Chapter

Effect of Foot Morphology and Anthropometry on Bipedal Postural Balance

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Abstract

Maintenance of accurate postural balance is imperative to avoid falls and incapacities especially in overweight and older population. Normal postural balance is affected by various factors like age, gender, body characteristics like lean muscle mass, soft tissue mass, stature, foot anthropometry, etc. A cross-sectional study was conducted among 1000 young population of north Karnataka in which human stature, weight, body mass index, foot anthropometric parameters, etc. along with postural sway were measured. The correlation of these parameters with human stature, weight and postural sway was studied. Data obtained were tabulated, graphically represented and statistically analyzed. Correlation coefficient was formulated for each variable. Foot length and width showed positive significant correlation with height, weight and other variables. Study observations were compared with those obtained from previous studies. The study observations will enable us to understand the influence of foot anthropometry on postural balance and help researchers to formulate weight transfer strategies, thereby facilitating management and rehabilitation of patients with postural instability.

Keywords: anthropometry, bipedal posture, postural stability, gait, body mass

1. Introduction

Postural balance is dynamic and demands constant amendments to adapt to external disturbances, by using vision, muscle activity, articular positioning and proprioception, and the vestibular system to prevent falls [1, 2]. Awareness of the body's position in space is determined by the integration of the visual, vestibular and somatosensory systems [3, 4]. The study of postural control is imperative for diagnosing balance disorders, as well as for assessing the effects of both therapeutic interventions and fall prevention programs. Postural stability is determined by mechanical factors that include both individual and environmental characteristics. This chapter focuses on various factors influencing the bipedal postural stability and provides an insight into the measures to facilitate improvement in the accuracy of diagnosis and quality of treatment and rehabilitation, thereby preventing falls and incapacities.

2. Evolution of bipedal posture

Our ancestors would have probably become extinct if they had not developed their bipedal posture including the corresponding transitional behavioral constraints. "Bipedalism evolved more as a terrestrial feeding posture than as a walking adaptation" [5]. The adapted bipedal posture brought various disadvantages like decreased velocity, increased time for social interaction, more chances of injuries from fall, more energy consumption, etc.

Advantages of bipedal posture could be many, namely freeing of hands, the visual advantage of being able to survey the surrounding, ability to acquire the skill of throwing, ability to carry infants while running, ability to reach out for food, ability for carrying food or provisioning, etc. But the most important hypothesis is that the ability to venture into shallow water made the ancestors to adapt bipedal posture.

3. Biomechanics of bipedal posture

Upright postural balance describes the dynamics of body posture to prevent falling over a relatively small base of support under gravitational field. As for postural balance without stepping, the stable balancing condition can be analyzed using the following equation under assumption that a one link inverted pendulum describes human sway motions.

$$Fy.xcop–Mg.xcom = I\ \theta a. \tag{1}$$

where Fy is vertical reaction force, Mg is human total weight, xcop is the center of pressure (COP), xcom is the horizontal component of the center of mass (COM) (e.g., the center of gravity (COG)), I is the moment of inertia of the total body about the ankle joint, and θa is the ankle joint angle [6].

Two basic models for biped locomotion are walking and running. A gait of walking consists of stance and swing phases and a gait of running consists of stance and flight phases. Stance phase describes the period when a foot remains on the ground, and either swing or flight describes the period when a foot does not touch the ground. At midstance, the COM is at its highest point and gravitational potential energy is at maximal and kinetic energy at minimal. The exchange between kinetic and gravitational potential energies is cyclical over gaits. On the other hand, a running leg acts as a spring; therefore, a simple running model is a mass-spring system. At the braking phase during stance, the spring gets compressed and energies are stored as elastic energy. At midstance, the COM reaches its lowest point. The stored elastic energy recoils the spring at propulsive phase during stance to produce kinetic and gravitational potential energies. Both models principally exchange and store energies repeatedly to produce forward thrust and stability [6].

4. Factors affecting postural balance

Numerous determinants like age, gender and body characteristics like body mass, height and body mass index affect postural stability. Anthropometric parameters of ankle joint and foot also affect bipedal and unipedal postural stability.

4.1 Effect of age and gender on postural balance

Vijada Raiva et al. [6] stated that females have more postural stability than males. Hageman et al. [7] stated that compared to younger population, older generation showed more tendency to sway. Older adults performed the timed movement task much slower than the younger adults. Longer response times by the elderly have been attributed to slower event detection and impaired sensorimotor integration. Greve et al. [8] stated that women showed less movement on Biodex Balance System than men did, and these findings were similar to those of Rozzi et al. [9] who evaluated basketball and American football players using the same equipment. Lee and Lin [10] studied children and observed that girls presented better postural balance than boys. This could be due to anthropometric factors (greater in men), but other factors such as neuromuscular (flexibility) and neurophysiologic (processing of inferences), as well as the habit of using higher heels, may also account for the differences.

4.2 Effect of body mass on postural balance

Ledin and Odkvist [11] demonstrated that a 20% increase in body mass reduced the ability to make adjustments in response to external perturbations in the orthostatic position, with a consequent increase in postural instability. Chiari et al. [12] and Molikova et al. [13] in their respective studies conducted on individuals with normal or slightly higher than normal BMI have shown low correlations between body mass and balance. Majority of studies indicate that there was a direct relationship between obesity and increased postural instability, as evaluated by means of various tools and methods. Greve et al. [14] showed that in young adult males, the higher the BMI, the worst the postural balance, needing more postural adjustments to maintain balance in single leg stance. Greve et al. [8] proposed that the male group demonstrated stronger correlations for overall, anteroposterior and mediolateral stability index with body mass index (BMI) compared to women. They stated that there was a need for greater movements to maintain postural balance. Hue et al. [15] found that body mass was responsible for more than 50% of balance at speed and Chiari et al. [12] demonstrated a strong correlation between body mass, anteroposterior movements and the area of detachment. McGraw et al. [16] reported that greater postural adjustments are necessary to maintain an erect posture when there is a build-up of adipose tissue, thus causing a reduction in balance and an increase in injuries and falls. Due to the high degree of correlation between balance and body mass, we can safely infer that the mechanical factor of body mass inertia requires greater musculoskeletal force to balance it against the force of gravity, and therefore, to maintain balance, obese individuals require greater movement from the center of gravity to remain in the orthostatic position.

4.3 Impact of stature on postural balance

There is a consensus that the greater the height, the worse the balance. Berger et al. [17] and Alonso et al. [3] stated that ankle displacements and the response of the gastrocnemius increased with increasing height. Allard et al. [18] and Lee and Lin [10] reported that tall individuals present greater postural sway than do short individuals, and they attributed this to the higher position of the center of mass. Kejonen et al. [19] and Hue et al. [15] have found that body stability is inversely related to the height of the center of gravity and that, for this reason, posturography measurements are affected by individuals' anthropometric characteristics.

4.4 Role of foot anthropometry in maintaining postural balance

The architecture of the vertebral column, upper and lower appendages, and organs and tissues that attach to or are suspended from the spinal column affects postural stability. Very few studies are available on correlation of foot parameters with unipedal and bipedal postural balance [18].

4.5 Effect of muscle strength and fatigue on postural balance

As the age advances particularly after forties, the muscle mass goes on decreasing so does the muscle strength. Muscle fatigue, which is a common condition affecting the elderly population, can result in mobility, postural and gait deficiencies. The state of mind can influence the activity of the muscular system, that is, the muscular tonus. The muscular activation or, in the contrary case, the muscular relaxation influences postures adopted by people. The body height and the lower limb length constitute partly to weight transfer strategy. The trunk-cephalic length does not correlate to the postural sway. Body mass is located above the hips, so it is not the main factor for the mediolateral sway. The weight transfer strategy for men depends on the size of the basis of support and their lean mass, while, for women, only the lengths (whole body and lower limbs) are important. Lower basis of supports leads to higher postural sway in the ML direction (Chiari et al. [11]; Chou et al., [20]), and to control the increase in body sway, it is necessary to increase the lean mass, probably and mainly the muscle mass to be able to generate more muscle force. The increase in body height affects the body mass and soft tissue mass (lean and fat masses) increases the postural sway. The increase in body mass indeed enlarges the postural sway.

5. Research study

A study was conducted in central population of northern Karnataka on 1000 young adult population in which foot anthropometry was measured and correlated with stature, weight, body mass index and bipedal posture stability [21].

6. Methodology

Study design: Descriptive cross-sectional study.

Setting: Anthropometric section of department of Anatomy, ESIC Medical College and Hospital, Gulbarga, Karnataka.

Duration of study: 14 months; from 31 October 2017 to 31 December 2018.

Sample size: 1000 participants included medical, dental and nursing students aged between 18 and 21 years of age.

Inclusion criteria: Medical, dental and nursing students aged between 18 and 21 years of age in ESIC Medical College, Gulbarga.

Exclusion criteria: Students of NRI quota and students with poorly defined wrist creases, deformities of vertebral column and limbs, contractures, missing limbs, history of trauma to hand and foot, with features suggestive of dysmorphic syndromes, chronic illness and hormonal therapy were excluded from the study.

Sample selection: Simple random sampling method [13] as we selected 1000 participants out of total 3000 medical, dental and nursing students in our institute satisfying the inclusion criteria. As subjects belonging to the first to third year, they were easily accessible and also represented the young adult age group.

6.1 Data collection procedure

Foot length: Each subject will stand on a calibrated foot board with his/her back against the wall in such a manner that the posterior most point of the heel will

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Figure 1.
Measurement of foot length.

gently touch the wall. A vertical stop was placed against the anterior most point of the foot. The distance between the posterior most point of the heel and the anterior most point of the foot was measured as the foot length [22] (**Figure 1**).

Foot breadth: It will be measured as distance between metatarsal tibiale (point projecting most medially on the head of the 1st metatarsal bone) and metatarsal fibulare (point projecting most laterally on the head of the 5th metatarsal bone) [23].

Height: Standing height will be measured to the nearest centimeters (cm) using a stadiometer with the subject standing erect on a horizontal resting plane bare footed having the palms of the hands turned inward and the fingers pointing downwards. The height will be measured from the sole of the feet to the vertex of the head as recommended by International Biological Program [23].

Body weight: It will be taken using the Mechanical Weighing Balance to the nearest kg according to the standard procedures A. Ibegbu, David et al. [24].

Body mass index: It will be calculated by dividing weight by height squared [weight/height squared (kg/m^2)] David et al. [24].

6.2 Data collection tools

Vernier slide calipers, calibrated foot board, stadiometer, regular weight machine, questionnaire for collection of personal details, academic scores, lead pencils, stationary, etc. Data collected were tabulated, graphically represented and statistically analyzed.

7. Observations

In our study, mean foot length was observed as 24.34 cm on the right side and 24.32 cm on the left side. Mean body mass index was calculated as 20.97. Correlation between foot length and body mass index was done. No statistically significant correlation between BMI and foot length of the right and left sides ($P > 0.05$) was observed. For further details, refer to **Table 1**.

In the present study, mean foot breadth was observed as 8.95 cm on the right side and 8.96 cm on the left side. Mean body mass index was calculated as 20.97. Correlation between foot length and body mass index was done. There was a statistically significant correlation between BMI and foot breadth of the right and left sides ($P < 0.01$). The observations in the study stated that foot breadth of both sides was considerably more in participants who had higher body mass index. Linear regression coefficient was derived. For further details, refer to **Table 2**, **Figure 2.**

Variables	Minimum	Maximum	Range	Mean	SD	N	Correlation r	P value
Body mass index (kg/m^2)	12.22	40.61	28.39	20.97	4.66	1000	—	—
Foot length right (cm)	21.0	28.9	7.9	24.34	1.54	1000	r = 0.073	P > 0.05 NS
Foot length left (cm)	21.5	29.0	7.5	24.32	1.50	1000	r = 0.024	P > 0.05 NS

Table 1.
Correlation of foot length and body mass index.

Variables	Minimum	Maximum	Range	Mean	SD	N	Correlation r	P value
Body mass index (kg/m^2)	12.22	40.61	28.39	20.97	4.66	1000	—	—
Foot breadth right (cm)	7.5	10.9	3.4	8.95	0.78	1000	r = 0.124	P < 0.05 S
Foot breadth left (cm)	7.7	11.5	3.8	8.96	0.68	1000	r = 0.115	P < 0.05 S
Linear regression equation	BMI = 19.306 + 0.168 (foot breadth right)							
Linear regression equation	BMI = 17.214 + 0382 (foot breadth left)							

Table 2.
Correlation of foot breadth and body mass index.

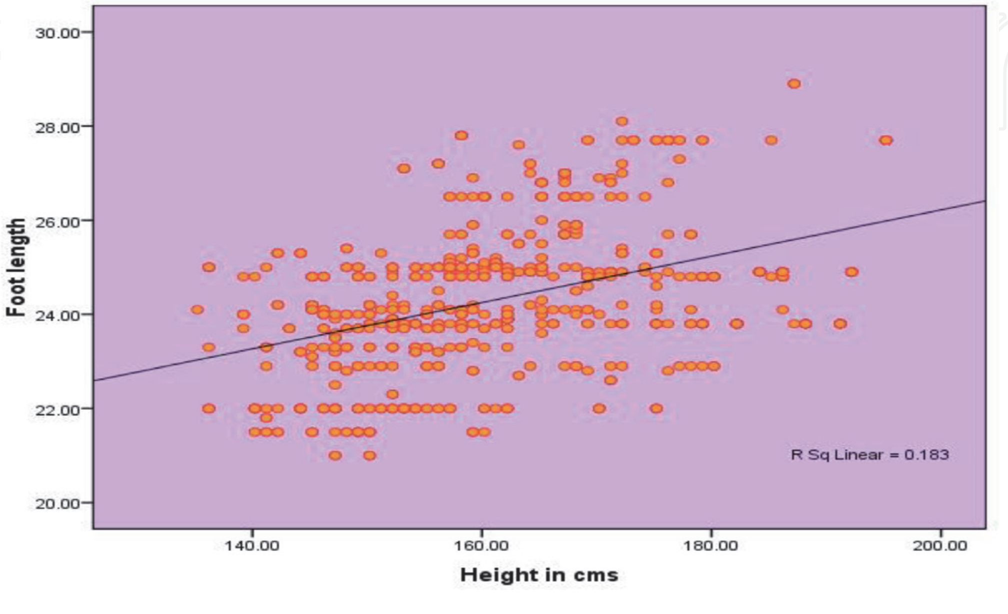

Figure 2.
Correlation between foot length and body mass index.

Variables	Minimum	Maximum	Range	Mean	SD	N	Correlation r	P value
Height (cm)	135.2	195.2	60.0	161.88	13.45	1000	—	—
Foot length right (cm)	21.0	28.9	7.9	24.34	1.54	1000	r = 0.428	P < 0.01 HS
Foot length left (cm)	21.5	29.0	7.5	24.32	1.50	1000	r = 0.516	P < 0.01 HS
Linear regression equation	Height = 71.391 + 4.782 (foot length right)							
Linear regression equation	Height = 49.706 + 4.786 (foot length left)							

Table 3.
Correlation of foot length and human stature.

Figure 3.
Measurement of foot breadth.

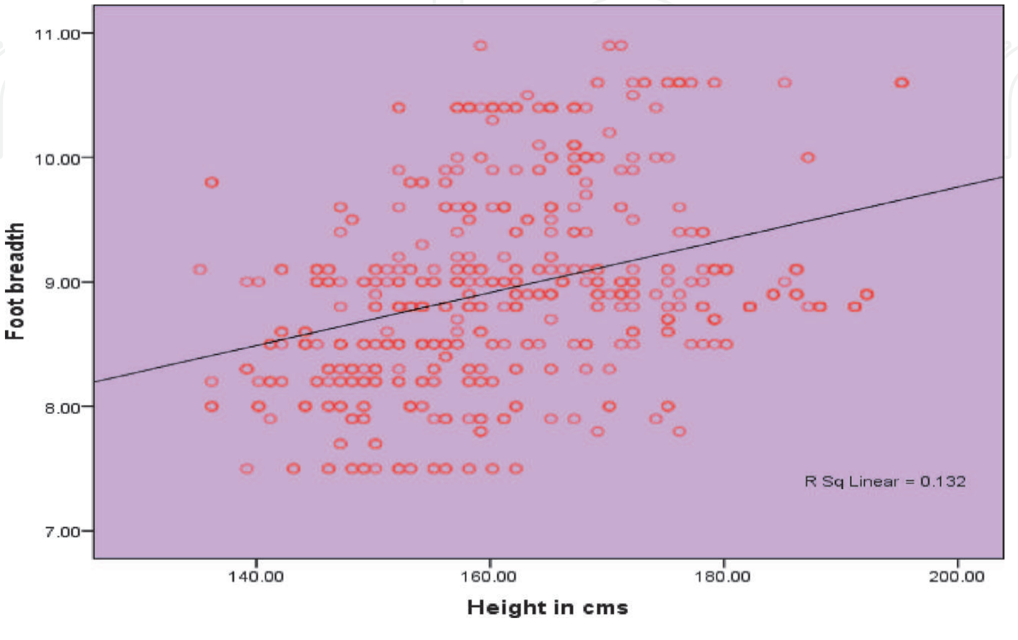

Figure 4.
Correlation between foot breadth and body mass index.

Variables	Minimum	Maximum	Range	Mean	SD	N	Correlation r	P value
Height (cm)	135.2	195.2	60.0	161.88	13.45	1000	—	—
Foot breadth right (cm)	7.5	10.9	3.4	8.95	0.78	1000	r = 0.364	P < 0.01 HS
Foot breadth left (cm)	7.7	11.5	3.8	8.96	0.68	1000	r = 0.367	P < 0.01 HS
Linear regression equation	Height = 106.01 + 6.240 (foot breadth right)							
Linear regression equation	Height = 96.843 + 7.253 (foot breadth left)							

Table 4.
Correlation of foot breadth and human stature.

We also observed foot length on both sides. Mean foot length on the right side was observed as 24.34 cm, and on the left side, it was 24.32 cm. Correlation of foot length was conducted with human stature. Linear regression equation was derived for both sides. Statistically highly significant positive correlation was observed between height and foot length of both sides (P < 0.01). **Table 3** reveals that foot length of both sides was also significantly more among those having more height (**Figures 3** and **4**).

Foot breadth was observed on both sides. Mean foot breadth on the right side was observed as 8.95 cm, and on the left side, it was 8.96 cm. Correlation of foot breadth was conducted with human stature. Linear regression equation was derived

Figure 5.
Measurement of human stature.

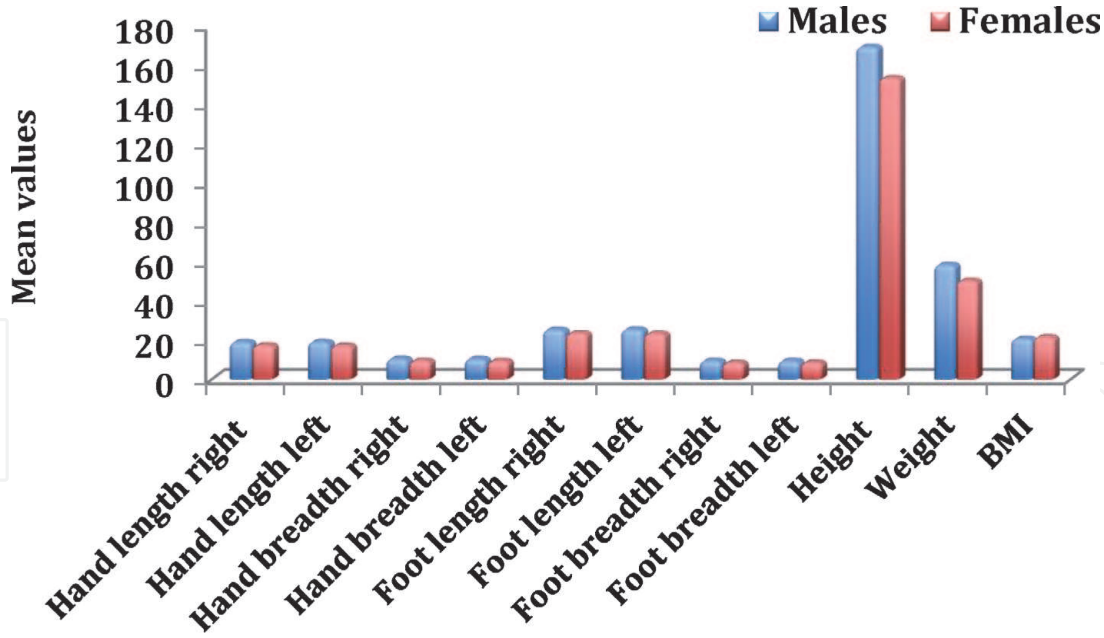

Figure 6.
Correlation between foot length and stature.

Variables	Male (N = 500) Mean ± SD	Female (N = 500) Mean ± SD	Z-test value	P value and significance
Foot length right (cm)	25.18 ± 1.32	23.39 ± 1.19	Z = 30.07	P < 0.001, VHS
Foot length left (cm)	25.31 ± 1.16	23.19 ± 0.96	Z = 31.19	P < 0.001, VHS
Foot breadth right (cm)	9.39 ± 0.71	8.45 ± 0.52	Z = 22.97	P < 0.001, VHS
Foot breadth left (cm)	9.35 ± 0.59	8.52 ± 0.47	Z = 23.21	P < 0.001, VHS
Height (cm)	169.28 ± 11.75	153.42 ± 9.75	Z = 22.26	P < 0.001, VHS
Weight (kg)	58.21 ± 11.91	50.14 ± 9.85	Z = 11.21	P < 0.001, VHS
BMI (kg/m^2)	20.58 ± 4.94	21.41 ± 4.27	Z = 2.53	P < 0.05, S

NS, not significant; S, significant; HS, highly significant; VHS, very highly significant.

Table 5.
Gender-wise comparison of parameters.

for both sides. Statistically highly significant positive correlation was observed between height and foot breadth of both sides ($P < 0.01$). **Table 4** reveals that foot breadth of the right or left side was significantly more in those participants whose height was more (**Figures 5** and **6**).

Gender-wise comparison of observations was done. We observed very highly significant difference in foot length, foot breadth, height and weight among males and females. The foot length, foot breadth, height and weight were significantly more in males compared to females, whereas body mass index was significantly more in females as compared to males. The observations have been tabulated in **Table 5**, **Figures 7** and **8**.

Postural sway was measured in the participants both male and female in anteroposterior and mediolateral direction (**Figure 9**). Correlation of postural sway with foot length and foot breadth was conducted. Mediolateral postural sway amplitude was the same, that is, −0.3 cm in both males and females.

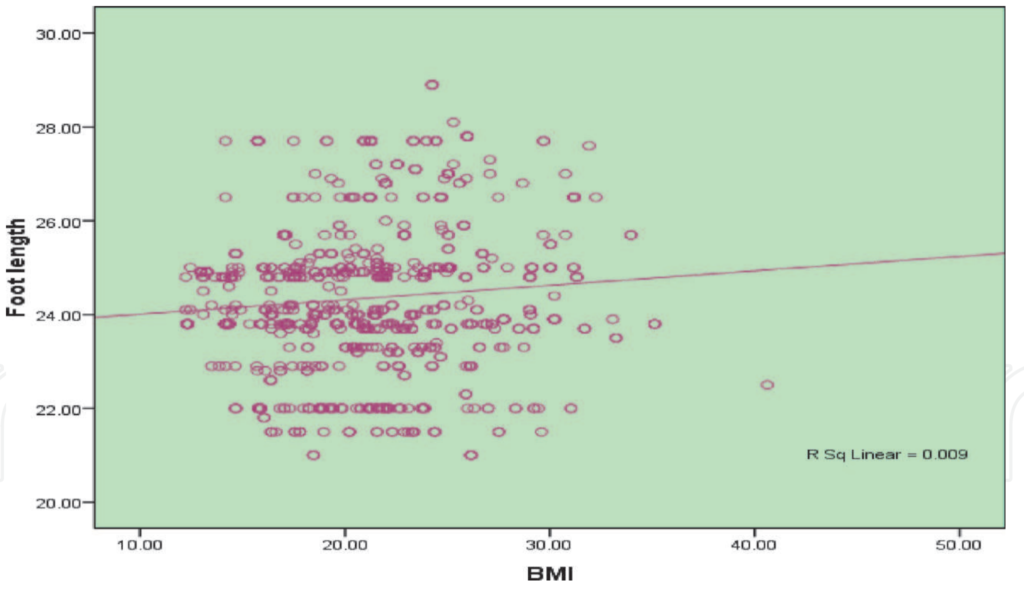

Figure 7.
Correlation between foot breadth and stature.

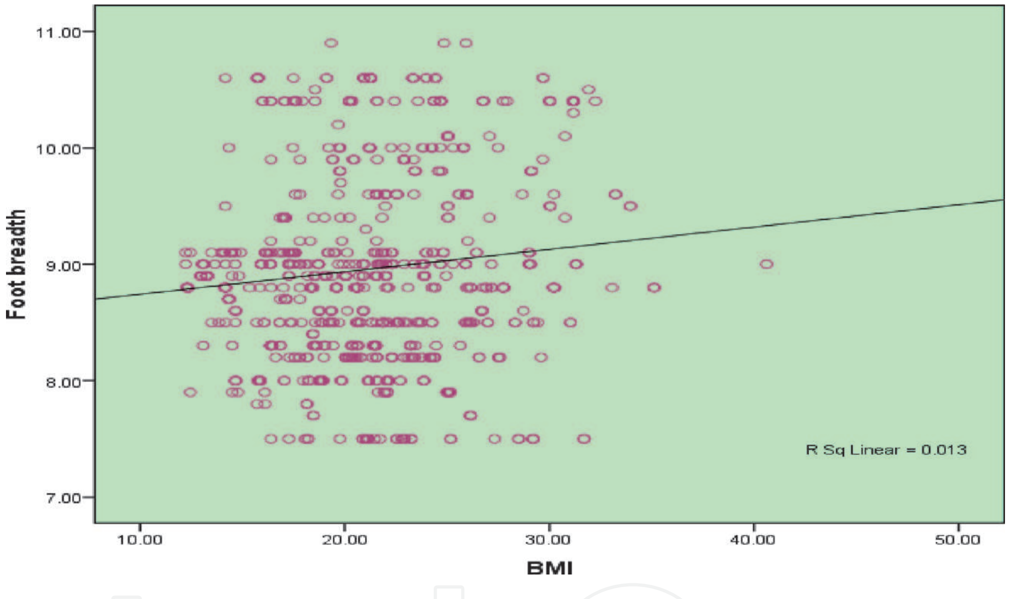

Figure 8.
Multiple bar diagram represents gender-wise comparison of variables.

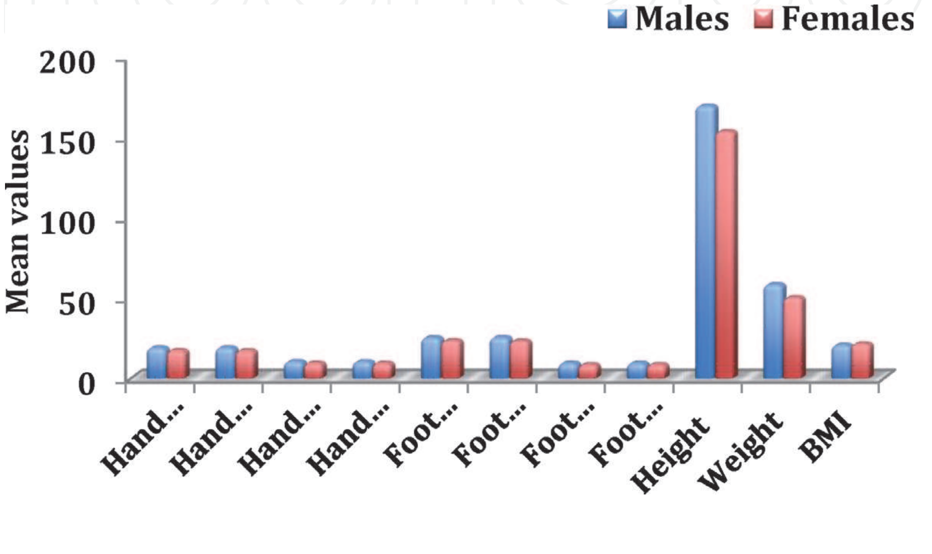

Figure 9.
Gender-wise comparison of parameters.

Variables	Foot length (cm) r(p)	Foot breadth (cm)	Angle (°)
Female			
Mediolateral sway (cm)	0.01 (0.88)	0.01 (0.80)	−0.01 (0.89)
Mediolateral ampl sway (cm)	0.05 (0.54)	0.01 (0.82)	−0.03 (0.70)
Anteroposterior sway (cm)	0.07 (0.43)	0.05 (0.53)	−0.12 (0.21)
Anteroposterior ampl sway (cm)	0.09 (0.35)	−0.11 (0.25)	−0.95 (0.35)
Sway velocity (cm/s)	0.05 (0.56)	−0.12 (0.22)	0.11 (0.25)
Sway area (cm^2)	0.67 (0.50)	−0.24 (0.80)	−0.12 (0.22)
Male			
Mediolateral sway (cm)	0.32 (0.00)	0.02 (0.84)	−0.04 (0.68)
Mediolateral ampl sway (cm)	0.27 (0.00)	0.02 (0.83)	−0.03 (0.69)
Anteroposterior sway (cm)	0.29 (0.00)	0.00 (0.94)	−0.11 (0.24)
Anteroposterior ampl sway (cm)	0.27 (0.00)	−0.06 (0.52)	−0.10 (0.31)
Sway velocity (cm/s)	0.15 (0.13)	−0.08 (0.42)	−0.09 (0.37)
Sway area (cm^2)	0.36 (0.00)	0.02 (0.78)	−0.10 (0.32)

*Spearman's correlation, *$\rho \leq 0.05$. ampl, amplitude.*

Table 6.
Correlation between foot anthropometric measurements and postural balance.

Anteroposterior sway amplitude was −.95 cm in females and − .10 cm in males. **It was observed that men exhibited more postural sway compared to females in anteroposterior direction**. The findings were statistically significant. Refer to **Table 6** for details.

8. Discussion

Few studies have worked on the relationship of foot anthropometry with balance. Clarke [25] analyzed the angle of foot. Swanenburg et al., [26] examined static posturography using the center of pressure (COP) oscillation on a force platform. Our study suggested association between greater foot length and higher stabilometric parameters only in the male group. Our study observations matched with those of Alonso et al. [27], Kejonen et al., [19] and Molikova et al., [13]. Previous studies by Alonso et al., [3] and Chou et al., [20] also demonstrated that an increase in the size of the support base can improve the balance.

Our study states that neither the foot length nor the foot width influences postural balance. These observations matched with Alonso et al., [28], but they had conducted the study using unipedal standing balance task. Our findings contradicted with those of Chiari et al.[12] in which foot width showed positive correlation with postural balance. They conducted the study by bipedal standing balance task. They stated that the increase in lean mass correlates to the decrease of the amplitude of the postural sway. They added that the percentage of fat mass explains part of the anteroposterior postural sway in men, but not in women.

Mainenti et al. [29] showed that elderly women with more fat mass had larger balance sway and Winters and Snow [30] reported that 31% of postural sway variability in premenopausal women was caused by the fat mass. Hence, it can be concluded that the effect of fat mass on the postural control is age dependent.

The increase in body height indeed increases the postural sway. Hence, in our study, the greater height in the male group may have been the reason for the greater influence of this parameter on COP in comparison to the female participants.

In our study, conducted among young adults, without major health diseases or other abnormalities, the anthropometric measurements showed gender-related differences.

9. Conclusions

1. Bipedal postural sway shows sexual dimorphism.

2. Significance of body composition in maintenance of postural sway also shows sexual dimorphism.

3. Lean muscle mass is inversely proportional to the degree of postural sway.

4. Soft tissue mass is directly proportional to the degree of postural sway.

5. Human height is directly proportional to the degree of postural sway.

6. Foot length and foot width do not influence postural balance.

7. Overweight individuals require greater movement from the center of gravity to remain in the orthostatic position.

10. Suggestions

1. Gender-related variations in factors maintaining postural balance should be considered during ankle and weight transfer strategies.

2. Foot anthropometric parameters should be taken into consideration while facilitating diagnosis, treatment and rehabilitation of patients with postural instability.

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