%)	Left: 5 (62.55)
Diagnosis	ICH: 5 (55.5%)	ICH:2 (25.0%)
	CI: 3 (33.3%)	CI: 5 (62.5%)
	PI: 1 (11/1%)	SAH: 1 (12.5%)
AFO	Anterior type: 3 (33.3%)	None
	Posterior type: 6 (66.7%)	
Assistive device	Cane: 4 (44.5%)	Cane: 4 (50.0%)
	None: 5 (55.5%)	None: 4 (50.0%)
MAS (grade)	G0: 2 (22.2%)	G0: 2 (25.0%)
	G1: 1 (11.1%)	G1: 2 (25.0%)
	G1+: 6 (66.7%)	G1+: 3 (37.5%) G2: 1 (12.5%)

AFO: ankle-foot orthosis, ICH: intracerebral hemorrhage, CI: cerebral infarction, PI: pontine infarction, SAH: subarachnoid hemorrhage, MAS: Modified Ashworth scale, G: grade.

Table 2. Differentiation of kinematic data in AFO and NO-AFO groups after wearing Elastic Neutral AFO at stance phase.

Affected Limb		AFO Group		No-AFO Group	
		Pre	Post	Pre	Post
Thoracic Axial Rotation (°)					
Max	Mean (SD)	5.03 (5.00)	3.89 (4.94)	−2.34 (14.18)	2.49 (8.03)
	z	−1.599		−1.260	
	p	0.110		0.208	
Min	Mean (SD)	−4.18 (4.71)	−1.80 (5.32)	−9.25 (13.85)	−3.36 (7.89)
	z	−1.125		−1.680	
	p	0.260		0.093	
Hip External Rotation (°)					
Max	Mean (SD)	22.72 (8.11)	16.77 (17.43)	16.15 (12.38)	7.23 (11.01)
	z	−1.244		−2.240	
	p	0.214		0.025 *	
Min	Mean (SD)	8.04 (9.64)	4.82 (16.81)	3.45 (10.22)	−2.36 (10.02)
	z	−0.296		−2.521	
	p	0.767		0.012 *	
Ankle Inversion (°)					
Max	Mean (SD)	3.18 (4.87)	5.24 (6.45)	10.51 (10.18)	6.01 (11.34)
	z	−0.770		−2.100	
	p	0.441		0.036 *	
Min	Mean (SD)	7.37 (4.00)	−8.02 (4.78)	−5.45 (3.43)	−6.19 (5.82)
	z	−0.415		−0.700	
	p	0.678		0.484	

Table 2. *Cont.*

Less-Affected Limb		AFO Group		No-AFO Group	
		Pre	Post	Pre	Post
Thoracic axial rotation (°)					
Max	Mean (SD)	5.24 (5.43)	3.89 (5.40)	−2.44 (13.98)	3.51 (9.20)
	z	−1.362		−2.100	
	p	0.173		0.036 *	
Min	Mean (SD)	−1.06 (5.18)	−1.98 (5.39)	−9.24 (13.31)	−3.52 (8.12)
	z	−1.007		−1.680	
	p	0.314		0.093	
Hip External Rotation (°)					
Max	Mean (SD)	7.46 (9.26)	4.55 (5.00)	11.13 (7.61)	19.60 (11.87)
	z	−1.362		−2.521	
	p	0.173		0.012 *	
Min	Mean (SD)	−1.43 (8.60)	−2.67 (6.83)	0.91 (7.73)	6.88 (12.31)
	z	−0.770		−1.960	
	p	0.441		0.050	
Ankle dorsiflexion (°)					
Max	Mean (SD)	15.78 (4.22)	12.85 (5.70)	12.18 (4.51)	8.26 (6.46)
	z	−1.244		−2.521	
	p	0.214		0.012 *	
Min	Mean (SD)	−3.79 (4.00)	−3.11 (3.69)	−6.90 (4.39)	−9.57 (8.51)
	z	−0.889		−0.840	
	p	0.374		0.401	
Foot External Rotation (°)					
Max	Mean (SD)	7.11 (9.53)	5.87 (7.46)	8.85 (14.31)	18.94 (17.48)
	z	−0.415		−2.100	
	p	0.678		0.036 *	
Min	Mean (SD)	3.10 (11.13)	3.43 (10.51)	1.90 (17.13)	11.08 (21.15)
	z	−0.296		−1.960	
	p	0.767		0.050	

AFO: ankle foot orthosis. * $p < 0.05$.

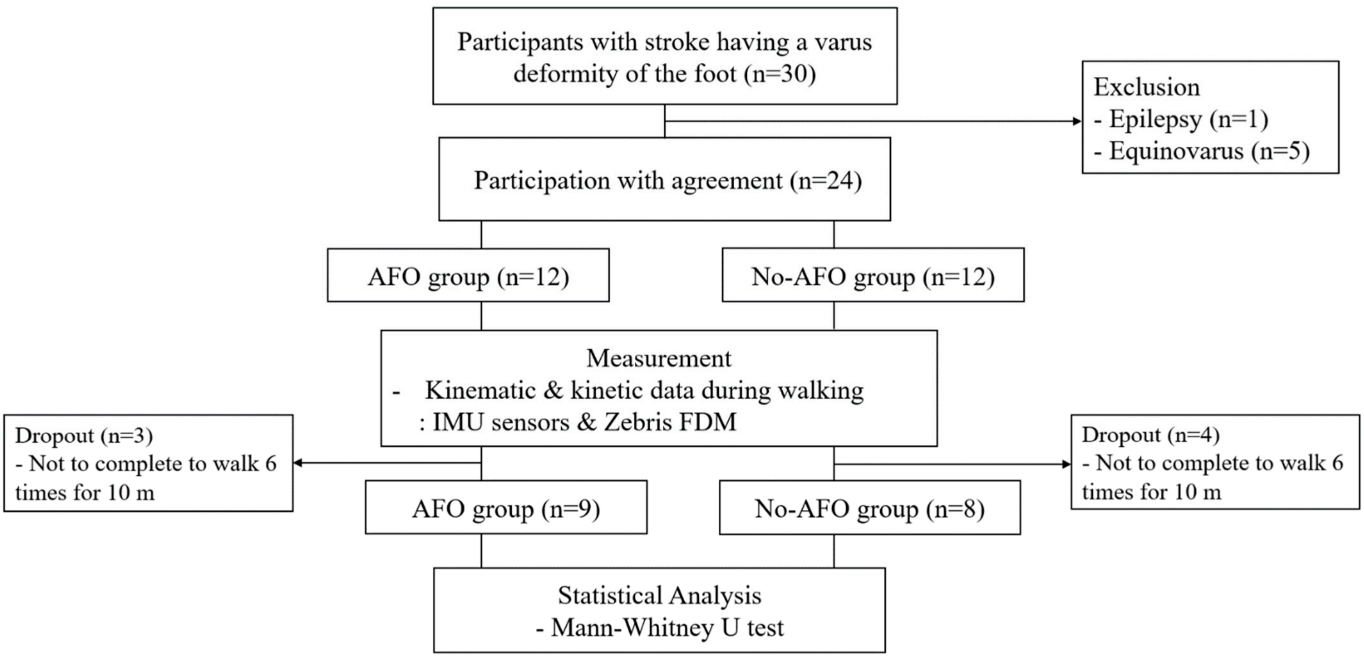

Figure 1. A flowchart of the study.

2.2. Inertial Measurement Unit (IMU) Sensor

The Noraxon MyoMOTION motion analysis system (100 Hz, Noraxon USA Inc., Scottsdale, AZ, USA) was used to analyze kinematic variables (Figure 2). This system utilizes small inertial measurement units (IMUs), which are capable of measuring the 3D angular orientation of body segments. IMUs overcome the limitations of traditional optical motion capture systems, which may fail to track movement if the subject's motion is occluded by the camera [21]. The IMU system has a dynamic measurement accuracy of 1.2 degrees [21].

Figure 2. The force plate (dark area) to analyze kinetic variables.

2.3. Force Plate

The Zebris FDM-1.5 system (100 Hz, zebris Medical GmbH, Isny im Allgäu, Germany) was used to analyze kinetic variables, including force and pressure (Figure 2). The system has dimensions of 1580 mm in length, 605 mm in width, and 21 mm in height. It contains a total of 11,264 sensors (64 × 176), covering a sensor surface area of 1440 × 560 mm (L × W). The Zebris system was synchronized with the Noraxon MyoMotion motion analysis system to ensure accurate coordination between kinetic and kinematic data. This system is capable of measuring only vertical ground reaction forces and does not capture horizontal forces. Two non-slip platforms, each with a height of approximately 20 mm, matching the height of the Zebris system, were placed in front of the Zebris system, and three additional platforms were positioned behind it. This setup allowed subjects to walk straight for approximately 7 m. The dimensions of each non-slip platform are 1150 mm by 1150 mm (L × W).

2.4. Elastic Neutral AFO

The Elastic Neutral Ankle-Foot Orthosis (EN-AFO) was designed to improve gait patterns in stroke patients with foot varus deformity [10].

It is composed of Velcro straps (a), fabric (b), and an elastic band (c,d) that wraps around the lower leg and forefoot (Figure 3). The elastic band (c,d) utilized a gray-colored band produced by the Theraband company. A thin plastic piece was attached in the area around the second toe, as shown in Figures 3(d) and 4(f-1,f-2). The inner side of the EN-AFO is described in Figure 3: (a) Velcro strap; (b-1,b-2) joint between elastic band and fabric, (c) fabric, (d) the elastic support, (e) the elastic band wearing the lower leg and forefoot, (f-1,f-2) stiches in the shape of an overshoe in an area where thin plastic was attached (Figure 4) [10]. The researchers individually adjusted the elastic tension for each patient to ensure optimal support, allowing patients to walk with the EN-AFO once before re-assessing and adjusting the elastic tension as needed.

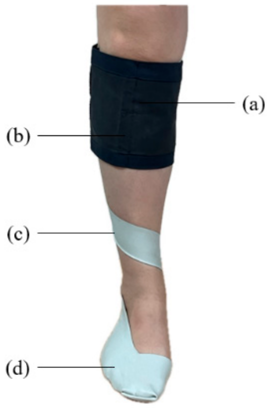

Figure 3. The EN-AFO device in use. (a) Velcro straps; (b) fabric belt with elastic reinforcement; (c,d) elastic bands securing the lower leg and forefoot.

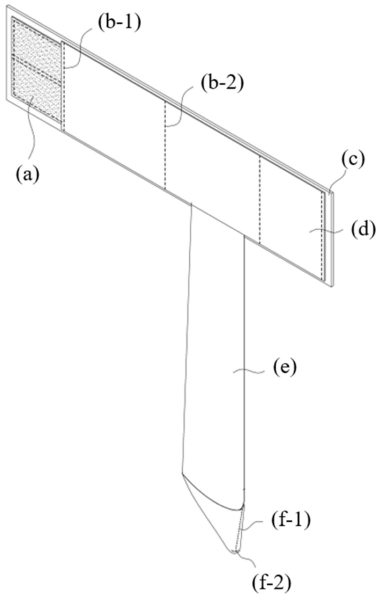

Figure 4. The inner side of the EN-AFO. (a) Velcro strap; (b-1,b-2) joint between elastic band and fabric, (c) fabric, (d) the elastic support, (e) the elastic band wearing the lower leg and forefoot, (f-1,f-2) stiches in the shape of an overshoe in an area where thin plastic was attached. (Cited from Hwang and Park (2021) [10]).

2.5. Procedure

All participants in this study had their kinematic and kinetic data measured during gait using a 3D motion analysis system (Noraxon MyoMotion) and a force plate (Zebris FDM-1.5). To capture kinematic data, nine IMU sensors were attached to the following body locations: the C7 spinous process and T12 spinous process for trunk measurements [22], the midpoint between the PSISs for pelvis data, the frontal aspect of the femur on both thighs, the anterior aspect of the tibia on both lower legs, and the dorsum of the foot between the first and second toes on both ankles while wearing shoes [23] (Figure 5). After attaching the IMU sensors, calibration was performed in an anatomical standing position. Before testing, the researcher demonstrated the walking procedure to the participants. All participants performed the walking trials while wearing their own shoes. In the AFO group, participants walked with their AFOs worn inside their shoes, followed by walking with the EN-AFO inside their shoes. In the No-AFO group, participants initially walked wearing only their shoes and then performed subsequent trials with the EN-AFO worn inside their shoes.

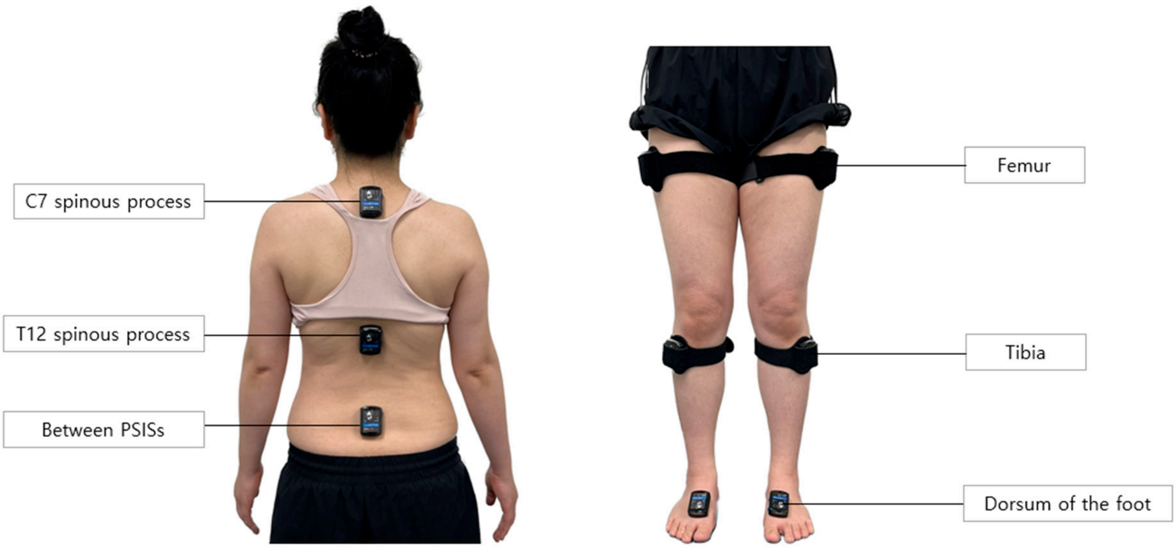

Figure 5. The attachments of the IMU sensors.

All participants walked a straight 7 m path, and an assistant walked 1 m behind them to prevent falls. The AFO group performed three walking trials with their regular AFO and three trials with the EN-AFO. The No-AFO group completed three walking trials without an AFO and three trials with the EN-AFO. A 10 min rest period was provided between each set of trials, with additional rest offered if requested by the participants. The 3D motion analysis system was synchronized with the force plate to collect kinematic and kinetic data, capturing stance and swing phase parameters during gait.

2.6. Statistical Analysis

Statistical analyses were performed using SPSS software (version 20.0; IBM Corporation, Armonk, NY, USA) to examine between-group changes before and after wearing EN-AFO in neurological patients with ankle varus. Since the data did not follow a normal distribution, the non-parametric Mann–Whitney U test was conducted for between-group comparisons. In the intergroup comparisons, the gait cycle was not divided into specific sections but was analyzed by separating the stance phase and swing phase. For each participant, the gait phases (stance and swing) were standardized, and the maximum and minimum values were analyzed accordingly. Additionally, the Wilcoxon signed-rank test, a non-parametric method, was employed to compare the effects of EN-AFO within the AFO and No-AFO groups. The significance level (α) was set at less than 0.05.

3. Results

The characteristics of participants in the AFO group and No-AFO group are as follows (Table 1). In the AFO group, there were nine participants (four males and five females) with an average age of 61.6 $\pm$ 13.0 years, height of 166.9 $\pm$ 7.1 cm, weight of 63.8 $\pm$ 13.3 kg, and an onset duration of 60.4 $\pm$ 24.7 months (Table 1). In the No-AFO group, there were eight participants (five males and three females) with an average age of 63.9 $\pm$ 9.8 years, height of 163.9 $\pm$ 7.2 cm, weight of 62.1 $\pm$ 11.4 kg, and an onset duration of 48.9 $\pm$ 27.8 months (Table 1).

In this study, the pre-test condition refers to measurements taken with the AFO group wearing an AFO and shoes, and the No-AFO group wearing shoes only. The post-test condition refers to measurements taken with both groups wearing the EN-AFO along with the same shoes used in the pre-test condition. The results regarding the differences within the AFO and No-AFO groups are presented in Tables 2–4, while the results for the between-group differences are described in Tables 5 and 6.

Table 3. Differentiation of kinematic data in AFO and NO-AFO groups after wearing Elastic Neutral AFO at swing phase.

Affected Limb		AFO Group		No-AFO Group	
		Pre	Post	Pre	Post
Thoracic Axial Rotation (°)					
Max	Mean (SD)	4.55 (5.32)	3.21 (5.23)	−3.21 (13.95)	2.27 (8.24)
	z	−1.836		−1.400	
	p	0.066		0.161	
Min	Mean (SD)	0.37 (5.32)	−0.87 (5.59)	−7.91 (14.16)	−1.96 (8.43)
	z	−1.599		−1.680	
	p	0.110		0.093	
Hip External Rotation (°)					
Max	Mean (SD)	21.84 (7.81)	16.00 (17.86)	15.97 (13.12)	8.53 (12.58)
	z	−1.244		−2.100	
	p	0.241		0.036 *	
Min	Mean (SD)	13.24 (9.06)	9.22 (18.51)	7.96 (13.26)	0.27 (11.51)
	z	−0.296		−1.960	
	p	0.767		0.050	
Ankle dorsiflexion (°)					
Max	Mean (SD)	−2.71 (6.53)	−1.95 (6.01)	−0.47 (6.29)	−4.61 (8.51)
	z	−0.296		−1.680	
	p	0.767		0.093	
Min	Mean (SD)	10.61 (6.76)	−14.17 (7.75)	−9.85 (8.21)	−12.08 (5.40)
	z	−2.073		−0.840	
	p	0.038 *		0.401	
Ankle Inversion (°)					
Max	Mean (SD)	2.61 (7.08)	4.93 (7.63)	10.56 (11.40)	4.63 (13.26)
	z	−0.889		−2.240	
	p	0.374		0.025 *	
Min	Mean (SD)	−3.06 (5.85)	−3.46 (6.11)	1.55 (9.86)	−1.44 (11.51)
	z	−0.533		−1.400	
	p	0.594		0.161	
Less-Affected Limb		**AFO Group**		**No-AFO Group**	
		Pre	**Post**	**Pre**	**Post**
Thoracic axial rotation (°)					
Max	Mean (SD)	2.07 (4.84)	−0.01 (5.98)	−4.93 (13.37)	1.10 (8.36)
	z	−1.362		−2.100	
	p	0.173		0.036 *	
Min	Mean (SD)	0.38 (5.26)	−0.08 (5.58)	−7.85 (13.58)	0.32 (5.55)
	z	−0.889		−2.240	
	p	0.374		0.025 *	
Hip External Rotation (°)					
Max	Mean (SD)	6.14 (9.11)	5.63 (7.42)	10.63 (6.41)	18.49 (11.34)
	z	−0.296		−2.240	
	p	0.767		0.025 *	
Min	Mean (SD)	13.24 (9.06)	9.22 (18.51)	7.96 (13.26)	0.27 (11.51)
	z	−0.296		−1.960	
	p	0.767		0.050	

Table 3. *Cont.*

Less-Affected Limb		AFO Group		No-AFO Group	
		Pre	Post	Pre	Post
Ankle Inversion (°)					
Max	Mean (SD)	12.01 (8.64)	7.95 (10.11)	6.46 (5.83)	4.38 (9.30)
	z	−2.310		−0.140	
	p	0.021 *		0.889	
Min	Mean (SD)	−3.06 (5.85)	−3.46 (6.11)	1.55 (9.86)	−1.44 (11.51)
	z	−0.533		−1.400	
	p	0.594		0.161	
Foot External Rotation (°)					
Max	Mean (SD)	6.72 (10.38)	6.16 (7.98)	9.27 (16.84)	18.27 (21.10)
	z	−0.533		−2.100	
	p	0.594		0.036 *	
Min	Mean (SD)	0.73 (11.88)	0.60 (9.69)	1.30 (15.82)	8.27 (19.29)
	z	−0.178		−1.960	
	p	0.859		0.050	

* $p < 0.05$.

Table 4. Differentiation of peak force and pressure of affected limb in AFO and No-AFO groups after wearing Elastic Neutral AFO at stance phase.

Affected Limb			AFO Group		No-AFO Group	
			Pre	Post	Pre	Post
Forefoot (N)		Mean (SD)	182.76 ± 61.45	211.55 ± 70.57	195.89 ± 73.45	208.70 ± 57.68
		z	−2.073		−1.120	
		p	0.038 *		0.263	
Midfoot (N)		Mean (SD)	184.29 ± 60.42	187.94 ± 44.10	128.91 ± 50.05	137.37 ± 61.44
		z	−0.770		−0.980	
		p	0.441		0.327	
Hindfoot (N)		Mean (SD)	210.67 ± 107.88	231.85 ± 105.38	247.44 ± 139.65	246.14 ± 144.11
		z	−2.073		−0.140	
		p	0.038 *		0.889	
Total Force (N)			Pre	Post	Pre	Post
	Max	Mean (SD)	556.90 ± 170.24	511.54 ± 111.49	490.16 ± 209.83	418.02 ± 168.82
		z	−0.889		−0.420	
		p	0.374		0.674	
	Min	Mean (SD)	9.50 ± 4.65	8.33 ± 6.61	7.81 ± 9.16	6.40 ± 3.55
		z	−0.889		−0.140	
		p	0.374		0.889	
Total Max Pressure(N/cm^2)			Pre	Post	Pre	Post
	Max	Mean (SD)	18.13 (6.11)	15.35 (4.24)	17.64 (6.37)	17.06 (7.27)
		z	−1.955		−0.280	
		p	0.051		0.779	
	Min	Mean (SD)	2.54 (0.84)	2.47 (1.04)	2.46 (1.50)	2.43 (1.41)
		z	−0.178		−0.560	
		p	0.859		0.575	

AFO: ankle foot orthosis, SD: standard deviation. * $p < 0.05$.

Table 5. Differentiation of kinematic data between AFO and No-AFO groups after wearing EN-AFO at stance phase.

Affected Limb	**AFO Group**	**No-AFO Group**		
Thoracic Axial Rotation (°)			**z**	***p***
Max	−1.13 (1.80)	4.83 (8.05)	−2.117	0.034 *
Min	−1.06 (2.45)	5.89 (7.56)	−2.406	0.016 *
Less-Affected Limb	**AFO Group**	**No-AFO Group**		
Hip External Rotation (°)			z	*p*
Max	−2.90 (7.23)	8.46 (5.41)	−2.887	0.004 *
Min	−1.23 (5.28)	5.97 (6.27)	−2.117	0.034 *
Foot External Rotation (°)				
Max	−1.23 (6.30)	10.09 (11.57)	−2.117	0.034 *
Min	−0.25 (9.36)	9.17 (12.65)	−1.732	0.083

Mean (SD). * $p < 0.05$.

Table 6. Differentiation of kinematic data between AFO and NO-AFO groups after wearing EN-AFO at swing phase.

Affected Limb	**AFO Group**	**No-AFO Group**		
Thoracic Axial Rotation (°)			z	*p*
Max	−1.33 (2.13)	5.49 (7.82)	−2.213	0.027 *
Min	−1.24 (2.43)	5.95 (7.12)	−2.502	0.012 *
Ankle Inversion (°)				
Max	2.32 (5.82)	−5.92 (4.88)	−2.694	0.007 *
Min	−0.39 (2.92)	−2.99 (4.81)	−1.058	0.290
Less-Affected Limb	**AFO Group**	**No-AFO Group**		
Thoracic axial rotation (°)			z	*p*
Max	−2.09 (4.18)	6.04 (6.90)	−2.502	0.012 *
Min	−0.47 (2.13)	8.18 (10.45)	−2.598	0.009 *
Hip External Rotation (°)				
Max	−0.50 (6.50)	7.86 (6.04)	−2.406	0.016 *
Min	−0.85 (6.33)	2.90 (11.28)	−1.540	0.124
Ankle Inversion (°)				
Max	−4.05 (4.75)	−2.08 (9.25)	−2.021	0.043 *
Min	−1.73 (3.43)	−4.03 (12.22)	−0.481	0.630

Mean (SD). * $p < 0.05$.

In the No-AFO group during the stance phase, the maximal hip external rotation of the affected limb significantly decreased from 16.15° (SD 12.38) to 7.23° (SD 11.01) ($p = 0.025$), and the minimal hip external rotation also significantly decreased from 3.45° (SD 10.22) to −2.36° (SD 10.02) ($p = 0.012$). Additionally, the maximal ankle inversion decreased significantly from 10.51° (SD 10.18) to 6.01° (SD 11.34) ($p = 0.036$). On the less-affected limb during the stance phase, the maximal thoracic axial rotation significantly increased from −2.44° (SD 13.98) to 3.51° (SD 9.20) ($p = 0.036$). Furthermore, the maximal hip external rotation increased significantly from 11.13° (SD 7.61) to 19.60° (SD 11.87) ($p = 0.012$), and the minimal hip external rotation increased significantly from 0.91° (SD 7.73) to 6.88° (SD 12.31) ($p = 0.05$). Maximal ankle dorsiflexion decreased significantly from 12.18° (SD 4.51) to 8.26° (SD 6.46) ($p = 0.012$), and the maximal foot external rotation significantly increased from 8.85° (SD 14.31) to 18.94° (SD 17.48) (Z = −2.100, $p = 0.036$). However, in the AFO group, no significant differences were observed in the stance phase with and without EN-AFO (Table 2, Figures 6 and 7).

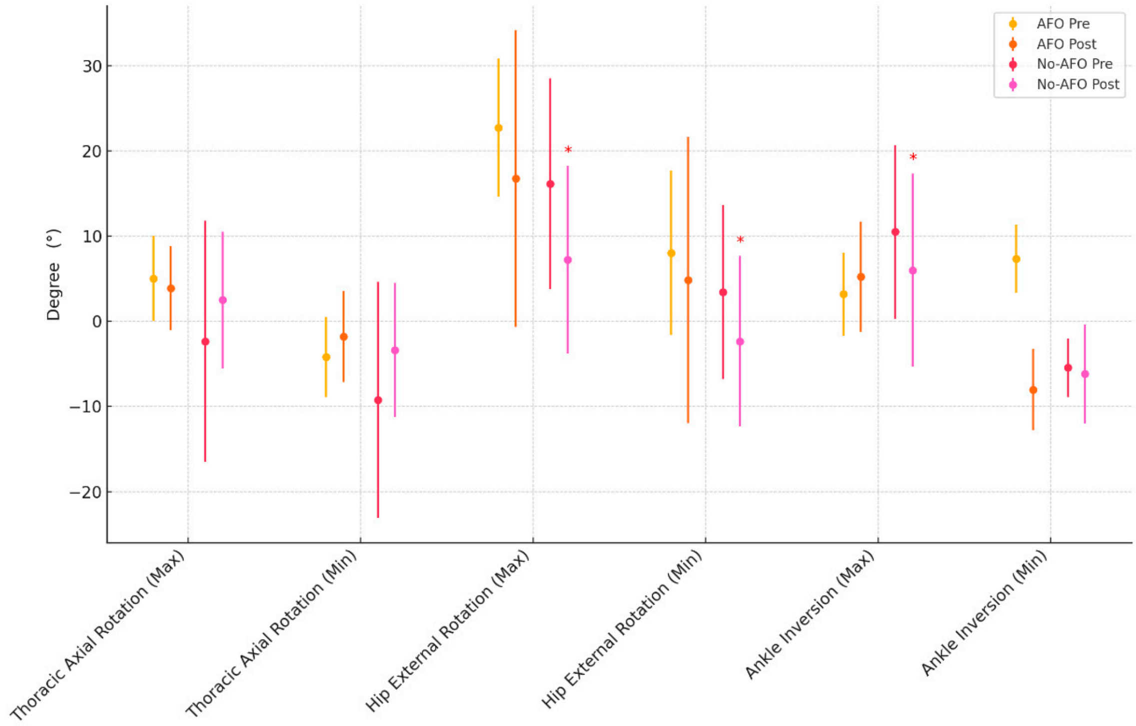

Figure 6. Differentiation of kinematic data of the affected side in AFO and No-AFO groups after wearing Elastic Neutral AFO at stance phase (* $p < 0.05$).

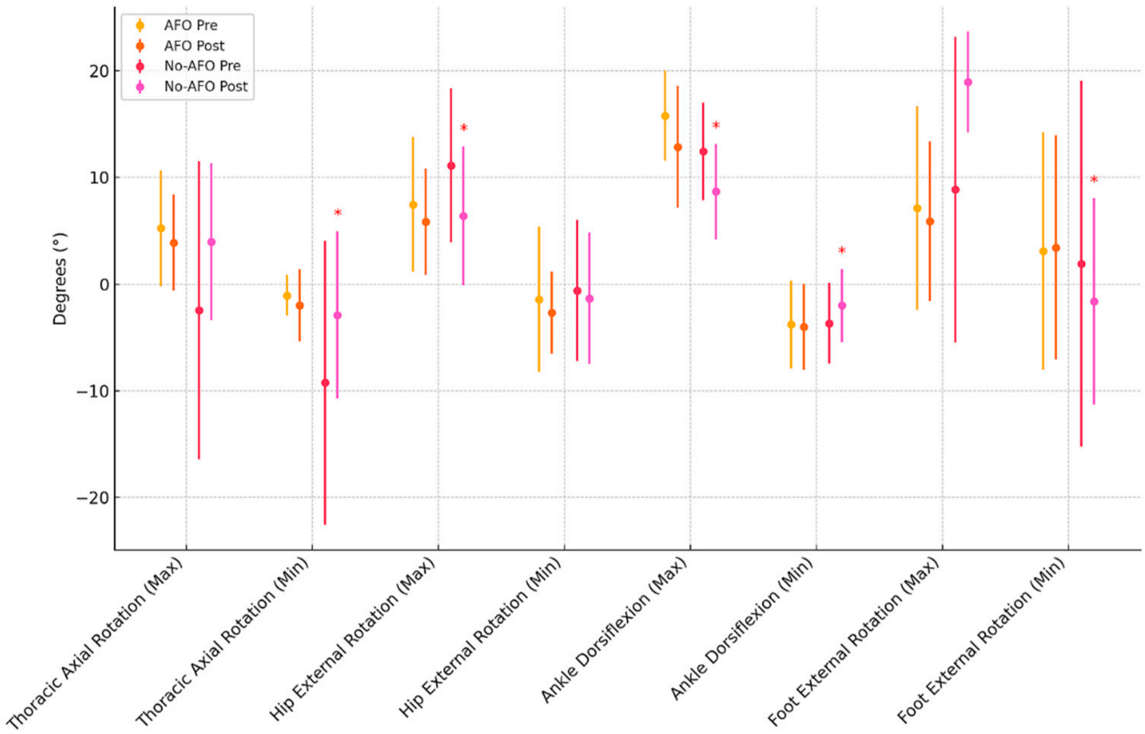

Figure 7. Differentiation of kinematic data of the less-affected side in AFO and No-AFO groups after wearing Elastic Neutral AFO at stance phase (* $p < 0.05$).

In the AFO group during the swing phase, the minimal ankle dorsiflexion of the affected limb significantly decreased from −10.61° (SD 6.76) to −14.17° (SD 7.75) ($p = 0.038$). Additionally, the maximal ankle inversion of the less-affected limb significantly decreased from 12.01° (SD 8.64) to 7.95° (SD 10.11) (p = 0.021) (Table 3, Figure 8). In the No-AFO group during the swing phase, the maximal hip external rotation of the affected limb significantly decreased from 15.97° (SD 13.12) to 8.53° (SD 12.58) (p = 0.036), and the maximal ankle inversion significantly decreased from 10.56° (SD 11.40) to 4.63° (SD 13.26) (p = 0.025) (Table 3, Figure 8). On the less-affected limb, the maximal thoracic axial rotation significantly increased from −4.93° (SD 13.37) to 1.10° (SD 8.36) (p = 0.036), and the minimal thoracic axial rotation also significantly increased from −7.85° (SD 13.58) to 0.32° (SD 5.55) (p = 0.025). Furthermore, the maximal hip external rotation significantly increased from 10.63° (SD 6.41) to 18.49° (SD 11.34) (p = 0.025), and the maximal foot external rotation significantly increased from 9.27° (SD 16.84) to 18.27° (SD 21.10) (p = 0.036) (Table 3, Figure 9).

In the AFO group, the peak forward force on the affected limb significantly increased from 182.76N (SD 61.45) to 211.55N (SD 70.57) with the application of the EN-AFO (p = 0.038). Additionally, the peak force on the heel significantly increased from 210.67N (SD 107.88) to 231.85N (SD 105.38) (p = 0.038). However, no significant differences in maximum pressure were observed in either the AFO or No-AFO group (Table 4).

Comparing the stance phase between the AFO and No-AFO groups with the application of the EN-AFO, the affected limb showed a significant increase in both maximal and minimal thoracic axial rotation (p = 0.034, p = 0.016, respectively). In the less-affected limb, significant increases were observed in both maximal and minimal hip external rotation (p = 0.004, p = 0.034, respectively) and in maximal foot external rotation (p = 0.034) when the No-AFO group wore the EN-AFO (Table 5, Figure 10).

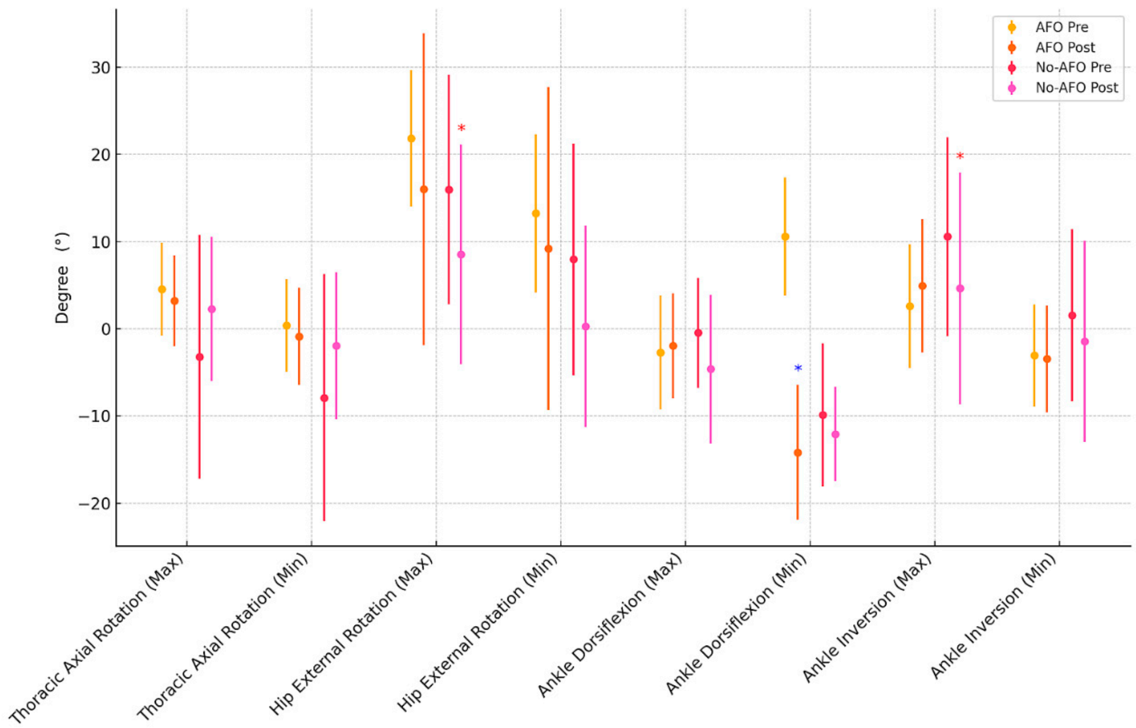

Figure 8. Differentiation of kinematic data of the affected side after wearing Elastic Neutral AFO at swing phase (* p < 0.05).

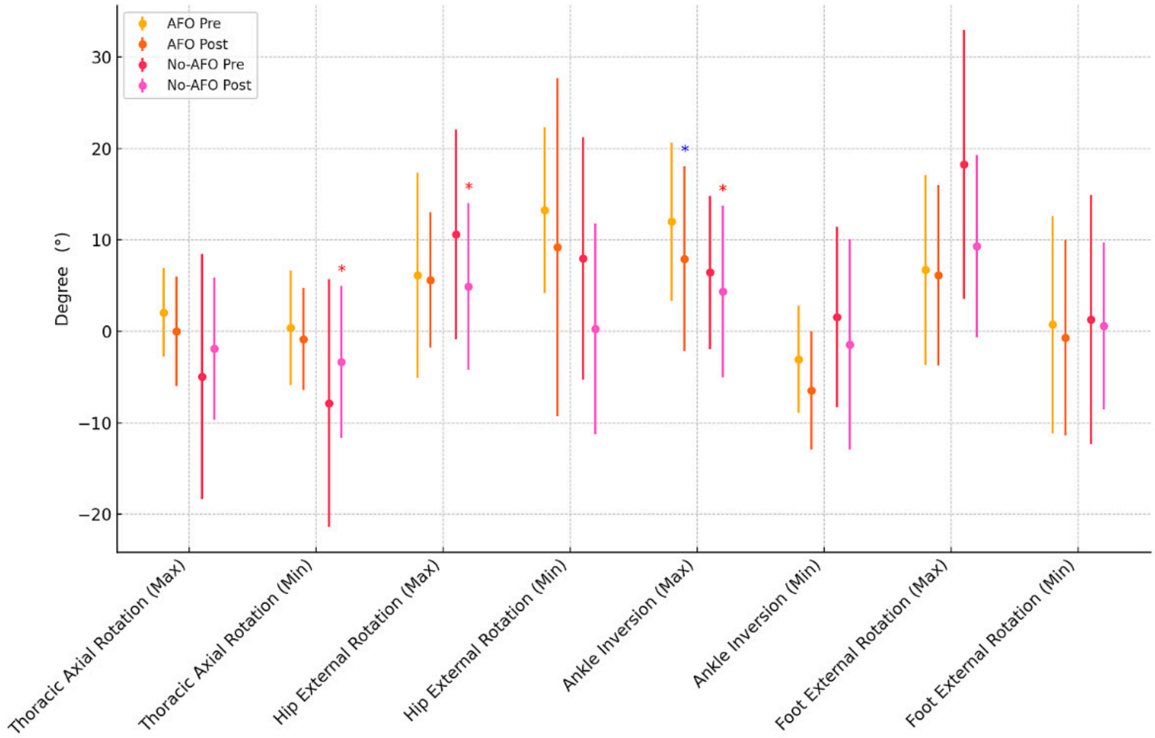

Figure 9. Differentiation of kinematic data of the less-affected side after wearing Elastic Neutral AFO at swing phase (* $p < 0.05$).

The results of the swing phase between the AFO and No-AFO groups following the application of the EN-AFO revealed significant differences in the affected limb for both maximal and minimal thoracic axial rotation ($p = 0.027$, $p = 0.012$, respectively) as well as for maximal ankle inversion ($p = 0.007$). In the less-affected limb, significant differences were also noted for maximal and minimal thoracic axial rotation ($p = 0.012$, $p = 0.009$), maximal hip external rotation ($p = 0.016$), and minimal ankle inversion ($p = 0.043$) (Table 6, Figure 11).

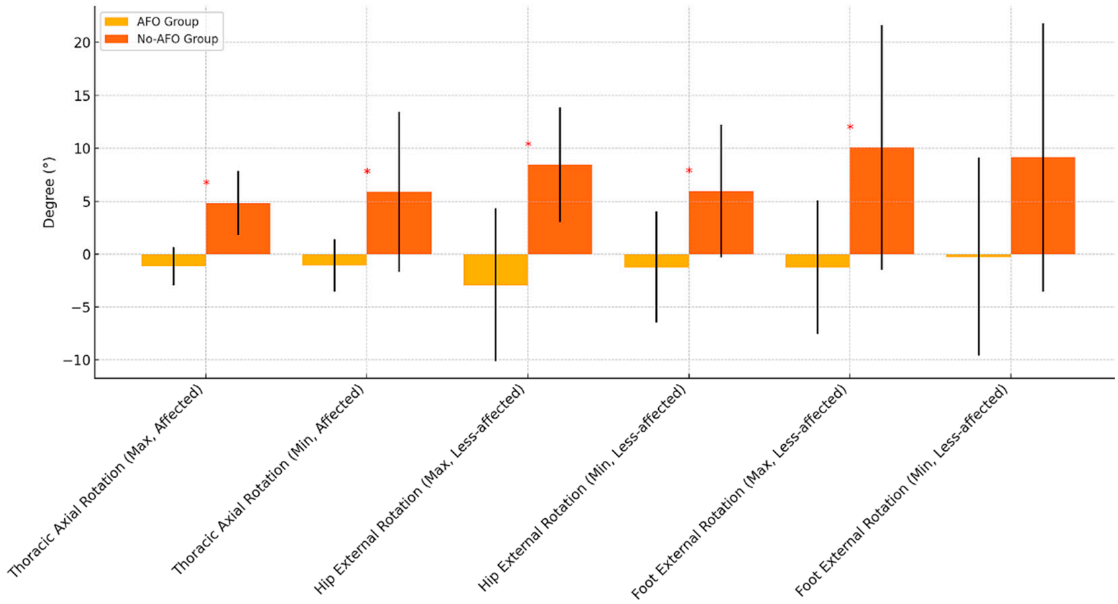

Figure 10. Differentiation of kinematic data between AFO and NO-AFO groups after wearing EN-AFO at stance phase (* $p < 0.05$).

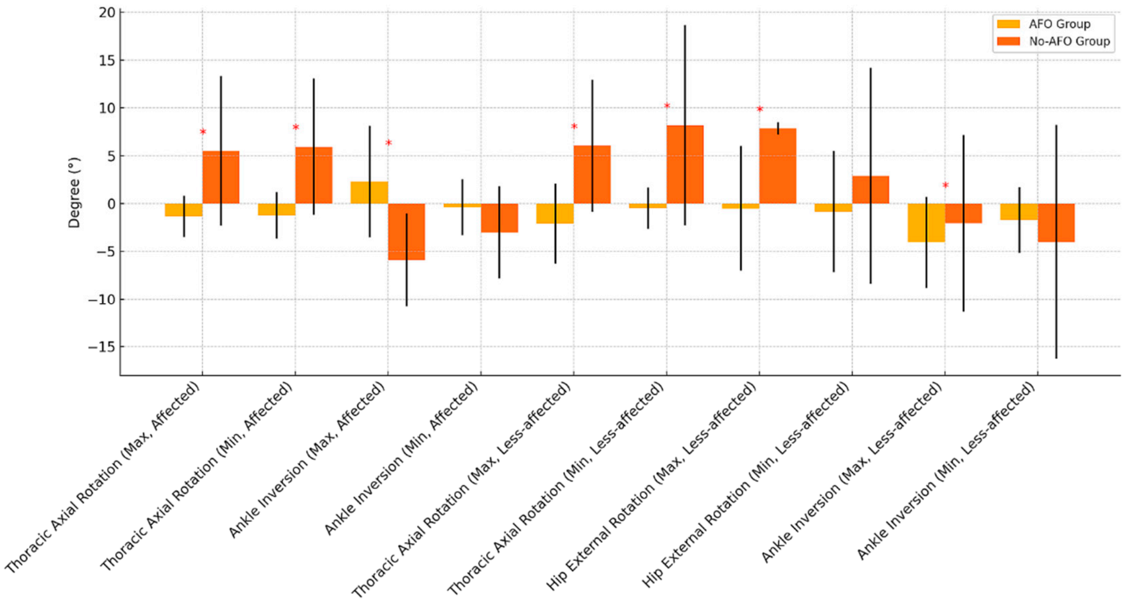

Figure 11. Differentiation of kinematic data between AFO and NO-AFO groups after wearing EN-AFO at swing phase (* $p < 0.05$).

The gait cycles of the AFO and the No-AFO groups were included in Figures 12 and 13.

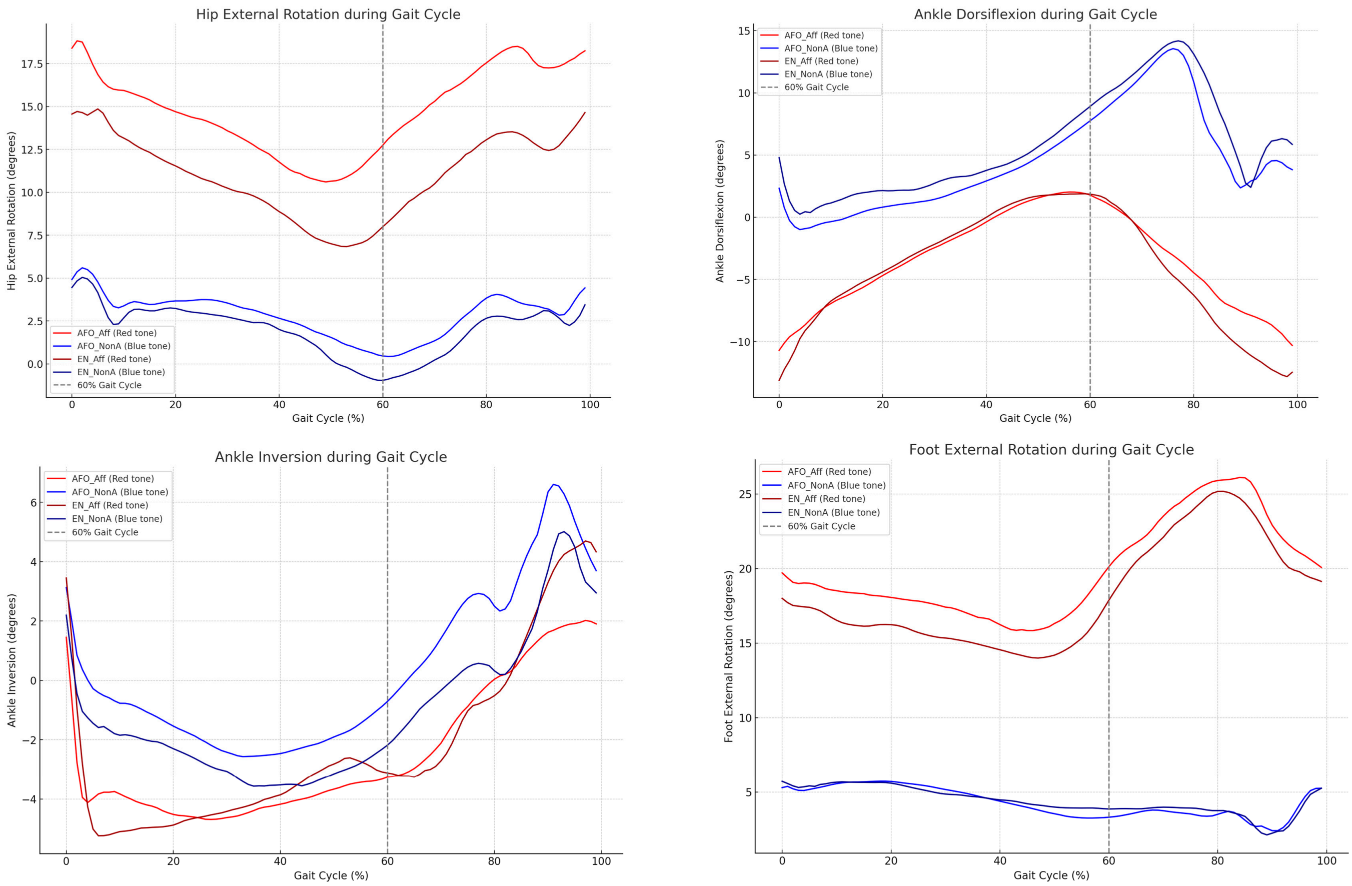

Figure 12. Gait cycle in the AFO group: hip external rotation, ankle dorsiflexion, ankle inversion and foot external rotation.

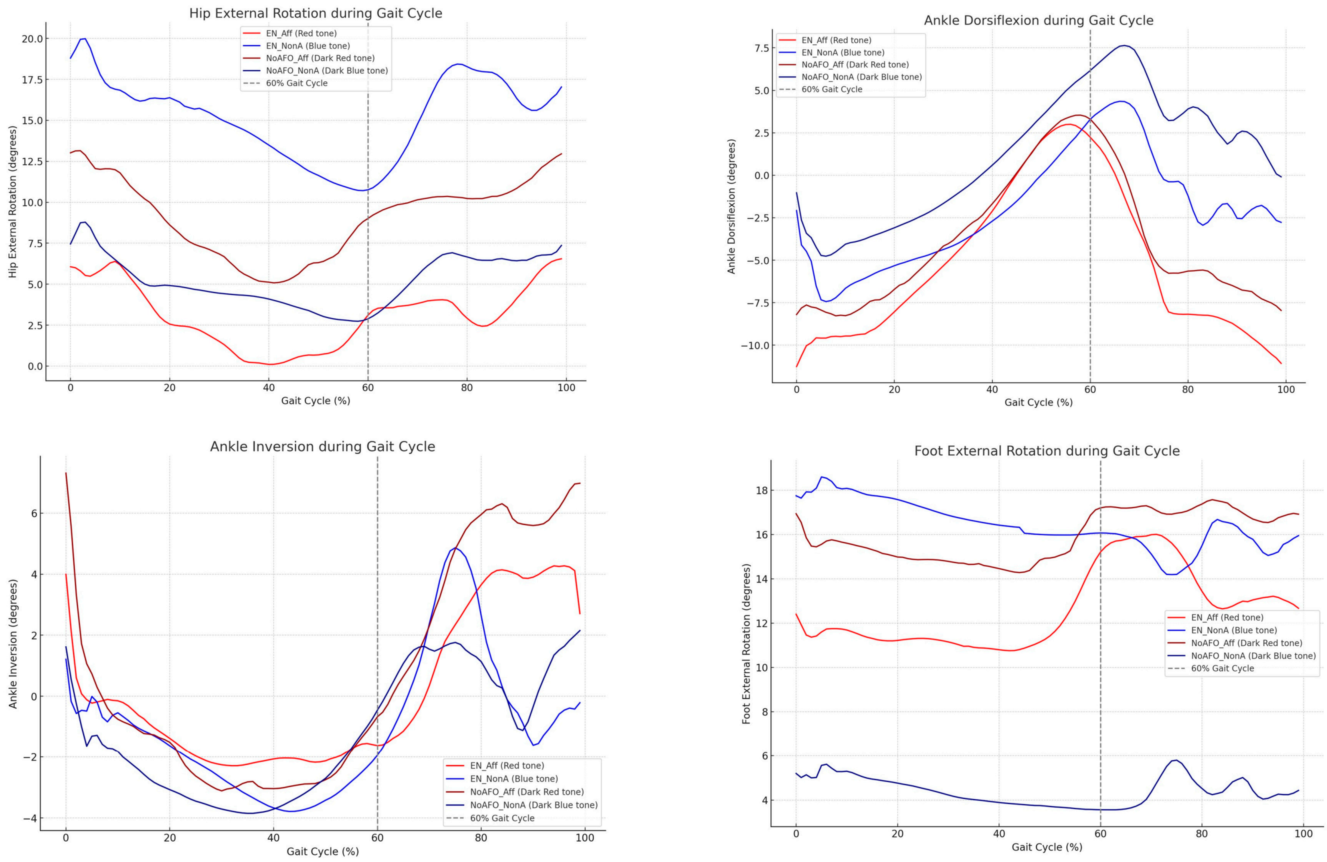

Figure 13. Gait cycle in the No-AFO group: hip external rotation, ankle dorsiflexion, ankle inversion, and foot external rotation.

4. Discussion

This study aims to investigate gait pattern differences among stroke patients with ankle inversion by dividing participants into two groups: an AFO group (walking with an ankle-foot orthosis) and a No-AFO group (capable of walking without an AFO). The analysis compares three-dimensional gait parameters during regular walking and after applying an elastic neutral AFO (EN-AFO) to assess the impact of EN-AFO use on gait patterns between the two groups.

The study results aligned with our hypothesis, showing significant kinematic changes primarily in the No-AFO group compared to the AFO group. In the No-AFO group, stance phase improvements included significant increases in maximal and minimal thoracic axial rotation on the paretic side, as well as significant increases in maximal and minimal hip external rotation and maximal foot external rotation on the less-affected side. During the swing phase, the No-AFO group showed significant improvements in maximal and minimal thoracic axial rotation on the paretic side, with a significant reduction in maximal ankle inversion. Additionally, the No-AFO group exhibited significant increases in maximal and minimal thoracic axial rotation and maximal hip external rotation on the less-affected side, while the AFO group saw a significant reduction in maximal ankle inversion.

Most stroke patients experience gait disturbances due to various factors, with impaired trunk control being a significant contributor [24–27]. Van Criekinge et al. (2017) reported that stroke patients exhibit issues with trunk rotation during gait [28]. Our findings show that the No-AFO group exhibited significantly greater changes in the maximal and minimal thoracic axial rotation values on both the affected and less-affected sides compared to the AFO group. Furthermore, within the No-AFO group, maximal thoracic axial rotation on the less-affected side shifted from a negative to a positive direction, indicating increased forward rotation. Excessive trunk rotation, which can cause gait errors in stroke patients [9], was not observed in our study, with thoracic axial rotation values remaining within a normal range of 12° seen in typical gait [29].

Our findings indicate that the group without AFO showed overall improvements in kinematic gait patterns on both the affected and less-affected sides compared to the AFO group. This suggests that EN-AFO may be effective for patients who experience ankle inversion but can walk without an AFO. Similar to the results of Hwang and Park (2021), this study observed a significant reduction in maximal ankle inversion during the swing phase on the affected side and overall kinematic improvement. Enhanced movement on the less-affected side in swing is likely due to better support from the affected side in the stance phase [30]. Footwear can also influence gait patterns, as indicated by previous research [31], and in this study, all subjects wore shoes. With AFOs, one often requires a larger shoe size [32], whereas EN-AFO comfortably fits within regular footwear. Additionally, the open heel design of the EN-AFO may stimulate proprioception, aiding in natural gait pattern recognition and encouraging a smoother gait [32–34]. Thus, for patients with ankle inversion who can ambulate without an AFO, the EN-AFO may serve as an effective assistive device to enhance kinematic gait patterns during gait training or outdoor walking.

Conversely, the AFO group comprises patients who experience significant ankle inversion and thus cannot walk without an AFO. Therefore, EN-AFO may not be a feasible substitute for patients requiring AFOs. AFOs are typically prescribed to patients with limitations in foot clearance during the swing phase, poor foot placement at initial contact, and reduced stability in the stance phase [16,35,36]. To effectively address gait issues, the mechanical properties of AFOs, especially stiffness, must be considered [37]. Material properties of AFOs influence flexibility, which in turn affects ankle mobility [38]. Consequently, the stiffness of EN-AFO may not provide adequate ankle stability for these patients. This limitation likely arises because EN-AFO's material, designed with an elastic band, promotes ankle mobility and assists ankle eversion to achieve a neutral position [10]. To apply EN-AFO in the AFO group, it would be necessary to enhance its material properties to better support ankle stability.

However, there were also notable changes observed within the AFO group when using the EN-AFO. During the swing phase, minimal ankle dorsiflexion on the affected side decreased, and maximal ankle inversion on the less-affected side significantly decreased. Additionally, peak force increased significantly at the forefoot and heel on the affected side. The significant decrease in minimal ankle dorsiflexion implies greater allowance for ankle plantarflexion, likely due to the EN-AFO's elastic band design, which contrasts with the typical restrictions of a standard AFO [10]. This aligns with prior studies reporting that braces lacking stiff materials, like plastic, tend to permit more plantarflexion in stroke patients compared to AFOs [39]. Since plantarflexion resistive stiffness in AFOs plays a crucial role during initial contact [40,41], EN-AFO may not fully replace AFO for these patients. Nonetheless, the reduction in maximal ankle inversion on the less-affected side and increased peak force at the forefoot and heel on the affected side suggest improved support on the affected side, a positive aspect to consider for future EN-AFO modifications.

Lairamore et al. (2011) reported that when comparing dynamic AFOs and passive AFOs, wearing a dynamic AFO significantly reduced the muscle activity of the tibialis anterior during the swing phase [42]. An examination of the study's participants revealed that 10 out of 15 individuals had an MMT grade of 3+ or higher for ankle dorsiflexion [42]. It is crucial to select appropriate assistive devices tailored to the patient's condition. Similar to the dynamic AFOs in the aforementioned study, the EN-AFO not only allows free forefoot movement but also facilitates dorsiflexion during the swing phase through adjustable tension in its elastic bands. In addition, its affordability makes it a practical option for gait training with physical therapists. Following such training, the EN-AFO could be replaced with a traditional AFO to ensure patient safety, presenting a feasible and cost-effective approach for clinical use.

The limitations of this study are as follows. First, the small sample size restricts the generalizability of these findings to a broader stroke patient population, necessitating future studies with larger samples. Second, due to equipment constraints, gait analysis was limited to stance and swing phases, making it challenging to assess movements essential for daily life. Including a qualitative tool, such as the Wisconsin Gait Scale [43], may allow for a more comprehensive evaluation of functional gait in stroke patients. Third, the distinction between groups wearing and not wearing AFOs lacks specificity in anatomical characteristics. Future studies should consider classifying groups using a refined scale for spasticity or functional assessment to identify appropriate candidates for EN-AFO use. In addition, as the EN-AFO was compared to the conventional passive-type AFO, future studies should include comparative analyses with various other types of AFOs to provide a more comprehensive evaluation.

5. Conclusions

This study aimed to examine changes in kinematic motion and kinetic data when using EN-AFO in patients with ankle inversion, divided into groups with and without AFOs. Results showed that in the AFO group, EN-AFO use during gait led to improved maximal ankle inversion on the less-affected side during the swing phase, though minimal ankle dorsiflexion decreased on the affected side. Conversely, the No-AFO group exhibited significant improvements in maximal and minimal thoracic axial rotation and maximal ankle inversion during the swing phase. These findings suggest that EN-AFO may be clinically applicable for improving gait patterns in stroke patients with ankle inversion who do not use AFOs.

Author Contributions: Conceptualization, D.-J.P. and Y.-I.H.; methodology, D.-J.P. and Y.-I.H.; software, D.-J.P. and Y.-I.H.; validation, D.-J.P. and Y.-I.H.; formal analysis, D.-J.P. and Y.-I.H.; investigation, D.-J.P. and Y.-I.H.; resources, Y.-I.H.; data curation, D.-J.P. and Y.-I.H.; writing—original draft preparation, D.-J.P. and Y.-I.H.; writing—review and editing, D.-J.P. and Y.-I.H.; visualization D.-J.P. and Y.-I.H.; supervision, D.-J.P. and Y.-I.H.; project administration, D.-J.P. and Y.-I.H.; funding acquisition, Y.-I.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Foundation of Korea (NRF) under grant number NRF-2019R1F1A1063237.

Data Availability Statement: Due to ethical restrictions concerning patient confidentiality, the data cannot be made available to researchers, but the data is included within the article.

Acknowledgments: Reproduced with permission from Hwang and Park, "Effects of Elastic Neutral Ankle-Foot Orthoses on 3-Dimensional Parameters During Gait Training in Patients with Stroke," published by the Journal of Bodywork and Movement Therapies, 2021. In addition, we extend our sincere gratitude to all participants for their valuable contributions to this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Laurent, G.; Valentini, F.; Loiseau, K.; Hennebelle, D.; Robain, G. Claw Toes in Hemiplegic Patients After Stroke. *Ann. Phys. Rehabil. Med.* **2010**, *53*, 77–85. [CrossRef]
2. Given, J.D.; Dewald, J.P.; Rymer, W.Z. Joint Dependent Passive Stiffness in Paretic and Contralateral Limbs of Spastic Patients with Hemiparetic Stroke. *J. Neurol. Neurosurg. Psychiatry* **1995**, *59*, 271–279. [CrossRef] [PubMed]
3. Thilmann, A.F.; Fellows, S.J.; Ross, H.F. Biomechanical Changes at the Ankle Joint After Stroke. *J. Neurol. Neurosurg. Psychiatry* **1991**, *54*, 134–139. [CrossRef] [PubMed]
4. Mandiroglu, S.; Firat, M. Foot and Ankle Deformities in Stroke: Relationship with Ambulation, Balance, and Daily Living Activities: A Cross-Sectional Study. *Somatosens. Mot. Res.* **2022**, *39*, 106–110. [CrossRef] [PubMed]
5. Li, S. Ankle and Foot Spasticity Patterns in Chronic Stroke Survivors with Abnormal Gait. *Toxins* **2020**, *12*, 646. [CrossRef]
6. Khamis, S.; Carmeli, E. A New Concept for Measuring Leg Length Discrepancy. *J. Orthop.* **2017**, *14*, 276–280. [CrossRef]
7. Andrew, A.; Bohannon, R. Short-Term Recovery of Limb Muscle Strength After Acute Stroke. *Arch. Phys. Med. Rehabil.* **2003**, *84*, 125–130. [CrossRef] [PubMed]
8. Kenney, L.; Bultstra, G.; Buschman, R. An Implantable Two-Channel Drop Foot Stimulator: Initial Clinical Results. *Artif. Organs* **2002**, *26*, 267–270. [CrossRef] [PubMed]
9. Perry, J.; Burnfield, J.M. *Gait Analysis: Normal and Pathological Function*, 2nd ed.; SLACK Incorporated: Thorfare, NJ, USA, 2010; pp. 252–290.

10. Hwang, Y.I.; Park, D.J. Effects of Elastic Neutral Ankle-Foot Orthoses on 3-Dimensional Parameters During Gait Training in Patients with Stroke: A Pilot Study. *J. Bodyw. Mov. Ther.* **2021**, *27*, 300–306. [CrossRef]
11. Bohannon, R.W.; Andrews, A.W.; Smith, M.B. Rehabilitation Goals of Patients with Hemiplegia. *Int. J. Rehabil. Res.* **1988**, *11*, 181–184. [CrossRef]
12. Ferreira, L.A.B.; Neto, H.P.; Luanda André College Grecco; Christovão, T.C.L.; Duarte, N.A.; Lazzari, R.D.; Galli, M.; Oliveira, C.S. Effect of Ankle-Foot Orthosis on Gait Velocity and Cadence of Stroke Patients: A Systematic Review. *Physiotherapy* **2013**, *25*, 1503–1508. [CrossRef] [PubMed]
13. Leung, J.; Moseley, A. Impact of Ankle-Foot Orthoses on Gait and Leg Muscle Activity in Adults with Hemiplegia: A Systematic Literature Review. *Physiotherapy* **2003**, *89*, 39–55. [CrossRef]
14. Kesikburun, S.; Yavuz, F.; Güzelküçük, Ü.; Yaşar, E.; Balaban, B. Effect of Ankle-Foot Orthosis on Gait Parameters and Functional Ambulation in Patients with Stroke. *Turk. J. Phys. Med. Rehabil.* **2017**, *3*, 143–148. [CrossRef] [PubMed]
15. Zollo, L.; Zaccheddu, N.; Ciancio, A.; Morrone, M.; Bravi, M.; Santacaterina, F.; Milazzo, M.L.; Guglielmelli, E.; Sterzi, S. Comparative Analysis and Quantitative Evaluation of Ankle-Foot Orthoses for Foot Drop in Chronic Hemiparetic Patients. *Eur. J. Phys. Rehabil. Med.* **2015**, *51*, 185–196. [PubMed]
16. Gök, H.; Küçükdeveci, A.; Altinkaynak, H.; Yavuzer, G.; Ergin, S. Effects of Ankle-Foot Orthoses on Hemiparetic Gait. *Clin. Rehabil.* **2003**, *17*, 137–139. [CrossRef] [PubMed]
17. Park, J.H.; Chun, M.H.; Ahn, J.S.; Yu, J.Y.; Kang, S.H. Comparison of Gait Analysis Between Anterior and Posterior Ankle-Foot Orthosis in Hemiplegic Patients. *Am. J. Phys. Med. Rehabil.* **2009**, *88*, 630–634. [CrossRef]
18. Mulroy, S.J.; Eberly, V.J.; Gronely, J.K.; Weiss, W.; Newsam, C.J. Effect of AFO Design on Walking After Stroke: Impact of Ankle Plantar Flexion Contracture. *Prosthet. Orthot. Int.* **2010**, *34*, 277–292. [CrossRef] [PubMed]
19. Olney, S.J.; Richards, C. Hemiparetic Gait Following Stroke: Part I: Characteristics. *Gait Posture* **1996**, *4*, 136–148. [CrossRef]
20. Woolley, S.M. Characteristics of Gait in Hemiplegia. *Top. Stroke Rehabil.* **2001**, *7*, 1–18. [CrossRef] [PubMed]
21. Struzik, A.; Konieczny, G.; Stawarz, M.; Grzesik, K.; Winiarski, S.; Rokita, A. Relationship Between Lower Limb Angular Kinematic Variables and the Effectiveness of Sprinting During the Acceleration Phase. *Appl. Bionics Biomech.* **2016**, *2016*, 7480709. [CrossRef]
22. Heuvelmans, P.; Benjaminse, A.; Bolt, R.; Baumeister, J.; Otten, E.; Gokeler, A. Concurrent validation of the Noraxon MyoMotion wearable inertial sensors in change-of-direction and jump-landing tasks. *Sports Biomech.* **2022**, 1–16. [CrossRef] [PubMed]
23. Seel, T.; Raisch, J.; Schauer, T. IMU-based joint angle measurement for gait analysis. *Sensors* **2014**, *14*, 6891–6909. [CrossRef]
24. Karthikbabu, S.; Solomon, J.M.; Manikandan, M.; Rao, B.K.; Chakrapani, M.; Nayak, A. Role of Trunk Rehabilitation on Trunk Control, Balance, and Gait in Patients with Chronic Stroke: A Pre-Post Design. *Neurosci. Med.* **2011**, *2*, 61–67. [CrossRef]
25. Verheyden, G.; Vereeck, L.; Truijen, S.; Troch, M.; Herregodts, I.; Lafosse, C.; Nieuwboer, A.; De Weerdt, W. Trunk Performance After Stroke and the Relationship with Balance, Gait, and Functional Ability. *Clin. Rehabil.* **2006**, *20*, 451–458. [CrossRef]
26. Kramers De Quervain, I.A.; Simon, S.R.; Leurgans, S.; Pease, W.S.; McAllister, D. Gait Pattern in the Early Recovery Period After Stroke. *J. Bone Jt. Surg.* **1996**, *78*, 1506–1514. [CrossRef] [PubMed]
27. Tyson, S.F. Trunk Kinematics in Hemiplegic Gait and the Effect of Walking Aids. *Clin. Rehabil.* **1999**, *13*, 295–300. [CrossRef] [PubMed]
28. Van Criekinge, T.; Saeys, W.; Hallemans, A.; Velghe, S.; Viskens, P.-J.; Vereeck, L.; De Hertogh, W.; Truijen, S. Trunk Biomechanics During Hemiplegic Gait After Stroke: A Systematic Review. *Gait Posture* **2017**, *54*, 133–143. [CrossRef] [PubMed]
29. Krebs, D.E.; Wong, D.; Jevsevar, D.; Riley, P.O.; Hodge, W.A. Trunk Kinematics During Locomotor Activities. *Phys. Ther.* **1992**, *72*, 505–514. [CrossRef]
30. Hwang, Y.-I.; An, D.-H.; Yoo, W.-G. Effects of the Dual AFO on Gait Parameters in Stroke Patients. *NeuroRehabilitation* **2012**, *31*, 387–393. [CrossRef]
31. Churchill, A.J.; Halligan, P.W.; Wade, D.T. Relative Contribution of Footwear to the Efficacy of Ankle-Foot Orthoses. *Clin. Rehabil.* **2003**, *17*, 553–557. [CrossRef]
32. Choo, Y.J.; Chang, M.C. Commonly Used Types and Recent Development of Ankle-Foot Orthosis: A Narrative Review. *Healthcare* **2021**, *9*, 1046. [CrossRef] [PubMed]
33. Lim, K.D. Ankle Mechanism of Ankle Foot Orthoses. *J. Korean Soc. Prosthet. Orthot.* **2007**, *1*, 30–37.
34. Bae, D.Y.; Shin, J.H.; Kim, J.S. Effects of Dorsiflexor Functional Electrical Stimulation Compared to an Ankle/Foot Orthosis on Stroke-Related Genu Recurvatum Gait. *J. Phys. Ther. Sci.* **2019**, *31*, 865–868. [CrossRef] [PubMed]
35. Beckerman, H.; Becher, J.; Lankhorst, G.J.; Verbeek, A.L. Walking Ability of Stroke Patients: Efficacy of Tibial Nerve Blocking and a Polypropylene Ankle-Foot Orthosis. *Arch. Phys. Med. Rehabil.* **1996**, *77*, 1144–1151. [CrossRef]
36. de Wit, D.C.; Buurke, J.H.; Nijlant, J.M.; IJzerman, M.J.; Hermens, H.J. The Effect of an Ankle-Foot Orthosis on Walking Ability in Chronic Stroke Patients: A Randomized Controlled Trial. *Clin. Rehabil.* **2004**, *18*, 550–557. [CrossRef]
37. Sumiya, T.; Suzuki, Y.; Kasahara, T. Stiffness Control in Posterior-Type Plastic Ankle-Foot Orthoses: Effect of Ankle Trimline. Part 2: Orthosis Characteristics and Orthosis/Patient Matching. *Prosthet. Orthot. Int.* **1996**, *20*, 132–137. [CrossRef] [PubMed]
38. Hsu, J.D.; Michael, J.; Fisk, J. *AAOS Atlas of Orthoses and Assistive Devices (e-Book)*; Elsevier Health Sciences: Philadelphia, PA, USA, 2008.
39. Burdett, R.G.; Borello-France, D.; Blatchly, C.; Potter, C. Gait Comparison of Subjects with Hemiplegia Walking Unbraced, with Ankle-Foot Orthosis, and with Air-Stirrup Brace. *Phys. Ther.* **1988**, *68*, 1197–1203.

40. Kobayashi, T.; Leung, A.K.L.; Akazawa, Y.; Hutchins, S.W. Design of a Stiffness-Adjustable Ankle-Foot Orthosis and Its Effect on Ankle Joint Kinematics in Patients with Stroke. *Gait Posture* **2011**, *33*, 721–723. [CrossRef] [PubMed]
41. Yamamoto, S.; Miyazaki, S.; Kubota, T. Quantification of the Effect of the Mechanical Property of Ankle-Foot Orthoses on Hemiplegic Gait. *Gait Posture* **1993**, *1*, 27–34. [CrossRef]
42. Lairamore, C.; Garrison, M.K.; Bandy, W.; Zabel, R. Comparison of tibialis anterior muscle electromyography, ankle angle, and velocity when individuals post stroke walk with different orthoses. *Prosthet. Orthot. Int.* **2011**, *35*, 402–410. [CrossRef]
43. Guzik, A.; Drużbicki, M.; Wolan-Nieroda, A.; Przysada, G.; Kwolek, A. The Wisconsin Gait Scale—The Minimal Clinically Important Difference. *Gait Posture* **2019**, *68*, 453–457. [CrossRef]