European Journal of Therapeutics
pISSN: 2564-7784
eISSN: 2564-7040

Eur J Ther. 2023;29(3):606-619.
https://doi.org/10.58600/eurjther1701

Original Research

Three-Dimensional (3D) Morphometric Analysis of Plegic and Healthy Feet of Patients with Stroke

Mehmet Karagulle[1], Yilmaz Yıldırım[2], Umut Ozsoy[2], Lutfiye Bikem Suzen[3], Hatice Ikızler May[4]

[1] Department of Physiotherapy, Antalya Bilim University, Vocational School of Health Services, Antalya Turkey
[2] Department of Anatomy, Akdeniz University, Faculty of Medicine, Antalya, Turkey
[3] Department of Anatomy, Antalya Bilim University, Faculty of Dentistry, Antalya, Turkey
[4] Department of Physical Medicine and Rehabilitation, Antalya Atatürk State Hospital, Antalya, Turkey

Received: 2023-07-11 / **Accepted**: 2023-09-05 / **Published Online**: 2023-09-05

Correspondence
Mehmet Karagülle
Address: Antalya Bilim University, Vocational School of Health Services, Physiotherapy, Antalya, Turkey
Email: mehmet.karagulle@antalya.edu.tr

ABSTRACT

Objective: This study aimed to quantitatively assess the changes in foot morphology in stroke patients using 3D scanning and focused on parameters like foot volume, area, and the root mean square difference (RMS) values. The objective was to enhance our understanding of post-stroke foot morphology and its potential relevance for rehabilitation, especially in designing orthotic supports and specialized footwear for stroke patients.

Methods: Our study involved fourteen right hemiplegia patients and twenty healthy subjects. Stroke patients were assessed using international scales. We utilized a 3D scanning device to digitize and examine the differences in foot morphology between hemiplegic and healthy subjects, analyzing the data on a computer platform.

Results: In the context of post-stroke individuals with hemiplegic feet, our morphometric analysis revealed notable differences in foot area and foot volume when compared to their healthy counterparts. These distinctions extended to linear measurements encompassing foot length, foot width, instep height, bimalleolar width, and ball width. Significantly, RMS exhibited a substantial increase in the patient cohort compared to the healthy group ($p<0.05$). Our investigation also established correlations between these standing morphometric parameters and RMS alterations, with noteworthy coefficients for various parameters: RMS(Foot Length Difference, 0.41), RMS(Foot Width Difference, 0.45), RMS(Instep Height Difference, 0.58), RMS(Ball Width Difference, 0.58), RMS(Bimalleolar Width Difference, 0.19), RMS(Volume Difference, 0.74), and RMS(Area Difference, 0.62).

Conclusion: This study suggests incorporating RMS values as a novel parameter in the evaluation process. We anticipate that these findings will have practical implications, particularly in designing orthotic supports, specialized footwear for stroke patients, and the formulation of tailored rehabilitation programs within clinical settings.

Keywords: Stroke, 3D surface scanning, Plegic foot, Foot morphology

INTRODUCTION

Stroke is a prevalent and medically significant condition characterized by a high incidence rate, substantial mortality, and the potential for severe disabilities, if not fatal [1]. Among the most frequently encountered complications in stroke patients is the functional impairment of their affected extremities, leading to a condition known as hemiplegia, which manifests as motor deficits affecting both the upper and lower limbs [2].

Stroke patients often experience difficulties related to stepping and exhibit atypical gait patterns [3]. While variations exist in the presentation of atypical gait among individual patients, common features include diminished balance reactions and reduced weight-bearing capacity on the affected side during different phases of walking. Achieving full functionality in the initial base contact and stepping phases of walking proves challenging due to factors such as muscle atrophy or spasticity within the foot, hindering the normal function of walking-related muscles [4, 5].

Various international scales are employed in managing stroke patients to facilitate effective treatment, monitor recovery progress, and make informed decisions regarding patient needs. Notable scales include the Functional Independence Measure (FIM), Six Minute Walk Test (6MWT), Berg Balance Scale (BBS), Functional Ambulation Classification (FAC), and Modified Ashworth Scale (MAS) [6].

The temporal aspect is crucial in stroke recovery, as the trajectory varies across time intervals [7]. One commonly utilized framework for assessing recovery stages is the Brunnstrom healing stages, which categorize stroke recovery into seven distinct phases [8].

Morphometric measurements of the foothold are critical in evaluating their suitability for shoe design, orthotic support, and footwear. Distinctions between right and left feet should be carefully considered in equipment designs for stroke patients [9]. The evaluation of foot morphology traditionally relies on various platforms and digital calipers [10, 11]. However, the advent of 3D analysis, driven by advancing technology, has expanded its utility across various domains. Utilizing 3D analysis in foot measurements allows for determining numerous parameters, with 3D browsers emerging as a novel technology for visualizing foot dimensions, encompassing measurements such as length, width, and height, among others [12-14]. Notably, the accuracy of measurement outcomes in traditional digital caliper methods is significantly influenced by potential localization errors [15].

Using the 3D scanning method in research has consistently demonstrated high reliability in standing morphological measurements, as evidenced by prior studies [12, 16]. Lee et al. [12] compared 3D scanning and traditional measurement techniques, concluding that the 3D method exhibited superior reliability.

Ambulation is a pivotal requirement for stroke patients and is crucial to their recovery and psychological well-being [17]. Effective shoe design for individuals post-stroke is vital in characterizing their walking patterns.

Ankle Foot Orthosis (AFO) is an essential intervention to address musculoskeletal issues, facilitating the restoration of standard walking mechanics [18]. Appropriate AFO support can significantly enhance walking independence among stroke patients [19]. Traditional AFO design typically involves multiple materials and casting, resulting in an extended production timeline. However, this approach may limit the mechanical adjustments required to meet individual patient needs [20, 21].

In the context of our research, our primary objective was to perform a quantitative assessment of post-stroke foot modifications, employing the three-dimensional (3D) scanning technique. In addition to traditional linear measurements, our study aimed to expand the existing body of knowledge by examining the relationships among foot volume, foot area, and root mean square difference values (RMS), which serve as valuable indicators of inter-foot asymmetry. This research contributes to a deeper understanding of post-stroke foot morphology and its implications for rehabilitation and orthotic support design.

MATERIALS AND METHODS

Ethical clearance for this investigation was duly secured from the Ethics Committee of Clinical Research at Akdeniz University, denoted by approval number 70904504/582, granted on the 26th of December 2018. All participating volunteers provided written informed consent. Our study cohort comprised seven male and seven female right hemiplegia patients. Additionally, measurements were obtained from thirty-four individuals, comprising ten male and ten female volunteers in the healthy control group, to ensure age-matching.

Inclusion Criteria: Right hemisphere stroke dominance (ensuring uniformity among both patients and the control group); specific reference to Brunnstrom Stages 3 or 4; the absence of any pre-existing foot trauma or post-stroke foot trauma; and the absence of any open wound that might potentially influence foot measurements are the inclusion criteria. These criteria were meticulously applied to ensure the homogeneity and appropriateness of the study cohort.

Exclusion Criteria: Patients who were contraindicated to take the supine position to be used during the study and those who were contraindicated to elevate the leg due to deep vein thrombosis were not included.

Scales Used in the Study

Modified Ashworth Scale (MAS): We used MAS to determine the level of spasticity. Since our study was based on the foot, we evaluated only ankle plantar flexor spasticity between "0" and "4" points.

Functional Independence Measure (FIM): We used the FIM to obtain information about the addiction and functionality status of the patients. We made scoring in two main sections within the FIM itself: motor scoring and cognitive scoring. We scored the sub-parameters under these two main headings according to the condition of the patients. Patients scored between "1" and "7" points. We first collected the scores obtained in each category separately and determined the FIM motor score and the FIM cognitive score. Then, we found the FIM total score by summing the FIM motor score and the FIM cognitive score.

Six-Minute Walk Test (6MWT): This test was carried out in a controlled manner on walking bars prepared for patients. Extra precautions have been taken to prevent patients from falling. Many patients rested regularly by sitting in a chair and then continued walking. At the end of 6 minutes, the distance he took was recorded on the form.

Functional Ambulation Classification (FAC): We classified the patients according to the primary motor skills required for functional ambulation. In this classification, we gave the patients scores between "0" and "5" points. While evaluating the ambulation, we evaluated by taking the necessary precautions against the risk of falling.

Berg Balance Scale (BBS): We evaluated balance with BBS in our hemiplegic patients. We gave 14 instructions to the patients and evaluated their balance in these instructions by scoring between "0" and "4" points. Afterward, we determined the BBS total score by adding up the scores obtained in each directive.

Foot Evaluation Procedure with 3D Method

Each volunteer's foot was scanned using a 3D scanner. Scanning was supine, with the feet protruding from the bed just above the ankle level (Figure 1). After the patients and healthy volunteers in the control group were supine, a full rotation was made around the foot with the scanner. This way, images of both the right and left feet were taken. Each foot scan took about 40 seconds. The 3D scanned images were subjected to a series of processing in STL format with Artec Studio 11 software (version 11.2.2.16; licensed by Artec Group, Luxembourg).

Figure 1. 3D foot scan position.

Image Processing

First, global registration was made, and then the surface was created with sharp fusion. This image was cropped from the malleolus level. After that, A working image was created by applying a small object filter and mesh simplification. Then, the measurement process was started. For linear measurements, clicking on the measurement tab and selecting two points is necessary. The distance measurements between these two points were made by clicking make another sequentially. The volume and area measurement was made from the measurement section. RMS (Mean Square Root Difference Value): A statistical criterion used to measure the magnitude of changing quantities, the square root of the mean value of the square function of the instantaneous values is the RMS value. Differences between right and left feet were calculated using RMS. After scanning both feet, a mirror image of one foot was taken.

In order to calculate the RMS value, both images should be similar to each other as a protocol. Therefore, it is necessary to create a mirror image using Autodesk Netfabb software (Netfabb, Parsberg, Germany, Free trial version) and then transfer it to Artec Studio 11 software [22]. In our study, a mirror image of the left foot was taken.

Two comparable images are superimposed to analyze asymmetry. The RMS value is used to assess shape differences quantitatively. This number represents the difference between two 3D surfaces and illustrates how different or similar the compared shapes are. Higher values represent more diversity, while lower values represent more similar shapes than the compared one. The program produces maps of color deviation. These maps offer a quick analysis using color to highlight the differences between the two surfaces. Blue, which represents a negative distance, is replaced by red, which represents a positive distance, on the map. Green indicates that the difference between the surfaces is almost zero at this point [23]. In our research, the left and right foot mirror images were superimposed, and color deviation maps were created (Figure 2).

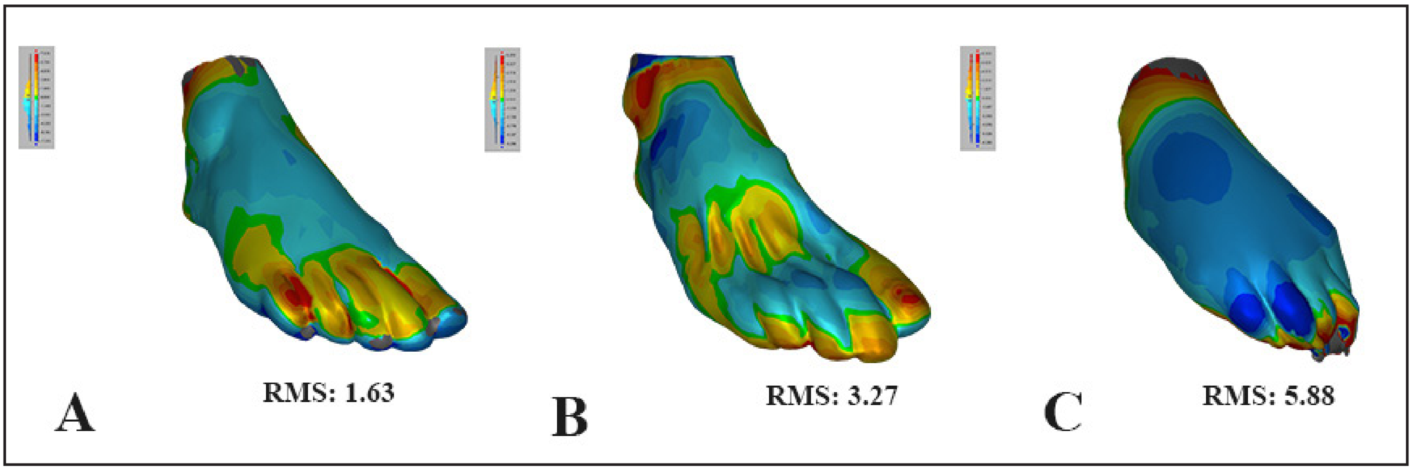

Figure 2. Color distance maps and RMS values. Green areas indicate no change. It shows a positive change as the color changes from green to yellow and red. As the darkness of the blue increases, it changes in the negative direction (A- Low RMS, B- Medium RMS, C-High RMS).

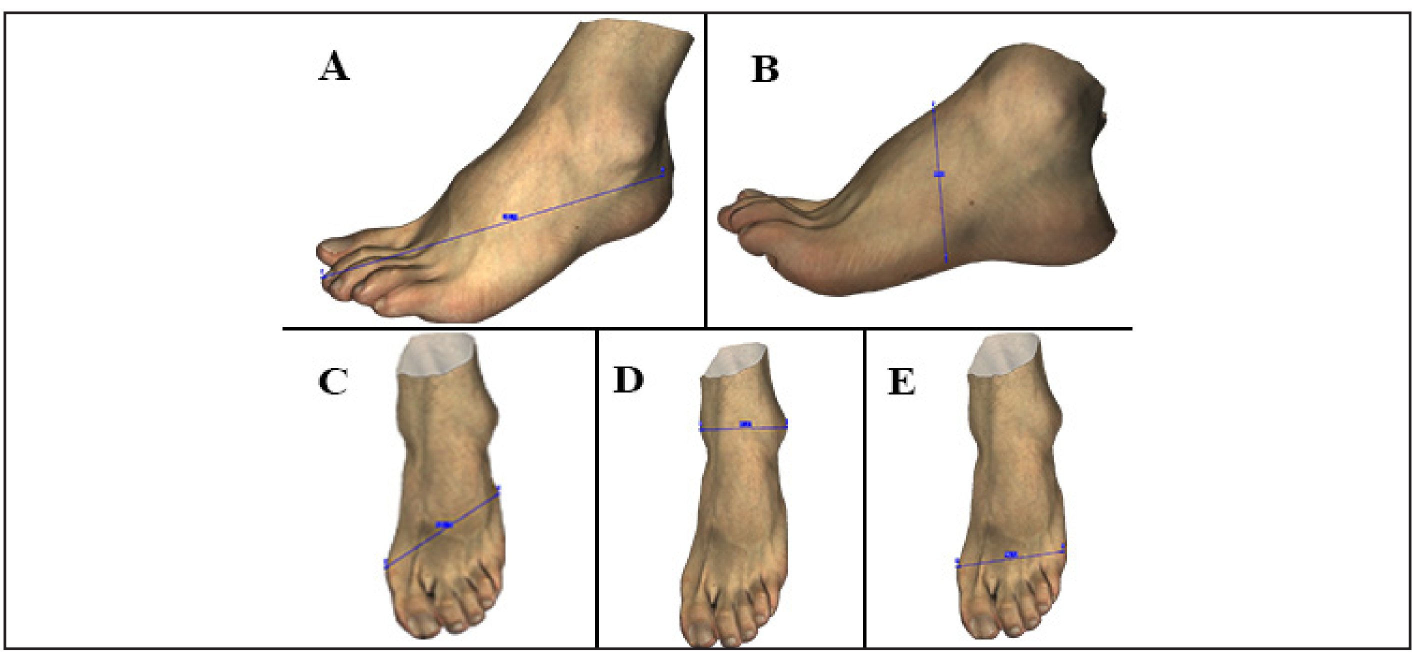

Figure 3. Linear measurements (A: Foot length, B: Instep height, C: Foot width, D: Bimalleolar width, E: Ball width)

Morphological Measurements

Foot length, foot width, instep height, bimalleolar width, and ball width were measured linearly. In addition to these, foot area and foot volumes are also morphological measurements provided by 3D scanning.

Foot length: The distance measured along the axis of the foot between the most posterior point of the foot (pterion) and the tip of the second toe (Figure 3-A).

Instep height: It is the distance between the sole and the vertical top of the dorsum of the foot (Figure 3-B).

Foot width: It is the distance between the most protruding points of the foot, medially and laterally (Figure 3-C).

Bimalleolar width: The distance between the most protruding points of the medial and lateral malleolus (Figure 3-D).

Ball width: The distance measured between the first metatarsal head's most protruding point and the fifth metatarsal head (Figure 3-E).

Foot area: The total area of the foot was calculated from the malleolus level.

Foot volume: The total volume of the foot was calculated from the malleolus level.

Statistical Analysis

SPSS 23.0 package program was used in the analysis. The assumption of normal distribution was checked with the Shapiro-Wilk test. T-test was performed if normal distribution was provided, and the Mann-Whitney U test was performed if not. Spearman correlation test was used because there was no normal distribution in the correlation. In statistical data, $p<0.05$ was considered statistically significant.

RESULTS

Our patients are fourteen right-stroke cases, seven women and seven men. We evaluated the general condition of selected patients in these groups using internationally used scales such as FIM, MAS, BBS, 6MWT, and FAC. These scales provided information about the patient's general condition (Table 1).

3D Scan Findings

Morphometric measurements of the foot were made on both feet in both the control group and the stroke patient group. First, the general averages were taken, and then the difference analysis process was started. In order to examine the significance of the study, the difference between the right and left feet was taken.

The dominant side is the right side in our study's control and patient group volunteers. While taking the difference operation, all the parameters of the control group were examined first, and with minor exceptions, the numerical magnitude was observed in the parameters of the right feet compared to the left feet.

Table 1. Scale results

		Count	Column N %	Valid N	Mean	Standard Deviation	Median	Percentile 25	Percentile 75
GENDER	male	7	50.0%						
	female	7	50.0%						
MAS (0-4)	1	6	42.9%						
	1+	5	35.7%						
	2	3	21.4%						
FIM MOTOR (0-91)				14	63.93	11.73	66.50	60.00	71.00
FIM TOTAL (0-126)				14	93.07	14.00	97.00	87.00	100.00
FAC (0-5)				14	3.21	1.31	3.50	3.00	4.00
BBS (0-56)				14	29.29	11.36	32.50	25.00	35.00
6MWT (METER)				14	47.00	21.71	55.50	40.00	60.00

Therefore, the difference operation is obtained by subtracting the left foot's numerical parameters from the right foot's numerical parameters. For standardization in our study, only right-stroke patients were included in the study, and the measurement parameters of the healthy left foot were subtracted from the measurement parameters of the dominant right plegic foot, and the difference process was created. The overall mean values for linear measurements are given in Table 2, and the difference values are given in Table 3. Mean values and difference values of area, volume, and RMS measurements are given in Table 4.

After taking the differences in the parameters, their significance was examined. After the statistical analysis, our study was found to be significant regarding the change in the difference value parameters ($p<0.05$). In other words, when the difference between the right and left feet of the control group and the difference between the right and left feet of the stroke group were examined, the right foot of the stroke group decreased significantly compared to the left foot (Tables 5 and 6).

There was no significant difference between the linear measurements of the left feet of both groups. In addition, when the measurements of the left feet of both groups, such as area and volume, are examined, there is no significant difference. This means that we created a comparison group that is close to each other regarding the left feet of our volunteers (Tables 5 and 6).

Table 2. Linear measurement results of right and left feet

		GROUP					
		Valid N	Mean	Standard Deviation	Median	Percentile 25	Percentile 75
Right foot length (cm)	Control	20	23.06	1.64	22.50	21.76	24.62
	Stroke	14	22.21	1.94	21.54	20.79	22.72
Left foot length (cm)	Control	20	22.85	1.67	22.37	21.42	24.42
	Stroke	14	22.74	1.65	22.52	21.63	23.22
Right foot width (cm)	Control	20	9.22	.51	9.11	8.79	9.70
	Stroke	14	8.94	0.75	9.01	8.38	9.50
Left foot width (cm)	Control	20	9.17	0.53	9.10	8.70	9.61
	Stroke	14	9.15	0.73	9.17	8.42	9.67
Right instep height (cm)	Control	20	8.11	0.88	8.34	7.74	8.55
	Stroke	14	7.43	0.56	7.57	7.12	7.83
Left instep height (cm)	Control	20	8.08	0.83	8.27	7.75	8.52
	Stroke	14	7.60	0.57	7.64	7.29	8.12
Right ball width (cm)	Control	20	8.23	0.81	8.03	7.55	8.54
	Stroke	14	8.07	0.66	7.89	7.60	8.23
Left ball width (cm)	Control	20	8.16	0.81	7.93	7.50	8.73
	Stroke	14	8.26	0.63	8.15	7.82	8.51
Right bimalleolar width (cm)	Control	20	7.32	0.48	7.25	6.97	7.65
	Stroke	14	7.08	0.68	6.93	6.50	7.81
Left bimalleolar width (cm)	Control	20	7.28	0.51	7.27	6.89	7.60
	Stroke	14	7.24	0.81	6.99	6.51	8.13

When we examined the right feet of both groups, there was no significant change in linear measurements in foot width, ball width, and bimalleolar width. However, there was a significant ($p<0.05$) change in instep height and a statistically marginal change in foot length ($p=0.61$). This means that the plegic feet are remarkably reduced in length and height. When the evaluation was made between the right and left foot, the RMS values were checked to see this change. A significant difference was found between the RMS values of the feet of healthy volunteers and the RMS values of the patients with stroke (Table 5) in terms of the RMS value, which is one of the most critical aspects of our study, in which the difference between the two feet is evaluated ($p<0.05$).

Correlation Evaluation

We examined the correlation between the standing difference values and the RMS. We found significant correlations between the morphometric difference values measured in the standing position and the change in the RMS value. RMS (Foot Length Difference, r =0.41), RMS (Foot Width Difference, r=0.45), RMS (İnstep Height Difference, r =0.58), RMS (Ball Width Difference, r =0.58), RMS (Volume Difference, r =0.74), RMS (Area Difference, r =0.62). This proves that the RMS value is a clinical finding that can quantitatively show the change in the foot. There was no significant correlation between only bimalleolar width difference and RMS (r =0.19). This is because the measurement of bone structures is at the forefront in the measured distance between the malleolus (Table 7).

Table 3. Difference values between right feet and left feet

		GROUP					
		Valid N	Mean	Standard Deviation	Median	Percentile 25	Percentile 75
Foot length difference (cm)	Control	20	0.14	0.24	0.11	0.05	0.25
	Stroke	14	-0.53	0.78	-0.34	-0.83	-0.03
Foot width difference (cm)	Control	20	0.06	0.17	0.07	0.04	0.19
	Stroke	14	-0.21	0.16	-0.19	-0.37	-0.09
Instep height difference (cm)	Control	20	0.03	0.16	0.04	0.00	0.13
	Stroke	14	-0.17	0.15	-0.10	-0.28	-0.06
Ball width difference (cm)	Control	20	0.07	0.14	0.07	0.05	0.12
	Stroke	14	-0.19	0.10	-0.20	-0.28	-0.08
Bimalleolar width difference (cm)	Control	20	0.04	0.10	0.03	-0.01	0.08
	Stroke	14	-0.16	0.21	-0.09	-0.32	-0.05

Table 4. Volume and area of the right and left feet and RMS value with the area and volume difference values of the feet

		GROUP					
		Valid N	Mean	Standard Deviation	Median	Percentile 25	Percentile 75
Right foot volume (cm^3)	Control	20	965.42	157.62	954.02	843.33	1038.80
	Stroke	14	866.81	193.44	853.63	696.20	1051.96
Left foot volume (cm^3)	Control	20	937.26	154.53	940.16	804.15	1005.53
	Stroke	14	925.39	189.75	899.44	768.15	1113.62
Foot volume difference (cm^3)	Control	20	28.16	39.43	31.71	4.31	43.05
	Stroke	14	-58.58	31.09	-49.88	-59.99	-44.13
Right foot area (cm^2)	Control	20	670.50	101.09	651.21	605.74	711.20
	Stroke	14	608.85	73.95	608.94	535.54	670.33
Left foot area (cm^2)	Control	20	642.14	73.88	633.18	579.38	684.88
	Stroke	14	653.07	79.54	674.62	586.28	713.92
Foot area difference (cm^2)	Control	20	28.36	72.18	15.30	-1.78	31.12
	Stroke	14	-44.22	32.86	-32.55	-71.99	-21.46
RMS value	Control	20	2.83	0.62	2.78	2.48	3.31
	Stroke	14	3.93	0.84	3.61	3.27	4.31

Table 5. Comparison of the mean values of the right and left feet of the control group and the stroke group and the comparison of the difference values of the feet (parameters that do not provide normal distribution)

Test Statistics[a]											
	Right foot length (cm)	**Right foot width (cm)**	**Foot width difference (cm)**	**Instep height difference (cm)**	**Right ball width (cm)**	**Ball width difference (cm)**	**Right bimalleolar width (cm)**	**Bimalleolar width difference (cm)**	**Volume difference (cm^3)**	**Area difference (cm^2)**	**RMS value**
Mann-Whitney U	86.500	109.000	29.500	21.500	125.500	14.000	112.000	47.000	13.000	9.000	38.000
Wilcoxon W	191.500	214.000	134.500	126.500	230.500	119.000	217.000	152.000	118.000	114.000	248.000
Z	-1.872	-1.085	-3.873	-4.149	-.508	-4.413	-.980	-3.258	-4.444	-4.584	-3.570
Asymp. Sig. (2-tailed)	0.061	0.278	0.000	0.000	0.612	0.000	0.327	0.001	0.000	0.000	0.000
Exact Sig. [2*(1-tailed Sig.)]	0.061	0.290	0.000	0.000	0.616	0.000	0.341	0.001	0.000	0.000	0.000

Table 6. Comparison of the mean values of the right and left feet of the control group and the stroke group and the comparison of the difference values of the feet (Parameters providing normal distribution)

Independent Samples Test									
	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Left foot length (cm)	0.291	0.593	0.192	32	0.849	0.11136	0.57967	-1.06938	1.29210
			0.193	28.343	0.849	0.11136	0.57846	-1.07292	1.29563
Foot length difference (cm)	8.421	0.007	3.622	32	0.001	0.66571	0.18379	0.29134	1.04009
			3.111	14.746	0.007	0.66571	0.21401	0.20889	1.12254
Left foot width (cm)	0.995	0.326	0.091	32	0.928	0.01957	0.21589	-0.42018	0.45933
			0.086	22.456	0.932	0.01957	0.22806	-0.45283	0.49198
Right instep height (cm)	1.902	0.177	2.551	32	0.016	0.68171	0.26718	0.13748	1.22595
			2.760	31.741	0.010	0.68171	0.24701	0.17842	1.18501
Left instep height (cm)	1.330	0.257	1.882	32	0.069	0.48157	0.25585	-0.03958	1.00273
			2.007	32.000	0.053	0.48157	0.23992	-0.00713	0.97027
Left ball width (cm)	1.916	0.176	-0.391	32	0.698	-0.10071	0.25767	-0.62558	0.42415
			-0.408	31.506	0.686	-0.10071	0.24675	-0.60363	0.40220
Left bimalleolar width (cm)	8.664	0.006	0.147	32	0.884	0.03336	0.22739	-0.42981	0.49653
			0.136	20.225	0.893	0.03336	0.24589	-0.47920	0.54591
Right foot volume (cm^3)	2.063	0.161	1.635	32	0.112	98.61193	60.30782	-24.23107	221.45493
			1.576	24.300	0.128	98.61193	62.56963	-30.44119	227.66505
Left foot volume (cm^3)	2.622	0.115	0.201	32	0.842	11.87657	59.14136	-108.59044	132.34358
			0.194	24.290	0.848	11.87657	61.36512	-114.69482	138.44796
Right foot area (cm^2)	0.738	0.397	1.943	32	0.061	61.64214	31.72690	-2.98345	126.26773
			2.053	31.904	0.048	61.64214	30.02689	0.47212	122.81217
Left foot area (cm^2)	0.764	0.389	-0.412	32	0.683	-10.93500	26.56221	-65.04045	43.17045
			-0.406	26.765	0.688	-10.93500	26.92087	-66.19479	44.32479

Table 7. Correlation diagram

			RMS value	Foot length difference (cm)	Foot width difference (cm)	Instep height difference (cm)	Ball width difference (cm)	Bimalleolar width difference (cm)	Foot volume difference (cm³)	Foot area difference (cm²)
Spearman's rho	RMS value	Correlation Coefficient	1.000	-0.411	-0.451	-0.585	-0.588	-0.193	-0.745	-0.627
		Sig. (2-tailed)		0.016	0.007	0.000	0.000	0.509	0.000	0.000
		N	34	34	34	34	34	34	34	34
	Foot length difference (cm)	Correlation Coefficient	-0.411	1.000	0.470	0.524	0.508	0.197	0.505	0.607
		Sig. (2-tailed)	0.016		0.005	0.001	0.002	0.500	0.002	0.000
		N	34	34	34	34	34	34	34	34
	Foot width difference (cm)	Correlation Coefficient	-0.451	0.470	1.000	0.581	0.732	0.060	0.617	0.635
		Sig. (2-tailed)	0.007	0.005		0.000	0.000	0.839	0.000	0.000
		N	34	34	34	34	34	34	34	34
	Instep height difference (cm)	Correlation Coefficient	-0.585	0.524	.581	1.000	.770	.339	.816	.791
		Sig. (2-tailed)	0.000	0.001	.000		.000	.236	.000	.000
		N	34	34	34	34	34	34	34	34
	Ball width difference (cm)	Correlation Coefficient	-0.588	0.508	0.732	0.770	1.000	0.022	0.734	0.712
		Sig. (2-tailed)	0.000	0.002	0.000	0.000		0.940	0.000	0.000
		N	34	34	34	34	34	34	34	34
	Bimalleolar width difference (cm)	Correlation Coefficient	-0.193	0.197	0.060	0.339	0.022	1.000	-0.128	0.190
		Sig. (2-tailed)	0.509	0.500	0.839	0.236	0.940		0.662	0.515
		N	34	34	34	34	34	34	34	34
	Foot volume difference (cm³)	Correlation Coefficient	-0.745	0.505	0.617	0.816	0.734	-0.128	1.000	0.935
		Sig. (2-tailed)	0.000	0.002	0.000	0.000	0.000	0.662		0.000
		N	34	34	34	34	34	34	34	34
	Foot area difference (cm²)	Correlation Coefficient	-0.627	0.607	0.635	0.791	0.712	0.190	0.935	1.000
		Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.515	0.000	
		N	34	34	34	34	34	34	34	34

DISCUSSION

Our study's utilization of the 3D scanning technique conferred a notable advantage by facilitating a more comprehensive analysis. In contrast to the conventional approach employing calipers and platforms for measurements, the 3D scanning method offered the capability to conduct multiple measurements within the same timeframe. Consequently, this approach enabled the replication of measurements and permitted the assessment of parameters such as volume, area, and RMS, which are otherwise unattainable through traditional methodologies. [12, 21, 23].

The application of 3D scanning affords flexibility in conducting imaging procedures, permitting data acquisition at the researcher's discretion, with the frequency of scans being adaptable. In contrast to techniques focused solely on analyzing select points on the dorsal surface, the 3D methodology comprehensively assesses the back surface by scrutinizing approximately thirty thousand data points (vertex). Notably, the hand-held scanner can be employed in hospital and polyclinic settings, obviating the necessity for specialized laboratory conditions. Furthermore, the device facilitates the examination of patients in their preferred bodily positions, enhancing clinical versatility and patient comfort. [22].

Surface scanning presents a significant innovation by generating colored surface deviation maps, which offer a valuable tool for identifying alterations and deformation regions within the foot. This map enables a streamlined visual assessment of the extent of deformation, quantified as the RMS value, thereby facilitating meaningful comparisons and analytical insights.[23].

The image processing process of the 3D method takes a relatively long time. In our study, it took an average of 10 minutes to process the image of a foot. This image processing can be learned quickly, but it takes time to gain experience. As experience increases, image processing can be faster [22, 23].

Several 3D scanning investigations have previously explored foot morphology aspects within the existing literature. These studies have predominantly concentrated on assessing disparities in foot structure between genders, employing parameters such as foot length, foot width, bimalleolar width, and instep height as crucial metrics. Moreover, findings from these studies have been instrumental in informing endeavors related to footwear design and the development of supplementary equipment, notably AFO, contributing to advancements in the field. [24-27].

In a study conducted by Saghazadeh et al.[26] the feet of 151 male and 140 female healthy elderly Japanese volunteers underwent comprehensive 3D scanning. The principal objective of this investigation was to employ 3D scanning technology to assess and discern disparities in foot morphology between males and females. The study's findings unequivocally underscored the observation that, on average, male foot dimensions were appreciably more prominent than their female counterparts.

In the research conducted by Chiroma et al. [24], which involved a comparative analysis of foot anthropometry among individuals aged 18-45 in Nigerian society, noteworthy findings were observed. Specifically, their study revealed that male participants exhibited notably higher numerical values in measurements related to instep height, foot length, and foot width when compared to their female counterparts.

Li et al. [13] employed a 3D scanning methodology to investigate foot anthropometric measurements in the context of elderly individuals in Hong Kong, specifically focusing on its implications for shoe design. Their study encompassed 49 volunteers, involving 98 feet, categorized into 26 healthy feet and 72 deformed feet based on physical examinations. Notably, our attention was drawn to the approach employed in Li's study, which primarily relied on physical examinations for classification. We assert that the exclusive reliance on physical examination may introduce subjective elements into the dataset about foot conditions. In contrast, in our investigation, a deliberate effort was made to enhance objectivity in selecting healthy volunteers. We rigorously established inclusion criteria, deliberately choosing fully healthy, non-deformed feet as the basis for comparison. Furthermore, within the patient group, we adhered to internationally recognized scales to ensure that individuals at equivalent levels of impairment were included in our study cohort, further enhancing our findings' comparability and scientific rigor.

In the study conducted by Liu et al. [25], a cohort comprising 12 stroke patients underwent 3D foot scans, with the primary objective of employing the acquired scan data to design AFO tailored to individual patients. 3D scanning technology in this clinical context facilitated the creation of AFO designs that exhibited enhanced functionality, marking a noteworthy advancement in patient-specific orthotic interventions.

In contrast to previous 3D studies focused on foot morphology, our present study incorporates a more comprehensive evaluation by considering key parameters such as foot volume, area, and RMS values. This holistic approach enhances the versatility of foot examination and serves as a valuable contribution to the existing literature. It is important to note that measuring area, volume, and RMS parameters necessitates a more significant investment of time and demands more expertise than conventional parameters like foot length, width, and height. However, this more nuanced assessment provides a deeper understanding of foot characteristics and has the potential to yield valuable insights for clinical and research purposes.

Using 3D scans of the feet enables the design of personalized footwear. Mickle et al. [28] observed significant foot morphology alterations in elderly individuals through 3D foot scanning, emphasizing the necessity for shoe designs that accommodate these changes. Our study similarly highlights morphological foot changes in elderly stroke patients, suggesting the potential requirement for specialized footwear. 3D scanning serves as a promising method for crafting such tailored footwear.

Yamashito et al. [29] used a smartphone to capture two-dimensional foot images and convert them into 3D representations within a computer environment. In contrast, our study directly acquired 3D images utilizing a dedicated 3D scanner. This approach affords distinct advantages, enabling precise parameter measurements such as area, volume, and RMS, which can be presented as comprehensive working data. It is noteworthy to distinguish our approach from that of Yamashito et al., who employed two-dimensional smartphone imaging and 3D reconstruction in a computer environment. In contrast, our study directly recorded 3D images using a dedicated 3D scanner, allowing for the presentation of parameters such as area, volume, and RMS as precise and comprehensive working data. This methodological distinction underscores the advantages of direct 3D scanning in facilitating a more detailed and accurate assessment of foot morphology.

However, our study does have notable limitations. It was exclusively conducted on volunteers with right hemiplegia, warranting further research encompassing a larger cohort that includes individuals with left hemiplegia to enhance the breadth of insights. Although essential, participants need to maintain stillness during the evaluation process may pose challenges for stroke patients and introduce motion artifacts, necessitating re-shooting in such instances. Additionally, due to registration difficulties, our study's limited number of patients underscores the need for future investigations with larger sample sizes to bolster the scientific literature. Furthermore, our study exclusively included patients within Brunnstrom stages 3 and 4 for homogeneity, yet exploring changes in patients with more severe or improved conditions could provide valuable insights. We hypothesize that RMS values may vary, with higher values associated with more severe atrophy or spasticity and lower values in patients in advanced recovery stages. Addressing this knowledge gap requires further studies to refine our understanding. The scarcity of existing research in this domain presents challenges regarding comparisons. Nevertheless, our study, which contrasts the hemiplegic foot with the healthy foot within stroke patients and compares both to healthy volunteer feet, generates data that can be valuable across multiple domains.

CONCLUSION

Our research offers a 3D analysis and quantitative evaluation of changes in hemiplegic feet. Linear measurements and parameters such as area, volume, and RMS present novel avenues for assessment. We anticipate that our findings will contribute to developing orthotic supports, specialized footwear design for patients, and the formulation of tailored rehabilitation programs within clinical settings.

Conflict of interest: There is no conflict of interest.

Funding: We declare that there is no financial support.

Author Contributions: Conception: MK, LBS - Design: MK, LBS, HİM -Materials: MK, UO, HİM - Data Collection and/or Processing MK, YY - Analysis and/or Interpretation: MK, UO - Literature: MK, LBS, UO, YY - Review: MK, Writing: MK, YY.

Ethical Approval: Ethics Committee of Clinical Research at Akdeniz University approved the study protocol 70904504/582 on the 26th of December 2018.

REFERENCES

[1] Duncan PW, Zorowitz R, Bates B, Choi JY, Glasberg JJ, Graham GD, Katz RC, Lamberty K, Reker D (2005) Management of Adult Stroke Rehabilitation Care: a clinical practice guideline. Stroke 36:e100-143. https://doi.org/10.1161/01.STR.0000180861.54180.FF

[2] Feigin VL, Krishnamurthi RV, Parmar P, Norrving B, Mensah GA, Bennett DA, Barker-Collo S, Moran AE, Sacco RL, Truelsen T, Davis S, Pandian JD, Naghavi M, Forouzanfar MH, Nguyen G, Johnson CO, Vos T, Meretoja A, Murray CJ, Roth GA, Group GBDW, Group GBDSPE (2015) Update on the Global Burden of Ischemic and Hemorrhagic Stroke in 1990-2013: The GBD 2013 Study. Neuroepidemiology 45:161-176. https://doi.org/10.1159/000441085

[3] Pohl M, Mehrholz J, Ritschel C, Ruckriem S (2002) Speed-dependent treadmill training in ambulatory hemiparetic stroke patients: a randomized controlled trial. Stroke 33:553-558. https://doi.org/10.1161/hs0202.102365

[4] De Quervain IA, Simon SR, Leurgans S, Pease WS, McAllister D (1996) Gait pattern in the early recovery period after stroke. J Bone Joint Surg Am 78:1506-1514. https://doi.org/10.2106/00004623-199610000-00008

[5] Hachisuka K, Umezu Y, Ogata H (1997) Disuse muscle atrophy of lower limbs in hemiplegic patients. Arch Phys Med Rehabil 78:13-18. https://doi.org/10.1016/s0003-9993(97)90003-4

[6] May Hİ, Özdolap Ş, Mengi A, Sarıkaya S (2020) The effect of mirror therapy on lower extremity motor function and ambulation in post-stroke patients: A prospective, randomized-controlled study. Turk J Phys Med Rehabil 66:154. https://doi.org/10.5606/tfrtd.2020.2719

[7] Frizzell JP (2005) Acute stroke: pathophysiology, diagnosis, and treatment. AACN Clin Issues 16:421-440; quiz 597-428. https://doi.org/10.1097/00044067-200510000-00002

[8] Brunnstrom S (1966) Motor testing procedures in hemiplegia: based on sequential recovery stages. Phys Ther 46:357-375. https://doi.org/10.1093/ptj/46.4.357

[9] Wang C-S (2010) An analysis and evaluation of fitness for shoe lasts and human feet. J Compind 61:532-540. https://doi.org/10.1016/j.compind.2010.03.003

[10] Krishan K, Sharma A (2007) Estimation of stature from dimensions of hands and feet in a North Indian population. J Forensic Leg Med 14:327-332. https://doi.org/10.1016/j.jcfm.2006.10.008

[11] McPoil TG, Vicenzino B, Cornwall MW, Collins N (2009) Can foot anthropometric measurements predict dynamic plantar surface contact area? J Foot Ankle Res 2:28. https://doi.org/10.1186/1757-1146-2-28

[12] Lee Y-C, Lin G, Wang M-JJ (2014) Comparing 3D foot scanning with conventional measurement methods. J Foot Ankle Res 7:1-10. https://doi.org/10.1186/s13047-014-0044-7

[13] Li P-L, Yick K-L, Ng S-P, Yip J (2016) Foot anthropometric measurements of Hong Kong elderly: implications for footwear design. JFBIM 9:133-143. https://doi.org/10.3993/jfbim00237

[14] Telfer S, Woodburn J (2010) The use of 3D surface scanning for the measurement and assessment of the human foot. J Foot Ankle Res 3:19. https://doi.org/10.1186/1757-1146-3-19

[15] Kouchi M, Mochimaru M, Tsuzuki K, Yokoi T (1999) Interobserver errors in anthrofometry. J Hum Ergol 28:15-24. https://doi.org/10.11183/jhe1972.28.15

[16] Noldner LK, Edgar HJ (2013) 3D representation and analysis of enthesis morphology. J Phys Anthropol 152:417-424. https://doi.org/10.1002/ajpa.22367

[17] Solanki D, Lahiri U (2018) Design of instrumented shoes for gait characterization: a usability study with healthy and post-stroke hemiplegic individuals. Frontiers in neuroscience 12:459. https://doi.org/10.3389/fnins.2018.00459

[18] Cikajlo I, Osrečki K, Burger H (2016) The effects of different types of ankle-foot orthoses on postural responses in individuals with walking impairments. Int J Rehabil Res 39:313-319. https://doi.org/10.1097/MRR.0000000000000189

[19] Maeshima S, Okazaki H, Okamoto S, Mizuno S, Asano N, Maeda H, Masaki M, Matsuo H, Tsunoda T, Sonoda S (2015) A comparison of knee-ankle-foot orthoses with either metal struts or an adjustable posterior strut in hemiplegic stroke patients. J Stroke Cerebrovasc Dis 24:1312-1316. https://doi.org/10.1016/j.jstrokecerebrovasdis.2015.02.003

[20] Vinci P, Gargiulo P (2008) Poor compliance with ankle-foot-orthoses in Charcot-Marie-Tooth disease. Eur J Phys Rehabil Med 44:27-31.

[21] Zuccarino R, Anderson KM, Shy ME, Wilken JM (2021) Satisfaction with ankle foot orthoses in individuals with Charcot-Marie-Tooth disease. Muscle & nerve 63:40-45.

https://doi.org/10.1002/mus.27027

[22] Yıldırım Y, Tombak K, Karaşin S, Yüksel İ, Nur AH, Ozsoy U (2021) Assessment of the reliability of hand-held surface scanner in the evaluation of adolescent idiopathic scoliosis. Eur Spine J 30:1872-1880. https://doi.org/10.1007/s00586-021-06769-5

[23] Ozsoy U (2016) Comparison of different calculation methods used to analyze facial soft tissue asymmetry: global and partial 3-dimensional quantitative evaluation of healthy subjects. J Oral and Maxillofac Surg 74:1847. e1841-1847. e1849. https://doi.org/10.106/j.joms.2016.05.012

[24] Chiroma SM, Philip J, Attah OO, Dibal NI (2015) Comparison of the foot height, length, breadth and foot types between males and females Ga'anda people, Adamawa, Nigeria. IOSR J Dent Med Sci 14:89-93. https//doi.org/ 10.9790/0853-14818993

[25] Liu Z, Zhang P, Yan M, Xie Y, Huang G (2019) Additive manufacturing of specific ankle-foot orthoses for persons after stroke: A preliminary study based on gait analysis data. Math Biosci Eng 16:8134-8143. https//doi.org/10.3934/mbe.2019410

[26] Saghazadeh M, Kitano N, Okura T (2015) Gender differences of foot characteristics in older Japanese adults using a 3D foot scanner. J Foot Ankle Res 8:1-7. https://doi.org/10.1186/s13047-015-0087-4

[27] Wang JZ, Lillia J, Farhan M, Bi L, Kim J, Burns J, Cheng TL (2021) Digital mapping of a manual fabrication method for paediatric ankle–foot orthoses. Sci Rep 11:19068. https://doi.org/10.1038/s41598-021-98786-z

[28] Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR (2010) Foot shape of older people: implications for shoe design. Footwear Sci 2:131-139. https://doi.org/10.1080/19424280.2010.487053

[29] Yamashita T, Yamashita K, Sato M, Kawasumi M, Ata S (2021) Foot-surface-structure analysis using a smartphone-based 3D foot scanner. Med Eng Phys 95:90-96. https://doi.org/10.1006/j.medengphy.2021.08.001

How to Cite;

Karagulle M, Yıldırım Y, Ozsoy U, Bikem Suzen L, Ikızler May H (2023) Three-Dimensional (3D) Morphometric Analysis of Plegic and Healthy Feet of Patients with Stroke. 29(3):606-619. Eur J Ther. https://doi.org/10.58600/eurjther1701