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Comparison of Frequency Spectrum of Ground Reaction Forces in Patients with Diabetic Neuropathy and Active Foot Ulcers During Walking

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Abstract

Background: Walking and running frequency domain analysis of ground reaction forces are associated with injuries. Comparison of frequency domain analysis of ground reaction forces could be useful in rehabilitation of Diabetic foot ulcers. The objective of this study was to Comparison of frequency spectrum of ground reaction forces and plantar pressure in patients with diabetic neuropathy and active foot ulcers during walking.

Methods: This study was a semi-experimental. The statistical sample of the present study include ninety males that divided into a healthy control group (n=30), group of patients with diabetic neuropathy (n=30) and a group of patients with Diabetic foot ulcers (n=30). A foot scan system (sampling rate: 300 Hz) was used for measuring ground reaction forces in ten regions of the foot during walking. Independent Pearson one-way ANOVA was used for statistical analysis. Alpha level was set at $p<0.05$.

Results: Most of the ulcers were on the plantar of the hallux and toes. When adjusted for age, sex, and body mass index, the frequency content with power 99.5% in the vertical of the ground reactionforce was lower in the diabetic neuropathy group compared to the healthy group ($p <0.001$) and in the diabetic neuropathy group compared to the Diabetic foot ulcers group were more common ($p = 0.006$). The essential number of harmonics in the second plantar bone was higher in the active foot ulcer group compared to the healthy group ($p = 0.020$). The median frequency in the second plantar bone was lower in the diabetic neuropathy group compared to the healthy group ($p <0.001$) and in the active foot ulcer group was lower than in the healthy group ($p <0.001$).

Conclusion: The findings of the present study showed that walking speed in the diabetic neuropathyand Diabetic foot ulcers groups was significantly lower than the walking speed in the healthy group.And this study also shows that in patients with active diabetic foot ulcers, the planter pressure on thefoot ulcers is expected to decrease despite the longer standing phase. Most of the components of thefrequency may be due to the guarded gait mechanism in these patients. Patients showed less stabilityin gait and it was concluded that the loss of depth of legs affects gait control.

Keywords: Diabetes, Foot ulcer, Plantar Pressure relief, Neuropathic Foot Ulcer

Introduction

Gait is the main human movement for displacement and physical activity [1]. Gait is a perfectly coordinated and complex activity that is performed in cooperation with the nervous, muscular and skeletal systems. Past research has shown that normal Gait requires controlled commands from the nervous system, the production of a certain amount of force by the muscles, and a specific range of motion for each joint. This means that the disorder in any of these cases can cause abnormal gait [2,3]. In patients with diabetes, the sole pressure in the metatarsals in the forefoot area is significantly increased and the highest incidence of Diabetic foot ulcers (DFU) is in this area [4]. Diabetes and its ulcers are one of the most important diseases that affect the ability of people to stand and walk.

The incidence of diabetes varies from country to country, with between 50,000 and 75,000 cases reported per million people [5,6]. More than 15% of people with diabetes have sores on their legs that eventually lead to amputation. According to a 2009 study, the prevalence of amputation in diabetics is 1.5 times higher than in healthy individuals [6]. The risk of amputation in these patients is mainly reduced by using appropriate treatment strategies. The most common causes of in diabetic patients include peripheral neuropathy, malformations, trauma, peripheral vascular disease, and peripheral edema. Among these, trauma and the forces applied on the foot are the most important of these factors [7]. In the case of diabetics with sensory disturbances in the foot, there are punitive solutions: cast plaster removes orthoses and allows them to provide insoles, rags and medical shoes are used to reduce foot pressure by healing wounds [8-10].

Among the methods of motion analysis, measuring the pressure distribution of the sole of the foot is one of the common and new methods that quantitatively examines the performance of the foot in static and dynamic conditions [11]. But the distribution of plantar pressure is considered as a biofeedback rehabilitation method to control the posture of gait stroke and amputation [12]. Measuring foot pressure also provides researchers with useful information about foot structure and foot function, and general gait and running mechanics, and is a useful tool for assessing people with lower limb problems [12]. Among the foot pressure parameters, the maximum foot pressure is often used, which shows the maximum load on different areas of the foot during the support phase of gait [13]. Information on the distribution of plantar pressure is used to diagnose foot problems [14], insole design [15], sports performance analysis, injury prevention (16), and improved balance control (17). Any change in the pressure pattern of the sole of the foot increases the likelihood of tissue damage and pain [14]. In general, the analysis of plantar pressure has created a new perspective on the behavior of pain and complaints of lower limb discomfort, for example, to find abnormal foot biomechanics and abnormal body alignment (19). Since the abnormal distribution of foot pressure is associated with increased treatment costs and the spread of pain injuries, it has attracted the attention of many researchers today (18). This prompted us to do more research on this anomaly. Therefore, in the present study, the role of pressure relief process on the sole of the foot during walking in diabetics with active DFU was investigated.

Methodology

Using G*Power software, the minimum sample size was estimated to be 90 people to achieve statistical power of 0.8, effect size of 0.95 at a significance level of 0.05 (20). The subjects of the present study included 30 healthy men with mean age, height and weight of 46.23 ± 2.29 years,

170.50 ± 2.58 cm, 76.03 ± 6.58 kg and 30 patients, respectively. Men with diabetic neuropathy with mean age, height and weight of 45.53 ± 1.30 years, 173.10 ± 1.49 cm, 78.93 ± 4.74 kg and 30 men with Diabetic foot ulcers with the mean age, height and weight were 43.46 ± 2.27 years, 171.73 ±

1.94 cm and 75.10 ± 6.33 kg, respectively. From this 30 Diabetic foot ulcers patients were identified with prior plantar ulcers of the forefoot (hallux or metatarsal heads) from repetitive stress. Criteria for inclusion in the present study were selected according to the study conditions of people with diabetic neuropathy and active foot ulcer, each subject completed and signed a consent form. Exclusion criteria included a history of lower torso surgery, spinal abnormalities, osteoporosis, fractures or disorders in the lower torso. The exclusion criteria were designed to avoid inclusion of people with problems impacting on mobility that would likely mask the impact of a plantar ulcer on gait. Before performing the test, the objectives and method of study were explained to the subjects.

The foot scanner was placed in the middle of the 12-meter walkway. The data of the floor pressure variables were recorded using software (RS, scan) with a sampling frequency of 300 Hz. Attempting to walk correctly involved a full foot impact on the middle of the foot scan machine. If the foot scan was targeted by the subject to adjust the stride or the subject's balance was disturbed, the gait attempt was repeated. To adjust the position of the subjects' feet on the photo-scan during walking, 5 gait operations were performed experimentally by each subject. After that, 5 acceptable attempts were made at a certain speed and the heel to toe (kinetic) walking pattern was recorded. Kinetic data were filtered using a fourth-order lowpass Butterworth filter with a 20 Hz cut-off frequency. (21, 22). Ground reaction force data were performed using a fourth-order Butterworth filter. After filtering the ground reaction force data, the harmonic analysis was converted from a time function to a frequency function according to the following equation using MATLAB software version 20. The data were analyzed using Pearson one way ANOVA.

Discrete spectrum, frequency range is determined as a multiple of base frequency, the sum of n harmonics is equal to:

Relationship (1)

$F(t) = \Sigma A_n \sin(nw_0 t + \theta_n)$

A_n = amplitude. ω0 = base frequency. n = harmonic coefficient. θn = fuzzy angle calculated (23,24).

Relationship (2)

$$\int_0^{f99.5} p(f)df = 0.995 \times \int_0^{f_{max}} p(f)df$$

p = calculated power, f_{max} = maximum signal frequency, middle frequency of the force, the middlefrequency occurs at a point where half of the signal power is above and the other half is below.

Relationship (3)

$$\int_0^{f_{med}} p(f)df = \int_{f_{med}}^{f_{max}} p(f)\,df$$

f_{max} = Maximum signal frequency

f_{med} = Medium frequency of signal

The force frequency bandwidth is equal to the difference between the maximum and minimum frequencies. The signal strength is equal to the harmonic power greater than half the maximum signalstrength.

Relationship (4)

$f_{band} = f_{max} - f_{min} (when\ p > 1/2x\ p_{max})$

f_{max}= Maximum signal frequency

f_{min} = Minimum signal frequency

f_{band}= signal bandwidth

p_{max}= Maximum signal strength

The fourth indicator was to determine the Essential number of harmonics in each direction. Accordingto Schneider's method, the number of harmonics ne required to reconstruct the 95% level of the datawas considered as the number of harmonics in which the sum of the relative amplitudes of each harmonic in the total amplitude is less than or equal to 0.95 (25).

Relationship (5)

$$\sum_{n=1}^{n_e} \frac{\sqrt{A_n^2 + B_n^2}}{\sqrt{A_n^2 + B_n^2}} \leq 0.95$$

Figure 1: Gait path and foot scan machine (a), Ten-foot areas (b)

Research Findings

The findings of the present study showed that gait speed in the healthy group was significantly higher than the gait speed in the group with diabetic neuropathy (p <0.001) and in the diabetic neuropathy group was higher compared to active foot ulcers (p <0.001) and was higher in the healthy group compared to the active foot ulcer group (p <0.001) (Table 1).

Table1: Demographic characteristics of healthy and deaf Males

	Groups		
	Healthy	Diabetic	Diabetic footulcers
N	30	30	30
Age (year)	46.23 ± 2.29	45.53 ± 1.30	43.46 ± 2.27
Mass (kg)	76.03 ± 6.58	78.93 ± 4.74	75.10 ± 6.33
Height (cm)	170.50 ± 2.58	173.10 ± 1.49	171.73 ± 1.94
BMI	26.16 ± 2.34	26.34 ± 1.58	25.47 ± 2.22
Gender	Male	Male	Male
Range of age	42-52	42-48	38-48
Gait speed(m/s)	1.45 ± 0.14 *	1.21 ± 0.06 *	1.07 ± 0.04 *

Note: Values are mean ± standard deviation. Abbreviations: n, number of participants; BMI, body mass index; * Significance level p<0.05

The results showed that the frequency with a power of 99.5% in the vertical component of the ground reaction force was lower in the diabetic neuropathy group compared to the healthy group (p <0.001) and in the diabetic neuropathy group compared to the Diabetic foot ulcers group were more common (p = 0.006). The frequency with 99.5% power in the big toe was lower in the active foot ulcer group compared to the healthy group (p <0.001) and in the diabetic neuropathy group was higher compared to the active foot ulcer group (p <0.001). The number of essential harmonies in the big toe was higher in the active base wound group compared to the healthy group (p <0.001). The median frequency in the big toe was lower in the diabetic neuropathy group compared to the healthy group (p <0.001) and in the active foot ulcer group was higher compared to the healthy group (p = 0.001) (Table 2).

The frequency with 99.5% power in the toes of 2 to 5 feet was higher in the active foot ulcer group compared to the healthy group (p = 0.001) and in the diabetic neuropathy group was lower comparedto the active foot ulcer group (p <0.001). The essential number of harmonics in the toes of 2 to 5 feetwas higher in the active foot ulcer group compared to the healthy group (p <0.005). The median frequency in the toes of 2 to 5 feet was lower in the diabetic neuropathy group compared to the healthy group (p <0.001) and in the active foot wound group was lower compared to the healthy group (p = 0.003) (Table 2).

Table 2: Mean and standard deviation of the components of the frequency spectrum of the ground reaction force

Therefore	Variable	Healthy (n=30)	Diabetic (n=30)	DFU (n=30)	P-Value Interaction
Vertical components of the earth's reaction force	Frequency withpower of 99.5%	9.60 ± 0.45	8.33 ± 0.50	6.40 ± 0.27	0.000 *
	Essential number ofharmonics	20.40 ± 0.98	22.53 ± 1.23	20.56 ± 0.87	0.281
	Medium frequency	2.26 ± 0.09	2.20 ± 0.07	2.13 ± 0.06	0.490
	Frequency Band width	1.26 ± 0.95	1.13± 0.06	1.13 ± 0.06	0.356
Toe	Frequency withpower of 99.5%	8.90 ± 1.03	8.53 ± 0.80	15.96 ± 1.35	0.000 *
	Essential number ofharmonics	15.26 ± 0.92	18.76 ± 1.17	22.40 ± 0.97	0.000 *
	Medium frequency	2.80 ± 0.13	2.20 ± 0.07	2.26 ± 0.08	0.000 *
	Frequency Band width	1.43 ± 0.14	1.20 ± 0.07	1.26 ± 0.08	0.266
Toes 2 to 5 feet	Frequency withpower of 99.5%	8.13 ± 0.72	7.90 ± 0.71	12.43 ± 0.89	0.000 *
	Essential number ofharmonics	16.23 ± 1.02	19.86 ± 1.18	21.16 ± 0.87	0.003 *
	Medium frequency	2.83 ± 0.13	2.20 ± 0.07	2.30 ± 0.09	0.000 *
	Frequency Band width	1.53 ± 0.14	1.20 ± 0.07	1.26 ± 0.08	0.073

Significance level P <0.05 *

The results of the present study showed that the frequency with 99.5% power in the first plantar bonewas higher in the diabetic neuropathy group compared to the healthy group (p = 0.008) and lower inthe diabetic neuropathy group compared to the active foot ulcer group. (P = 0.018) and was less in the active foot ulcer group compared to the healthy group (p = 0.006). The median frequency in the sole of the first foot was lower in the diabetic neuropathy group compared to the healthy group (p<0.001) and in the active foot ulcer group was lower than the healthy group (p <0.001) (Table 3).

The frequency with 99% power in the second plantar bone was lower in the diabetic neuropathy group compared to the active foot ulcer group (p = 0.000) and was higher in the active foot ulcer group compared to the healthy group (p <0.001). The essential number of harmonics in the second plantar bone was higher in the active foot ulcer group compared to the healthy group (p = 0.020). Themedian frequency in the second plantar bone was lower in the diabetic neuropathy group compared to the healthy group (p <0.001) and in the active foot ulcer group was lower than in the healthy group(p <0.001) (Table 3).

The frequency with 99% power in the third plantar bone was lower in the diabetic neuropathy groupcompared to the active foot ulcer group (p <0.001) and was lower in the active foot ulcer group compared to the healthy group (p <0.001). The essential number of harmonics in the third plantar bone was higher in the active foot ulcer group compared to the healthy group (p = 0.002). The medianfrequency in the third plantar bone was lower in the diabetic neuropathy group compared to the healthy group (p <0.001) and in the active foot ulcer group was lower than in the healthy group (p<0.001) (Table 3).

The frequency with 99% power in the fourth plantar bone was lower in the diabetic neuropathy groupcompared to the active foot ulcer group (p <0.001) and was higher in the active foot ulcer group compared to the healthy group (p <0.001). The essential number of harmonics in the fourth plantar bone was lower in the active foot ulcer group compared to the healthy group (p = 0.011). The medianfrequency in the fourth plantar bone was lower in the diabetic neuropathy group compared to the healthy group (p = 0.001) and in the active foot ulcer group was lower compared to the healthy group(p <0.001) (Table 3).

The frequency with 99% power in the fifth plantar bone was lower in the diabetic neuropathy groupcompared to the active foot ulcer group (p = 0.016). Also, the median frequency in the fifth plantar bone was higher in the diabetic neuropathy group compared to the healthy group (p = 0.002) and in the active foot ulcer group was lower compared to the healthy group (p = 0.027) (Table 3).

Table 3: Mean and standard deviation of the components of the frequency spectrum of the ground reaction force in theareas of the plantar bones.

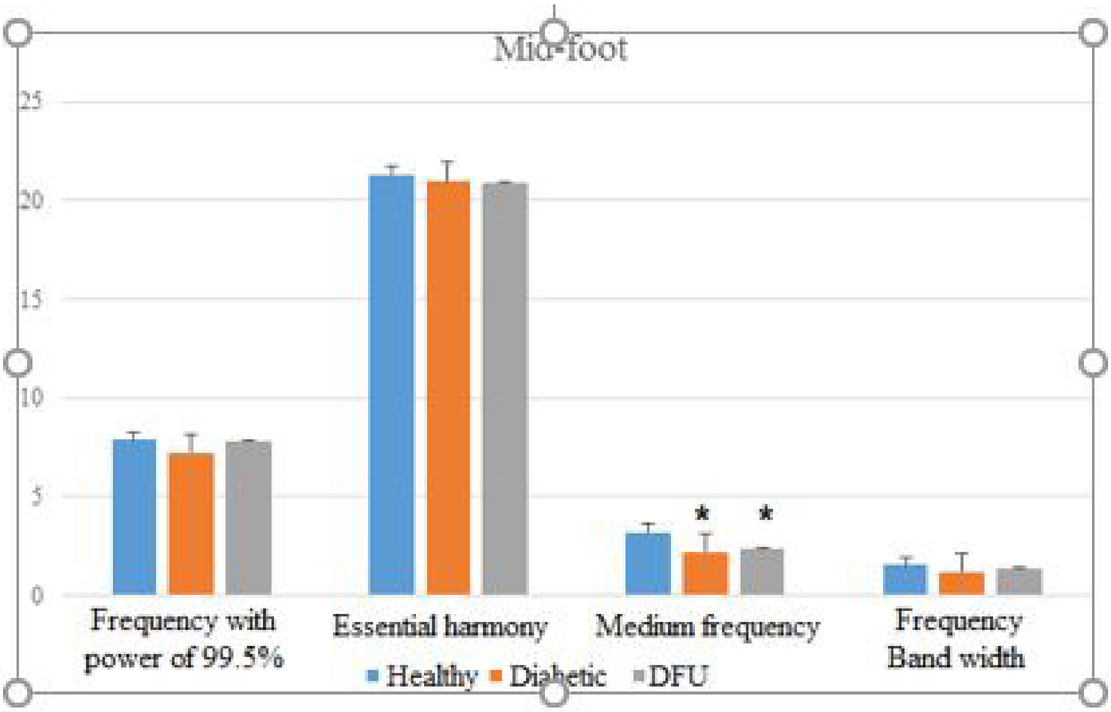
Therefore	Variable	Healthy (n=30)	Diabetic (n=30)	D F U (n=30)	P-Value Interaction
The first plantar bone	Frequency with powerof 99.5%	5.50 ± 0.23	7.80 ± 0.70	9.90 ± 0.42	0.000 *
	Essential number of harmonics	18.06± 1.19	19.93 ±1.18	20.96 ±0.95	0.184
	Medium frequency	3.13 ± 0.09	2.20 ± 0.07	2.50 ± 0.10	0.000 *
	Frequency Band width	1.53 ± 0.14	1.13 ± 0.06	1.46 ± 0.10	0.029 *
The secondplantar bone	Frequency with powerof 99.5%	6.63 ± 0.49	5.73 ± 0.29	10.00 ± 0.37	0.000 *
	Essential number of harmonics	17.63 ± 1.00	18.46 ± 1.21	22.00 ± 1.00	0.012 *
	Medium frequency	2.86 ± 0.11	2.20 ± 0.07	2.26 ± 0.08	0.000 *
	Frequency Band width	1.40 ± 0.13	1.20 ± 0.07	1.26 ± 0.08	0.356
Third plantarbone	Frequency with powerof 99.5%	5.43 ± 0.26	5.20 ± 0.26	9.53 ± 0.37	0.000 *
	Essential number of harmonics	16.83 ± 0.84	18.26 ± 0.72	21.13 ± 0.94	0.002
	Medium frequency	2.93 ± 0.11	2.23 ± 0.07	2.30 ± 0.09	0.000 *
	Frequency Band width	1.43 ± 0.14	1.20 ± 0.07	1.30 ± 0.09	0.314
the fourth plantar bone	Frequency with powerof 99.5%	6.06 ± 0.31	6.00 ± 0.29	8.73 ± 0.40	0.000 *
	Essential number of harmonics	17.13 ± 0.62	19.36 ± 0.94	20.60 ± 7.84	0.010 *
	Medium frequency	3.06 ± 0.10	2.20 ± 0.07	2.33 ± 0.09	0.000 *
	Frequency Band width	1.53 ± 0.14	1.16 ± 0.06	1.30 ± 0.09	0.065
the fifth plantar bone	Frequency with powerof 99.5%	8.20 ± 0.48	7.23 ± 0.44	9.20 ± 0.49	0.016 *
	Essential number of harmonics	18.93 ± 0.88	19.53 ± 1.00	20.50 ±0.94	0.501
	Medium frequency	2.76 ± 0.12	2.23 ± 0.07	2.36 ± 0.10	0.001 *
	Frequency Band width	1.40 ± 0.13	1.20 ±0.07	1.33 ± 0.09	0.693

Significance level P <0.05 *

The median frequency in the middle of the foot was lower in the diabetic neuropathy group comparedto the healthy group ($p < 0.001$) and in the active foot ulcer group was lower than in the healthy group($p < 0.001$) (graph 1).

The frequency with 99.5% power in the inside of the foot was lower in the diabetic neuropathy group compared to the active foot ulcer group ($p = 0.030$). The essential number of harmonics in the innerpart of the heel was higher in the diabetic neuropathy group compared to the active foot wound group($p = 0.002$) and in the active foot wound group was lower than the healthy group ($p < 0.004$)). The median frequency in the inside of the foot was lower in the diabetic neuropathy group compared to the healthy group ($p = 0.021$) (graph 1).

The frequency with 99.5% power in the outer part of the heel was higher in the active foot wound group compared to the healthy group ($p = 0.020$). Essential harmonics in the outer part of the heel were higher in the diabetic neuropathy group compared to the healthy group ($p = 0.045$) and in the diabetic neuropathy group compared to the active foot ulcer group ($p = 0.001$) (Graph 1).


Mid-foot
25
20
15
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5
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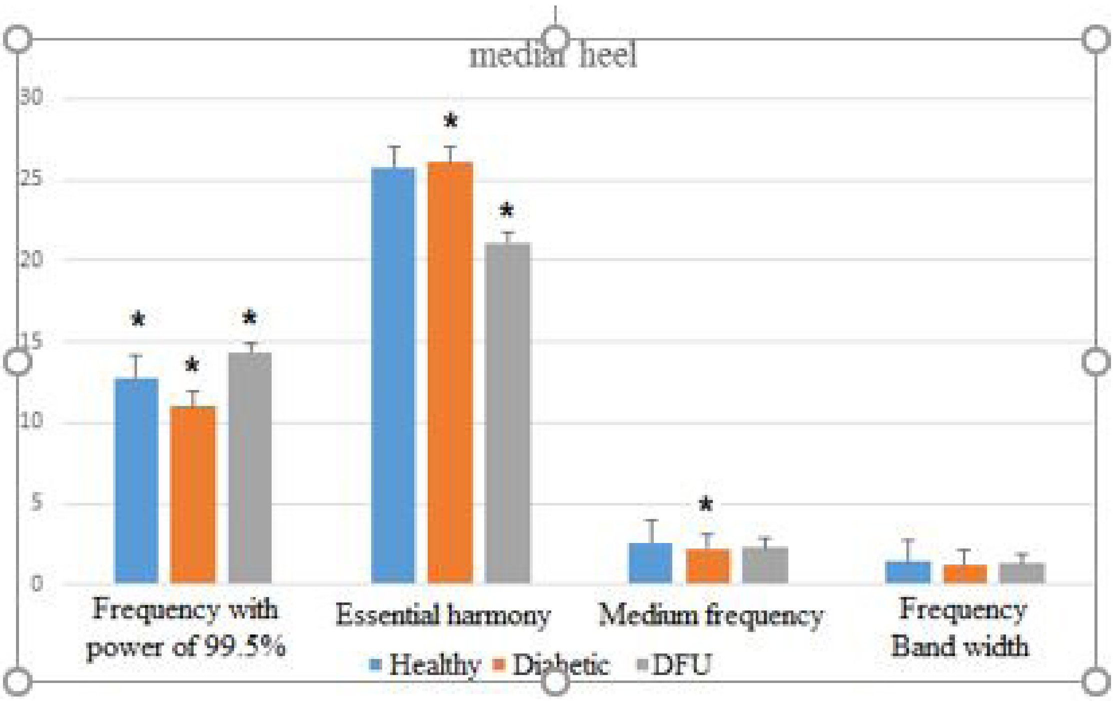
Frequency with power of 99.5%
Essential harmony
Medium frequency
Frequency Band width
Healthy
Diabetic
DFU


medial heel
30
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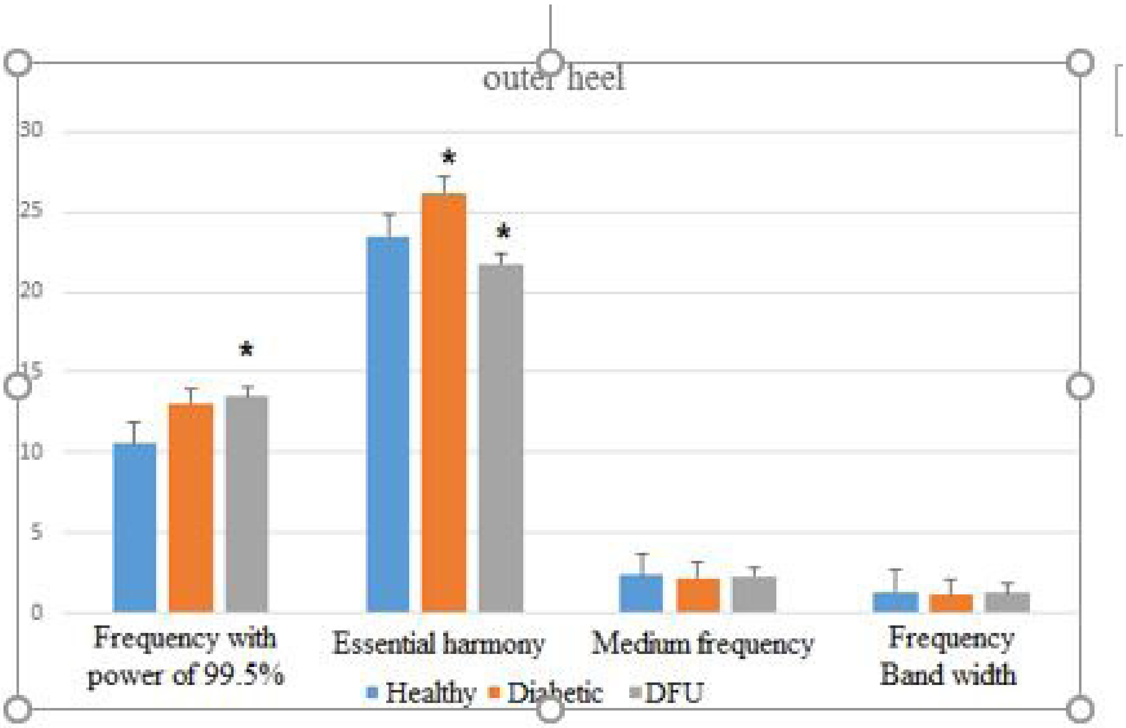
Frequency with power of 99.5%
Essential harmony
Medium frequency
Frequency Band width
Healthy
Diabetic
DFU



Graph. 1. Mean and standard deviation of the components of the frequency spectrum of the ground reaction force.

The significance level was P < 0.05 *

Discussion

The aim of this study was to compare the frequency spectrum of ground reaction forces in patients with diabetic neuropathy and active foot ulcers during walking. The findings of the present study showed that gait speed in the diabetic neuropathy and active foot ulcer groups was significantly lowerthan the gait speed in the healthy group. The present results are consistent with the results of Petrofskyet al. (2005) [26] and inconsistent with Rajhani Shirazi et al. (2012). Rajhani Shirazi et al. showed that although the average gait speed in the diabetic group was lower than the control group; but it was not statistically significant. Perhaps the reason for this difference is the greater severity of neuropathy in the study group. But Petrofsky et al. (2005) stated that [26] the gait speed in diabeticswas significantly lower than the control group. Courtemanche et al. showed that while gait, the gait speed and the percentage of fuzzy time spent in the individual it bore weight on one leg; it was shorterin patients than in the control group. Also, Van Deursen et al. They conducted a study and concludedthat in people with diabetic neuropathy, the sensory function of the muscle is reduced and this can affect the balance and gait of the person and make them out of normal [27,28]. Giacomozzi et al. Performed research on three diabetic groups with neuropathy, no neuropathy and with foot ulcers, and one healthy group. The duration of pressure on the sole of the foot while gait in diabetic patientswas less than the control and in the group with foot ulcers showed more reduction [29]. A study by Petrotsky et al showed that people with diabetes walk more slowly than controls [30].

The results showed that the frequency content in the vertical component of the ground reaction forceand the ten foot areas was significant in the three groups of diabetic, active and healthy foot ulcers. Studies show that patients with diabetic neuropathy are prone to balance problems and are at risk forfalls. On the other hand, another common complication of diabetic neuropathy is compression ulcersof the sole of the foot [31-37]. A study showed that the gait capacity of diabetic patients decreases even in the early stages of the disease, which can lead to an increased risk of falling in these patients[37].

Typically, diabetics are accustomed to similar gait strategies to reduce the force exerted, in which thegait speed is slower, the support surface is wider, and the standing time is longer [38]. The range of motion is greater in the hip and ankle joints (39). Studies by researchers in 2000 and 2002 showed that standing time on both feet increased in these patients and decreased in contrast to the average vertical force of the ground reaction [40,41]. At the same time, another study (1998) showed that the vertical force of the ground's reaction increases in diabetics, especially those with ulcers [42]. According to previous studies, slowing down is a neighborly mechanism to reduce the forces exertedon the feet in diabetics [44-42], but some studies claim that this mechanism is not effective; becauseit does not change the magnitude of these forces and in addition increases the integral force, which in turn leads to an increase in the static phase time. Also, some mechanisms such as decreasing gait speed, increasing the level of support, increasing the weight bearing time on both feet, reducing the stride length and reducing the range of motion of the ankle in diabetics have been mentioned [45,46].

Increasing the frequency content of the vertical component of the ground's reaction forces indicates an increase in oscillations during motion. Increased oscillation may indicate poorer postural control in the vertical direction [47]. Also, increasing the frequency content causes instability and slippage in the movement pattern [48]. In previous studies, it has been shown that reducing gait speed causes a significant reduction in ground reaction forces during the gait and running support phase [49,50]. Studies have shown that one of the reasons for the high range of reaction forces of the ground and lower gait speed can be less efficiency of gait and running and more load in the proximal joint area [49]. One of the possible reasons for the significant difference in most of the data of the frequency spectrum of the ground reaction forces in different areas of the sole of the foot can be the slow gait speed in diabetics. This study has its limitations. Due to the relatively small size of the group, we could not adjust all of us analyzes to a number of factors, such as foot deformities, arch type, and neuropathic severity. We examined barefoot gait rather than shod gait and purposefully did not controlgait speed as we wanted to examine the natural gait characteristics of our particiants. We believe thatby imposing minimal constraints, the observed gait would be consistent with the participant's everyday gait pattern. We used stance phase duration as a surrogate measure of gait speed. We were,however, unable to focus our investigation on individual ulcer sites due to a small sample-size and resultant lack of statistical power and this area still requires investigation. We believe that our findings, however, are consistent with plantar pressures representative of a majority of cases who hadDFUs in the forefoot region. There are differences in plantar pressure values obtained using differentplatforms with different resolutions and various methods of assessment, which is a clear limitation inthe field.

Conclusions

The findings of the present study showed that walking speed in the diabetic neuropathy and DFU groups was significantly lower than the walking speed in the healthy group. This altered walking speed and lower frequency content is suggestive of a lower mechanical efficiency of walking in the diabetic neuropathy and DFU. Patients showed less stability in gait and it was concluded that the lossof depth of legs affects gait control. Patients with diabetic neuropathy are prone to balance problems and are at risk for falls. In addition, this group of patients present a different gait pattern than healthyindividuals due to changes in the function of the muscles and joints of the lower limbs and also to reduce the pressure of the sole of the foot in high-pressure areas. Frequency domain analysis thus offers new insights into the gait improvements associated in patients with diabetic neuropathy and active foot ulcers.

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