EVALUATION OF METATARSAL RELATIONSHIPS IN THE BIOMECHANICS OF 332 NORMAL FEET USING THE METHOD OF MEASURING RELATIVE LENGTHS

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ABSTRACT

Objective: To identify the mean normal length of the metatarsals and the most common metatarsal formulas through a simple measurement method, thereby providing surgeons with data for planning treatment on symptomatic individuals with biometric abnormalities of the foot. Methods: We evaluated and measured dorsoplantar weight-bearing radiographs of normal adult feet (83 males and 83 females). Results: We found relative mean lengths for metatarsus I of 125.4 mm for males and 115.1 mm for females; for metatarsus II, 127.8 mm for males and 117.3 mm for females; for metatarsus III, 123.4 mm for males and 113.5 mm for females; for metatarsus IV, 114.2 mm for males and 105.3 mm for females; for metatarsus V, 99.5 mm for males and 91.7 mm for females. The mean forefoot width was 87.1 mm for males and 80.8 mm for females. Conclusion: Feet with index minus occurred most frequently in both sexes, although all three metatarsal formulas can be considered to be normal patterns. The mean normal pattern for males and females respectively was the following: metatarsus I 2.4 mm and 2.2 mm shorter than metatarsus II; metatarsus III 4.4 mm and 3.8 mm shorter than metatarsus II; metatarsus IV 9.2 mm and 8.2 mm shorter than metatarsus III; metatarsus V 14.7 mm and 13.6 mm shorter than metatarsus IV.

Keywords - Metatarsal Bones; Adult; Body Weights and Measures

INTRODUCTION

Many authors have affirmed that there is a high frequency of localized disorders in the feet[1-4]. In the normal population, it has been estimated that 70% of all individuals have or will have at least one episode of pain in the forefoot region during their lives[5]. If it is observed that the metatarsal lengths obey a standard relationship in individuals with pain-free static and dynamic functions, it can be concluded that there is a high likelihood that breaking this pattern will give rise to biomechanical changes. In up to 92% of such pathological conditions, abnormalities of metatarsal positioning are thought to be related as etiological factors[1,6].

We did not find in the literature any studies that focused on the normal mean length relationship between the metatarsals. For this reason, we did not observe any consensus with regard to choosing the best surgical alternative for use in treating metatarsal pain, especially when the procedure is carried out by means of osteotomy, which is still done empirically and without any scientific basis today. For

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Work received for publication: June 14, 2010; accepted for publication: August 23, 2010.

The authors declare that there was no conflict of interest in conducting this work

This article is available online in Portuguese and English at the websites: www.rbo.org.br and www.scielo.br/rbort

this reason, such surgical procedures may cause an iatrogenic pain transfer syndrome, which may result, for example, from excessive shortening of the osteotomized metatarsal.

In the light of this polemic, we sought to bring together information on length relationships between the metatarsals, with the initial aim of recognizing what the normal pattern is. From this information, it would be possible to predetermine the final size that the metatarsal should reach after carrying out osteotomy. Our objective was to create a simple and easily reproducible method for measuring the forefoot in order to ascertain the most frequent metatarsal formula.

METHODS

Our sample was composed of 166 individuals aged 25 to 50 years who did not have any previous or current complaints relating to their feet. There were 83 men (mean age of 35 years) and 83 women within the same age group (mean of 36 years), coming from the outpatient clinics of the orthopedics sector of Mario Covas State Hospital, in Santo André, thus totaling 332 feet evaluated. We did not make any distinction regarding ethnic group.

These volunteers underwent simple radiography on both feet, while bearing the body weight, in dorsoplantar view. We applied between 40 kV and 60 kV, with exposure of between 2 mAs and 10 mAs. The basic requirement was to have a clear radiographic image of the middle and forefoot. The beam was angled at 15º in relation to the vertical plane, in the cranial direction, as suggested by the great majority of authors, and a film holder measuring 24 cm x 30 cm was used[7-12]. During image acquisition, the subject remained in an upright standing position, with equal weight distribution between the feet, and the beam focus was centered between the navicular bones[7,13]. The distance from the beam focus to the film holder was 80 cm[13].

The relative lengths of the five metatarsals of each foot were measured. From a straight line over the Chopart joint (talonavicular and calcaneocuboid), tangential to the most medial and proximal points of the navicular bone and going as far as the lateral congruence point between the calcaneal and cuboid bone, we drew perpendicular straight lines to the most distal point of the head of each metatarsal, and measured these distances in millimeters (Figure 1). The width of the forefoot was measured as the distance between two straight lines perpendicular to the Chopart joint, tangential to the most medial and most lateral points of the heads of first and fifth metatarsals, respectively (Figure 2).

Figure 1 – Metatarsal length measurement method.

Figure 2 – Forefoot width measurement method.

In the statistical analysis, the quantitative variables were represented by the mean, standard deviation (SD) and maximum and minimum values, while the qualitative variables were represented by absolute frequencies (n) and relative frequencies (%).

To compare the right and left sides in relation to the parameters evaluated, Student's t test for independent samples was used, paired in groups of men and women separately. From the measurements obtained (length of the second metatarsal and width of the forefoot), the forefoot width/metatarsal II (FW/MII) index was calculated, and the correlation between age and the indices was evaluated using Pearson's correlation coefficient (r), separately for the groups of male and female feet. The samples of male and female feet (evaluated separately) were divided into age groups and these were compared in relation to the indices by means of the analysis of variance technique (ANOVA). Any differences were then located by means of the Tukey multiple comparisons test. It should be noted that this analysis had to be done because

of the small numbers of feet seen in some age groups. The significance level of 0.05 (a = 5%) was used, and descriptive levels (p) lower than this value were taken to be significant.

RESULTS

Comparison between the right and left sides

Tables 1 and 2 present the means and standard deviations for the parameters evaluated in the right and left feet, for both sexes, and the respective comparisons. From these results, the two sides were independent and therefore for the remaining evaluations on these parameters, the samples were duplicated. In relation to the side, the feet were compared regarding all the measurements obtained, and the results found were:
1. Both in the group of 83 pairs of male feet and in the group of 83 pairs of female feet, no statistically significant difference was found between the means of the measurements on the right and left feet, for any of the parameters evaluated ($p > 0.05$ in all the comparisons).

Table 1 – Mean and standard deviation of metatarsal size in the male subjects.

	Parameter			
	Right foot (SD) (n = 83)	Left foot (SD) (n = 83)	Difference between right and left foot (SD)	Paired Student's t test
M I	125.20 (8.42)	125.60 (8.18)	-0.40 (2.27)	p = 0.114
M II	127.75 (8.37)	127.87 (8.14)	-0.12 (1.89)	p = 0.563
M III	123.17 (8.23)	123.54 (7.94)	-0.37 (2.08)	p = 0.106
M IV	114.16 (7.93)	114.28 (7.59)	-0.12 (2.49)	p = 0.661
M V	99.46 (8.19)	99.64 (7.82)	-0.18 (3.08)	p = 0.595
Forefoot width	86.80 (5.75)	87.31 (5.52)	-0.52 (3.04)	p = 0.125
Forefoot width/MII index	0.681 (0.050)	0.684 (0.046)	-0.003 (0.024)	p = 0.235

Source: HRM-LA; HGF-LA. M – metatarsal length in millimeters SD – standard deviation (n) – number of subjects.

Table 2 - Mean and standard deviation of metatarsal size in the female subjects.

	Parameter			
	Right side (SD) (n = 83)	Left side (SD) (n = 83)	Difference between right and left foot (SD)	Paired Student's t test
M I	115.02 (7.22)	115.23 (7.70)	-0.20 (1.72)	p = 0.280
M II	117.53 (7.24)	117.58 (7.51)	-0.05 (1.71)	p = 0.798
M III	113.51 (7.13)	113.41 (7.40)	0.10 (2.02)	p = 0.664
M IV	105.46 (7.12)	105.22 (7.47)	0.24 (2.36)	p = 0.354
M V	91.70 (7.26)	91.66 (7.71)	0.04 (3.42)	p = 0.924
Forefoot width	80.92 (4.77)	80.72 (4.56)	0.19 (2.43)	p = 0.472
Forefoot width/MII indexI	0.690 (0.045)	0.688 (0.044)	0.002 (0.022)	p = 0.463

Source: HRM-LA; HGF-LA. M – metatarsal length in millimeters SD – standard deviation (n) – number of subjects.

Comparison between males and females

Table 3 presents the means, standard deviations and ranges (maximum and minimum values) of the parameters evaluated, between the feet of the male and female individuals, and the respective comparisons. The feet were compared in relation to all the measurements obtained and the results found were:
1. There was a statistically significant difference between the groups of 166 male feet and 166 female feet, in relation to the mean measurements of metatarsal length and forefoot width ($p < 0.001$ in all the comparisons), in which the means for the group of male feet were significantly greater than those for the group of female feet.
2. There was no statistically significant difference between the male and female groups in relation to the means for the FW/MII index ($p = 0.215$).

Relationship between age and FW/MII index

Figure 3 shows the dispersion of the FW/MII index in relation to the ages of our sample, according to sex. Table 4 details the values found. In the analysis on the correlation between age and the FW/MII index, the results found were:

Tabela 3 – Médias (dp) e variações (valores mínimos e máximos) dos parâmetros avaliados nos pés masculinos e femininos e respectivas comparações.

Sexo			
Parameters	**Male (SD) (n = 166)**	**Female (SD) (n = 166)**	**Independent Student's t test**
M I	125.40 (8.28) 100 – 153	115.13 (7.44) 99 – 133	p < 0.001 *
M II	127.81 (8.23) 102 – 153	117.55 (7.35) 102 – 137	p < 0.001 *
M III	123.36 (8.06) 99 – 146	113.46 (7.25) 98 – 132	p < 0.001 *
M IV	114.22 (7.74) 94 – 135	105.34 (7.28) 91 – 124	p < 0.001 *
M V	99.55 (7.98) 81 – 120	91.68 (7.47) 75 – 117	p < 0.001 *
Forefoot width	87.05 (5.63) 70 – 101	80.82 (4.65) 66 – 95	p < 0.001 *
Forefoot width/MII index	0.683 (0.048) 0.529 – 0.832	0.689 (0.044) 0.595 – 0.804	p = 0.215

Source: HRM-LA; HGF-LA. - M – metatarsal – mean length, min – max - SD – standard deviation - (n) – number of subjects.

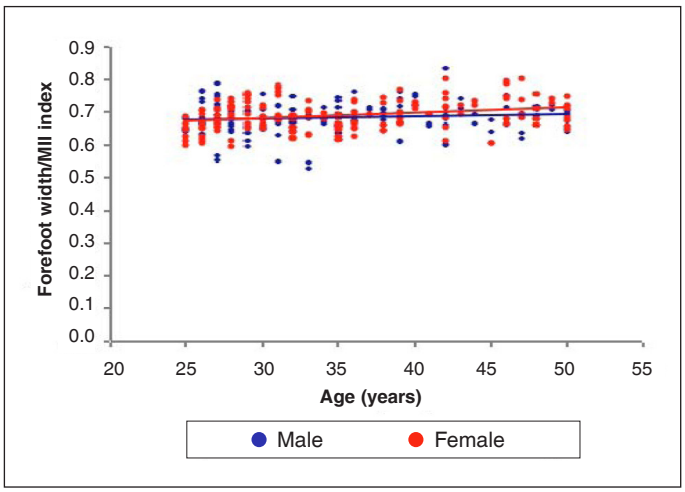

Figure 3 – Dispersion of the forefoot width/MII index in relation to the subjects' ages divided according to sex.

In the group of male feet, there was a positive but non-significant correlation between age and the index (r = 0.11; p = 0.154). In the group of female feet, there was a significant positive correlation between age and the index (r = 0.27; p < 0.001). Both correlation values were considered to be very low and would be subject to large numbers of errors in any attempt to predict the index using age alone.

Table 4 – Comparison between age groups in relation to the index, for both sexes.

Age group	Sex					
	Male			Female		
	Mean (SD)	mín – máx	n	Mean (SD)	mín – máx	n
25 – 26	0.678 (0.041)	0.633 – 0.766	20	0.642 (0.026)	0.598 – 0.686	10
27 – 28	0.693 (0.054)	0.554 – 0.789	26	0.669 (0.034)	0.606 – 0.739	20
29 – 30	0.661 (0.041)	0.594 – 0.758	18	0.687 (0.040)	0.595 – 0.722	14
31 – 32	0.675 (0.044)	0.551 – 0.750	16	0.705 (0.037)	0.653 – 0.761	22
33 – 34	0.657 (0.064)	0.529 – 0.713	10	0.689 (0.051)	0.619 – 0.783	20
35 – 36	0.684 (0.040)	0.615 – 0.763	16	0.685 (0.009)	0.678 – 0.697	4
37 – 38	0.693 (0.022)	0.649 – 0.713	8	0.666 (0.036)	0.617 – 0.739	14
39 – 40	0.704 (0.052)	0.608 – 0.763	12	0.690 (0.035)	0.643 – 0.769	18
41 – 42	0.692 (0.081)	0.600 – 0.832	10	0.711 (0.042)	0.613 – 0.802	16
43 – 44	0.703 (0.032)	0.664 – 0.742	4	0.688 (0.058)	0.607 – 0.748	8
45 – 46	0.692 (0.042)	0.641 – 0.752	8	0.732 (0.048)	0.661 – 0.804	12
47 – 48	0.684 (0.037)	0.620 – 0.719	8	0.724 (0.017)	0.709 – 0.748	4
49 – 50	0.685 (0.027)	0.642 – 0.721	10	0.667 (0.016)	0.649 – 0.684	4

Source: HRM-LA; HGF-LA - SD – standard deviation (n) – number of subjects.

The different age groups among the male feet were compared in relation to the index, and no statistically significant difference was found between them (p = 0.401). On the other hand, there was a statistically significant difference between the age groups of the female feet, in relation to the index (p < 0.001). The differences encountered did not show any tendency towards increases or decreases in the index as a function of age variation, and they were as follows:

1. The group of 25-26 years of age, with the lowest mean, was significantly different from the groups of 31-32 years, 41-42 years, 45-46 years and 47-48 years, which presented the highest means.
2. The group of 27-28 years, with the third lowest mean, differed significantly from the group of 45-46 years, which presented the highest mean.
3. The group of 37-38 years, with the second lowest mean, was significantly different from the group of 45-46 years, which presented the highest mean.

D. Metatarsal formula

Tables 5 and 6 present the classification patterns for the metatarsal formula found in the left and right feet, for each sex. In the group of 166 male feet, 119 (71.7%) were Index minus, 31 (18.7%) Index plus and 16 (9.6%) Index plus minus; while in the group of 166 female feet, 123 (74.1%) were Index minus, 30 (18.1%) Index plus and 13 (7.8%) Index plus minus. In evaluating the metatarsal formula, there was discordance in the classification between the feet of the same individual, in 16.2% of the 166 pairs of feet evaluated: 18.0% of the 83 male pairs and 14.4% of the female pairs.

Table 7 elucidates the metatarsal formulas found in our survey. The order of metatarsal formulas II > I > III > IV > V was the most common. We found *Index minus* in 71.7% of the men and in 74.1% of the women.

Table 5 – Classification patterns for metatarsal formulas found in the left and right feet among male subjects.

Right foot	Left foot	N (%)
Index minus	Index minus	54 (65.1)
Index minus	Index plus	2 (2.4)
Index minus	Index plus minus	3 (3.6)
Index plus	Index minus	3 (3.6)
Index plus	Index plus	11 (13.3)
Index plus minus	Index minus	2 (2.4)
Index plus minus	Index plus	5 (6.0)
Index plus minus	Index plus minus	3 (3.6)
Total		83 (100.0)

Source: HRM-LA; HGF-LA - (n) – number of subjects.

Table 6 - Classification patterns for metatarsal formulas found in the left and right feet among female subjects.

Right foot	Left foot	n (%)
Index minus	Index minus	57 (68.7)
Index minus	Index plus	2 (2.4)
Index minus	Index plus minus	3 (3.6)
Index plus	Index minus	1 (1.2)
Index plus	Index plus	12 (14.5)
Index plus	Index plus minus	2 (2.4)
Index plus minus	Index minus	3 (3.6)
Index plus minus	Index plus	1 (1.2)
Index plus minus	Index plus minus	2 (2.4)
Total		83 (100.0)

Source: HRM-LA; HGF-LA - (n) - number of subjects.

Table 7 – Metatarsal formulas encountered.

Male subjects (M)	(n)	Female subjects (M)	(n)
II>I>III>IV>V	57	II>I>III>IV>V	57
II>III>I>IV>V	44	II>III>I>IV>V	38
I>II>III>IV>V	29	I>II>III>IV>V	30
I=II>III>IV>V	15	II>I=III>IV>V	24
II>I=III>IV>V	14	I=II>III>IV>V	13
II=III>I>IV>V	3	II=III>I>IV>V	4
II=III>I=IV>V	1		
I=II=III>IV>V	1		
I>II=III>IV>V	2		
Total	166		166

Source: HRM-LA; HGF-LA - (n) – number of subjects M – metatarsus - I, II, III, IV and V – numbers of the five metatarsi.

Table 8 presents the means for the metatarsal measurements, for both sexes. From this table, the normal mean pattern found was that metatarsal I was 2.4 mm smaller than II in the men and 2.2 mm in the women; III was 4.4 mm smaller than II in the men and 3.8

mm in the women; IV was 9.2 mm smaller than III in the men and 8.2 mm in the women; and V was 14.7 mm smaller than IV in the mean and 13.6 mm in the women.

Table 8 – Mean measurements of the metatarsi in both sexes (mm).

	Male		Female
MI	125.4		115.1
MII	127.8	117.3	
MIII	123.4	113.5	
MIV	114.2		105.3
MV	99.5		91.7

Source: HRM-LA; HGF-LA - (n) - number of subjects M – metatarsal length.

DISCUSSION

Although many studies have not placed any emphasis on comparisons between the left and right feet, we found that their measurements were statistically similar, which thus made it possible for them to be grouped as a single sample. On the other hand, this could not be done between the sexes.

We found a variety of measurement methods in the literature, but none of them had very good reproducibility, and some did not take all five metatarsals into account. For example, some authors measured the angle formed by the heads of metatarsals I, II and V, but disregarded the measurements of III and IV[5,14-16]. Lerch[17] measured the angle formed by the axis of the metatarsal bone under examination and the straight line joining the anterior extremity of its head to the same point on its side, thus requiring instruments to measure the angle, as well as not making a measurement prediction on the normal bone. Other authors have believed that the foot should be evaluated considering a step angle (Fick) of 15° to 18°, but this not only does not give the standard angular precision but also creates the need for appropriate instruments[6,18-21]. Dragonetti and Romanòl[22] took the static axis of the foot as their reference. This is determined by joining the midpoint of the bimalleolar distance to the center of the metatarsophalangeal joint of the second toe. This also depends on a normal measurement of the talonavicular angle, which is usually abnormal in high-arch and flat feet. We could see that because of this great variability, it would be difficult to correlate the published results.

Our method is simple, easy to use, subject to little variation and minimally subject to errors, and does not require a transfer device or goniometry.

The foot grows until the age of 15 years in women and 17 years in men[23]. Fusion of the epiphysis takes place before two decades of life are completed[10,15,24-28]. We sought to evaluate individuals between the ages of 25 and 50 years, in order to avoid having immature feet in our sample and thus to avoid any possible type of bias.

Radiographic standardization is the basis for studying the biomechanical conditions of the foot[29,30]. We observed that Keim and Ritchie[31] drew attention to the importance of carrying out radiographic examination on the feet with loading applied and in the two usual projections (dorsoplantar and lateral). Moreover, Shereff et al[32] made a comparison between examinations with and without loading and concluded that significant widening of the forefoot occurred in 90% of the cases, and that the length of metatarsal bone I increased in 95% of the cases. The great variability in the measurements led us to choose a method with load-bearing, since this reproduces the situation in which complaints generally arise.

Also in relation to radiographic examinations, Fonseca Filho[33] emphasized that the aim of having the incidence of the central beam between the feet at the level of the navicular bones was to achieve a final image in a single shot and with the same degree of distortion, both for the right side and for the left side. We believe that this method actually has advantages, because it exposes patients just once for performing radiography, and because it avoids single-foot load--bearing for patients with intense pain in their feet.

Despite wide-ranging discussion in many studies, the anatomical configuration that enables pain-free functioning of the foot has still not been well determined. Marques[34] compared the feet of individuals of both sexes between different races and did not find any significant difference between their types. Honnart[35] reported that the metatarsal bones are their relative lengths had an important role in achieving adequate load-bearing. According to Steitz, apud Barbieri and Federzoni[36], anterior load-bearing of the foot is done

in 57% of the cases on the head of metatarsal I and in 20%, on II, while in 17%, it takes place on all the heads and in 6% there is no rule at all. In our study, we observed three metatarsal formulas in these normal feet.

The second metatarsal fits between the three cuneiform bones, which makes it relatively immobile in relation to the midfoot. It is generally the longest of the metatarsals. If the foot is not free to deviate laterally, the second metatarsal is overloaded at the time of toe push-off, with a weight that should be divided between this and the other metatarsals, which can be seen through the presence of a plantar callus in the region of its head[37].

Surgical removal of the base of the proximal phalanx of the hallux creates instability of the medial longitudinal arch, consequent to injury of the plantar aponeurosis and breakdown of the mechanism for arch elevation. This diminishes the load that is sustained by the head of the first metatarsal, thus resulting is weight transfer to the heads of the smaller metatarsals. If the base of the proximal phalanx of any of the smaller toes is resected, a similar problem of instability occurs, but to a lesser degree.

Resection of the head of a metatarsal, except in cases of severe deformities in a rheumatic or diabetic foot, produces a similar problem because the mechanism for plantar arch elevation is destroyed through relative shortening of the radius. This also generates increased stress and formation of calluses on the plantar face of the adjacent metatarsal head (iatrogenic compensation metatarsalgia). This makes it clear that there is a standard relationship between the lengths of the metatarsals, and that when this relationship is broken, some type of pain is caused in the affected foot[37].

Most authors have identified the presence of *Index minus* as the most common normal pattern[15,38-42]. This is in line with our results (71.7% in the male group and 74.1% in the female group).

There is a consensus that metatarsal V is always smaller than metatarsal IV, and that IV is always smaller than the first three. This pattern was obtained in 100% of our sample.

Dragonetti and Romano[22] and Marques and Napoli[43] described the presence of ten metatarsal formulas in normal feet. We found nine formulas in the male sample and six in the female sample, and all the formulas seen among the females were present in the males.

Differences of up to 2 mm, upwards or downwards, between metatarsals I and II are within normal occurrences[19]. We also found a mean difference of 2 mm between the lengths of metatarsals I and II, although in one individual the difference reached 13 mm.

CONCLUSIONS

1. Feet with *Index minus* predominated in both sexes, with three metatarsal formulas within the patterns of normality.
2. The mean normal pattern found was that metatarsal I was 2.4 mm smaller than II in the men and 2.2 mm in the women; III was 4.4 mm smaller than II in the men and 3.8 mm in the women; IV was 9.2 mm smaller than III in the men and 8.2 mm in the women; and V was 14.7 mm smaller than IV in the mean and 13.6 mm in the women.

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