Applied Ergonomics 40 (2009) 554–559

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Technical note

Dynamic foot function and morphology in elite rugby league athletes of different ethnicity

Jason K. Gurney [a,*], Uwe G. Kersting [b], Dieter Rosenbaum [c]

[a] Biomechanics Laboratory, Department of Sport and Exercise Science, The University of Auckland – Tamaki Campus, Auckland, New Zealand
[b] Center for Sensory-Motor Integration, Aalborg University, Aalborg, Denmark
[c] Motion Analysis Lab, Orthopaedic Department, University Hospital Muenster, Muenster, Germany

ARTICLE INFO

Article history:
Received 24 July 2007
Accepted 10 November 2008

Keywords:
Ethnicity
Foot
Geometry
Pressure
Footwear

ABSTRACT

It has long been assumed that foot function and morphology differ between ethnicities. However, quantitative research proving or disproving this relationship is sparse. As a starting point, the objective of this study was to investigate the plantar loading characteristics and foot geometry of athletes from three ethnicities, being Caucasian, Maori and Pacific Islanders. Four plantar pressure parameters were compared in 28 male elite rugby league players using an EMED-AT plantar pressure distribution platform [Novel GmbH, Munich, Germany] and the five-step method. Foot geometry measures were also taken, including arch index, coefficient of spreading, hallux angle and sub-arch angle. Five trials were collected per foot at a self-selected speed. It was found that Caucasian and Maori subjects had a relatively wider forefoot than the Pacific Island subjects; however the Pacific Islanders' foot was found to be wider than both these ethnicities in absolute terms. While Caucasian subjects loaded the toes to a much greater extent than the Maori and Pacific Island subjects, the latter demonstrated a greater loading of the mid and forefoot regions. Pacific Island subjects revealed a significantly more pronounced hallux valgus angle as compared to the Caucasian and Maori subjects. The results of this study may be relevant for/should be taken into consideration in footwear design issues, where allowances need to be made during the design process for anatomical differences between ethnicities. However these observations cannot be generalised to whole ethnic populations, and further research is required on non-athletes to build on the current research findings.

1. Introduction

While all humans reveal common characteristics in foot anatomy, morphology and function of the foot can vary/differ to a certain extent between individuals (Razeghi and Batt, 2002). However these differences may also exist between ethnic groups (Hayafune et al., 1999). Gottschalk et al. (1980) found a discrepancy in hallux valgus incidence between black and white South African females. In terms of foot function, Veves et al. (1995) showed that African- and Caucasian-American diabetics differed in mobility of the joints of the foot, as well as in plantar loading.

Differences in foot structure and loading characteristics between ethnicities are of considerable importance when shoe design issues are considered. Hawes et al. (1994) found that Caucasian-Americans differed in forefoot width compared to Japanese and Korean subjects, a finding that has significant implications for the development of shoe lasts which can be used generically across populations (Hayafune et al., 1999). From a clinical perspective, Abbott et al. (2005) found a threefold decrease in likelihood of foot ulceration among Asian diabetics when compared to European diabetics, a finding mainly ascribed to the overall lack of foot deformities among Asian diabetics.

However, quantitative information regarding the effects of ethnicity on dynamic foot function is sparse, and in particular no such study has been conducted on a Polynesian population. Our research group had the opportunity to measure dynamic foot function and morphology in a group of elite rugby league athletes of varying ethnicity, and this database could be useful as a starting point for further research on the effect of ethnicity on foot-related parameters. Therefore the purpose of this study was to compare foot shape and plantar load distribution in elite athletes of three different ethnicities: Caucasian, Maori and Pacific Islander.

2. Methods

Twenty-eight male elite athletes ($N = 28$, age 22 ± 2.85) from an elite local New Zealand rugby league team were recruited and gave informed consent to their involvement in this study. Participants

* Corresponding author. Tel.: +64 9 3737599.
E-mail address: jason.gurney@auckland.ac.nz (J.K. Gurney).

0003-6870/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apergo.2008.11.001

Table 1
Subject demographics and foot morphology results. N = number of subjects; BMI = body mass index; CoS = coefficient of spreading; AI = arch index; HA = hallux angle; HW = heel width; SA = sub-arch angle; FW = forefoot width; FL = foot length. Where significance is shown, $^*p < 0.05$ and $^{**}p < 0.01$.

	Caucasian		Maori		Pacific Islander		Significant differences
	Average	SD	Average	SD	Average	SD	
N	9	–	7	–	12	–	–
Age	22.6	2.67	21.9	3.53	22.25	2.57	–
BMI	29.18	2.88	29.57	1.09	30.75	2.01	C – PI*
CoS	0.37	0.02	0.37	0.02	0.36	0.02	C – PI* M – PI**
AI	0.25	0.03	0.25	0.04	0.27	0.05	C – PI** M – PI**
HA [°]	2.76	5.67	4.29	4.62	7.74	6.21	C – PI** M – PI**
HW [cm]	6.11	0.39	5.97	0.35	6.29	0.50	C – M* C – PI** M – PI**
SA [°]	104.96	13.31	101.45	10.27	117.44	22.22	C – PI** M – PI**
FW [cm]	10.77	0.67	10.70	0.60	10.96	0.50	C – PI* M – PI**
FL [cm]	29.17	1.36	28.75	1.22	30.19	0.89	C – M* C – PI** M – PI**

were free of neuromusculoskeletal injury at the time of the assessment. The frequency distribution of the ethnicities was as follows: 7 Caucasian, 9 Maori and 12 Pacific Island athletes. Table 1 shows subject demographic information for each ethnic group.

Plantar pressure was collected using an EMED-AT capacitive pressure distribution system (Novel GmbH, Munich, Germany), sampling at 50 Hz. The EMED-AT system has a resolution of 2 sensors per square centimetre, an effective measurement area of 36 cm by 19 cm and has a total of 1377 sensors. Dynamic plantar pressures were collected during normal gait at a self-selected speed (Bryant et al., 1999; Hayafune et al., 1999; Murphy et al., 2005), and subjects were allowed adequate time to familiarise themselves with the use of the platform (Rosenbaum and Becker, 1997). The five-step approach was employed, which required the subject to make contact with the platform on their fifth step. Five trials were collected per foot, which has been shown to be sufficient for the attainment of valid plantar pressure data (Gurney et al., 2008; Hughes et al., 1991). The participants were instructed not to look at or attempt to 'aim' for the platform, but asked to maintain an upright posture and fix their eyes on a target on the wall they were walking toward.

For analysis purposes the foot was subdivided into ten anatomical regions of interest using the PRC mask method (Fig. 1). Four loading parameters were investigated for each area, including peak pressure, maximum force, pressure–time integral and force–time integral. Post-analysis of plantar pressure data was completed using the Novel software programmes Multimask and Geometry (Novel GmbH, Munich, Germany).

Using the geometric analysis, foot geometry parameters were calculated for each trial (Fig. 1). These parameters included the arch index, coefficient of spreading, hallux angle and sub-arch angle. The arch index is defined by the ratio of the midfoot area divided by the total foot area, excluding the toes. The coefficient of spreading is calculated as the forefoot width (C) divided by the foot length. The hallux angle is the angle created by the deviation of the hallux (D) away from the tangential line which connects the medial heel with the medial forefoot (B). The sub-arch angle expresses the angle created by the arch between the forefoot and heel, with the origin point at the medial border of the narrowest part of the midfoot. Foot length, forefoot width and heel width were also measured using the Novel software (Novel GmbH, Munich, Germany).

A one-way ANOVA was performed with the least significant difference post-hoc test. Where correlation analyses were conducted between geometric and plantar pressure parameters, a Pearson's correlation coefficient was calculated. All statistical tests were performed in the statistical software package SPSS (version 15.0), and levels of significance were set at $p < 0.05$.

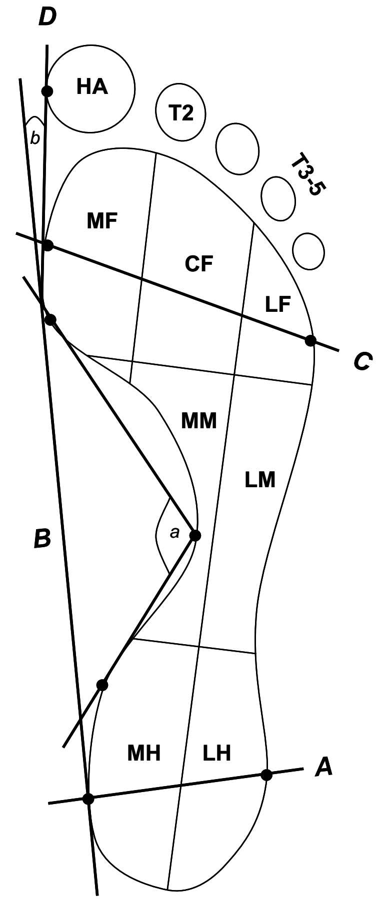

Fig. 1. PRC mask; [HA] = hallux; [T2] = second toe; [T3–5] = third to fifth toes; [MF] = medial forefoot; [CF] = central forefoot; [LF] = lateral forefoot; [MM] = medial midfoot; [ML] = lateral midfoot; [HM] = medial hindfoot; [HL] = lateral hindfoot. Geometry lines [A, B, C, D] were used to calculate arch index, coefficient of spreading, and various width and lengths. a = Sub-arch angle; b = hallux angle.

3. Results

3.1. Foot geometry

The Caucasian and Maori subjects were found to have a wider forefoot relative to foot length than the Pacific Islanders' foot, as indicated by the coefficient of spreading (C = 0.37, M = 0.37, PI = 0.36). The Caucasian and Maori feet had a significantly lower arch index than the Pacific Island foot, meaning that the midfoot comprised a lower percentage of the total foot contact area in these two ethnicities (C = 0.24, M = 0.25, PI = 0.27). The hallux angle was found to be significantly greater in the Pacific Island foot compared to the Caucasian and Maori feet (C = 2.76°, M = 4.3°, PI = 7.7°), as was the sub-arch angle (C = 105°, M = 100.3°, PI = 117.2°). The Pacific Island foot had a significantly wider forefoot than the Caucasian and Maori feet (C = 10.8 cm, M = 10.7 cm, PI = 11.0 cm). Significant differences were observed between all three ethnicities in heel width (C = 6.1 cm, M = 6.0 cm, PI = 6.3 cm) and foot length (C = 29.2 cm, M = 28.7 cm, PI = 30.2 cm), with the Pacific Island foot found to be significantly greater in both parameters [Table 1].

3.2. Plantar pressure

For peak pressure (kPa), significant differences were observed between all three ethnicities at the lateral midfoot, where the Maori foot exhibited the highest pressure (C = 135.1, M = 189.1, PI = 167.0), and medial forefoot, where the Pacific Island foot was highest ($C = 261.3$, $M = 301.6$, $PI = 355.3$). The Caucasian foot demonstrated higher peak pressures than both the Maori and Pacific Island feet at the hallux ($C = 455.6$, $M = 388.6$, $PI = 346.9$), the second toe ($C = 262.8$, $M = 149.6$, $PI = 178.5$) and the third to fifth toes ($C = 140.9$, $M = 96.3$, $PI = 129.0$). The Pacific Island foot had higher pressure than the Caucasian foot at the medial midfoot ($C = 115.2$, $PI = 127.8$) and the central forefoot ($C = 511.7$, $PI = 658.5$) [Fig. 2, Table 2].

For the pressure–time integral (kPa s), significant differences were observed between all three ethnicities at the second toe, with the Caucasian foot having the highest ($C = 50.8$, $M = 31.0$, $PI = 41.5$), and lateral midfoot, where the Maori foot was the highest ($C = 36.8$, $M = 54.6$, $PI = 47.0$). The Caucasian foot had a higher pressure–time integral than both the Maori and Pacific Island feet at the hallux ($C = 112.0$, $M = 86.8$, $PI = 81.2$). The Maori foot was greater than both the Caucasian and Pacific Island feet at the lateral heel ($C = 69.1$, $M = 81.6$, $PI = 73.5$) and medial heel ($C = 74.1$, $M = 86.2$, $PI = 77.7$). The Pacific Island foot demonstrated a greater value than both the Caucasian and Maori feet at the medial midfoot ($C = 20.9$, $M = 23.7$, $PI = 27.4$), central forefoot ($C = 147.4$, $M = 161.1$, $PI = 186.2$) and medial forefoot ($C = 91.3$, $M = 94.4$, $PI = 110.7$) [Table 3].

For maximum force (N), significant differences were observed between all three ethnicities at the second toe, with the Caucasian foot exhibiting the largest maximum force ($C = 35.8$, $M = 19.5$, $PI = 30.0$). The Caucasian foot demonstrated higher maximum force than both the Maori and Pacific Island feet at the hallux ($C = 193.9$, $M = 140.0$, $PI = 152.1$), while the Pacific Island foot showed higher maximum force than both the Caucasian and Maori foot at the lateral heel ($C = 293.6$, $M = 300.3$, $PI = 321.2$), lateral midfoot ($C = 157.0$, $M = 206.5$, $PI = 239.9$), medial midfoot ($C = 20.9$, $M = 25.6$, $PI = 58.1$), and the medial forefoot ($C = 185.8$, $M = 197.2$, $PI = 231.4$) [Fig. 3, Table 2].

For the force–time integral (N.s.), significant differences were observed between all three ethnicities at the lateral forefoot, with the Caucasian foot having the highest ($C = 149.6$, $M = 117.1$, $PI = 134.8$). The Caucasian foot showed a higher force–time integral than both the Maori and Pacific Island feet at the hallux ($C = 42.9$, $M = 29.2$, $PI = 33.3$), while the Pacific Island foot demonstrated a greater value than both the Caucasian and Maori feet at the medial midfoot ($C = 3.7$, $M = 5.1$, $PI = 10$), the central forefoot ($C = 89.7$, $M = 89.1$, $PI = 99.0$) and the medial forefoot ($C = 65.8$, $M = 59.4$, $PI = 76.3$) [Table 3].

4. Discussion

The purpose of this study was to investigate potential ethnicity-related differences in dynamic foot function and morphology in an athletic population. The results demonstrated a number of significant differences in plantar loading and foot geometry patterns between ethnicities. The Pacific Island (PI) foot was shown to have a significantly wider forefoot and heel, longer total foot, greater arch index and sub-arch angle, and a greater hallux angle than both the Caucasian and Maori feet. However, the Caucasian and Maori feet demonstrated a wider forefoot relative to total foot area than the PI foot, despite being significantly narrower in absolute terms. When combined, these

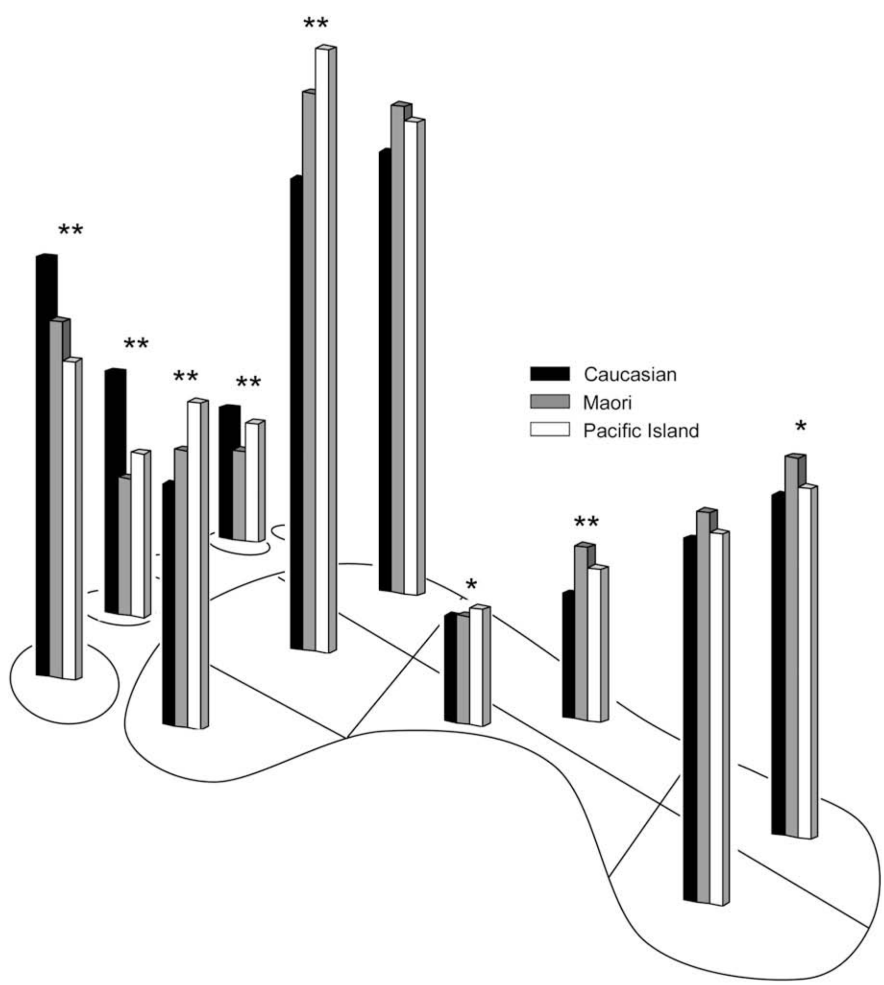

Fig. 2. Peak pressure results presented by region; $^{**}p < 0.01$; $^{*}p < 0.05$.

Table 2
Maximum force (*N*) and peak pressure (kPa) are compared between Caucasian, Maori and Pacific Island feet for maximum force and peak pressure, measured at each region. Total = total foot; HA = hallux; T2 = second toe; T3–5 = third to fifth toes; LH = lateral heel; MH = medial heel; LM = lateral midfoot; MM = medial midfoot; LF = lateral forefoot; CF = central forefoot; MF = medial forefoot. Significant differences between ethnicities are included. Where significance is shown, $^{*}p < 0.05$ and $^{**}p < 0.01$.

		Caucasian		Maori		Pacific Islander		Significant differences		
		Average	SD	Average	SD	Average	SD			
Maximum force	Total	1069.3	148.5	1003.8	68.2	1117.7	112.1	$C-M^{**}$	$C-PI^{**}$	$M-PI^{**}$
	HA	193.9	73.4	140.3	71.7	152.1	59.9	$C-M^{**}$	$C-PI^{**}$	–
	T2	35.8	14.2	19.5	10	30.0	23.1	$C-M^{**}$	$C-PI^{*}$	$M-PI^{**}$
	T3–5	34.5	21.2	18.9	14.7	34.8	27.7	$C-M^{**}$	$M-PI^{**}$	–
	LH	293.6	68.6	300.3	58.5	321.2	74.8	$C-PI^{**}$	$M-PI^{*}$	–
	MH	358.3	55.7	343.0	53.3	360.8	61.3	$M-PI^{*}$	–	–
	LM	157.0	53.9	206.5	102.6	239.9	131.9	$C-PI^{**}$	–	–
	MM	20.9	10.4	25.6	17.4	58.1	61.3	$C-PI^{**}$	$M-PI^{**}$	–
	LF	393.6	122.6	361.9	92.1	382.2	81.6	$C-M^{*}$	–	–
	CF	254.3	57.3	287.8	72.5	298.0	82.2	$C-M^{**}$	$C-PI^{**}$	–
	MF	185.8	60	197.2	66.3	231.4	80.8	$C-PI^{**}$	$M-PI^{**}$	–
Peak pressure	Total	653.2	162.4	732.9	207.50	728.6	267.5	$C-M^{*}$	$C-PI^{*}$	–
	HA	455.6	196.3	388.6	278.30	346.9	155.5	$C-M^{*}$	$C-PI^{**}$	–
	T2	262.8	139.1	149.6	75.50	178.5	109.9	$C-M^{**}$	$C-PI^{**}$	–
	T3–5	140.9	70.3	96.3	51.80	129.0	86.4	$C-M^{**}$	$M-PI^{**}$	–
	LH	369.3	67.8	413.0	110.80	381.6	137.1	$C-M^{*}$	–	–
	MH	394.7	74.4	426.4	102.90	405.3	148.6	–	–	–
	LM	135.1	29.9	189.1	103.70	167.0	51.4	$C-M^{**}$	$C-PI^{**}$	$M-PI^{*}$
	MM	115.2	35.4	117.7	54.20	127.8	38.2	$C-PI^{*}$	–	–
	LF	478.3	163.8	531.4	219.50	516.2	208.4	–	–	–
	CF	511.7	161.1	608.3	172.10	658.5	295	$C-M^{**}$	$C-PI^{**}$	–
	MF	261.3	92.3	301.6	86.40	355.3	138	$C-M^{*}$	$C-PI^{**}$	$M-PI^{**}$

findings lead to the conclusion that the PI foot has a wider, more 'flat' profile throughout the length of the foot.

The findings of this research also suggest that plantar loading patterns during gait may differ between ethnicities. While the Caucasian subjects seem to load the toes much more than the Maori and PI subjects, the latter seemed to load the mid and forefoot regions much more than the Caucasian subjects. This may be the result of a different toe-off strategy employed between ethnicities. Potential explanations for this may include a greater muscular contribution from the small intrinsic muscles of the foot in Caucasian subjects, since it appears that the toes are more actively involved in toe-off; however this would need to be further substantiated with EMG or strength analysis. Foot progression angle (Taranto et al., 2005) may also make some contribution; however analysis of this variable showed no significant differences between ethnicities, nor any correlation between foot progression angle and any of the plantar loading parameters ($C = 7.97°$, $M = 8.29°$, $PI = 7.39°$).

A particularly interesting finding was the difference in hallux angle between ethnicities. The PI foot demonstrated a significantly greater hallux angle than both the Caucasian and Maori feet. The Maori foot demonstrated a hallux angle which was almost twice that of the Caucasian foot; however this relationship was not statistically significant. These findings are in contrast to Gottschalk et al. (1984) who found no difference in hallux valgus angles between black and white South African males. It is possible that hallux valgus may be a trait in Polynesian feet, either as a result of genetic predisposition or environment; however a larger and more

Table 3
Force–time integral (N.s.) and pressure–time integral (kPa s) results. Where significance is shown, $^{*}p < 0.05$ and $^{**}p < 0.01$.

		Caucasian		Maori		Pacific Islander		Significant differences		
Force–time integral	Total	526.2	60.9	501.2	67	564.8	64.5	$C-M^{*}$	$C-PI^{**}$	$M-PI^{**}$
	HA	42.8	16.6	29.2	17.8	33.3	13.5	$C-M^{**}$	$C-PI^{**}$	–
	T2	7.2	2.6	3.9	2.2	6.7	5.8	$C-M^{**}$	$M-PI^{**}$	–
	T3–5	7.2	4.9	3.4	3	7.6	6.9	$C-M^{**}$	$M-PI^{**}$	–
	LH	56.2	15.9	62.0	13.9	63.0	17.9	$C-M^{*}$	$C-PI^{**}$	–
	MH	67.4	18.4	72.6	18.9	72.1	19.8	–	–	–
	LM	36.6	15.6	59.5	33.9	62.0	32.1	$C-M^{**}$	$C-PI^{**}$	–
	MM	3.7	2.7	5.0	3.9	10.0	9.8	$C-PI^{**}$	$M-PI^{**}$	–
	LF	149.6	47.4	117.1	30.8	134.8	29.2	$C-M^{**}$	$C-PI^{**}$	$M-PI^{**}$
	CF	89.7	22.8	89.0	27.2	98.9	27.8	$C-PI^{*}$	$M-PI^{*}$	–
	MF	65.8	20.2	59.4	18.3	76.3	27.6	$C-PI^{**}$	$M-PI^{**}$	–
Pressure–time integral	Total	246.4	38.1	259.8	72.2	264.2	72	$C-PI^{*}$	–	–
	HA	112.7	52.7	86.8	69	81.2	34.8	$C-M^{**}$	$C-PI^{**}$	–
	T2	50.8	22.1	30.9	17.1	41.5	28.5	$C-M^{**}$	$C-PI^{**}$	$M-PI^{**}$
	T3–5	31.5	15.2	19.7	10.6	30.7	22.5	$C-M^{**}$	$M-PI^{**}$	–
	LH	69.1	18.4	81.5	17.2	73.5	23.8	$C-M^{**}$	$M-PI^{**}$	–
	MH	74.1	18.3	86.2	19.6	77.7	27.4	$C-M^{**}$	$M-PI^{*}$	–
	LM	36.8	10.6	54.6	31.9	47.0	13.8	$C-PI^{**}$	$C-M^{**}$	$M-PI^{**}$
	MM	20.9	10.6	23.7	11.5	27.4	11.7	$C-PI^{**}$	$M-PI^{*}$	–
	LF	156.5	47.3	150.2	61.6	161.1	58.9	–	–	–
	CF	147.4	33.4	161.1	48.2	186.2	78.6	$C-PI^{**}$	$M-PI^{**}$	–
	MF	91.3	31.3	94.4	25.1	110.7	39.5	$C-PI^{**}$	$M-PI^{**}$	–

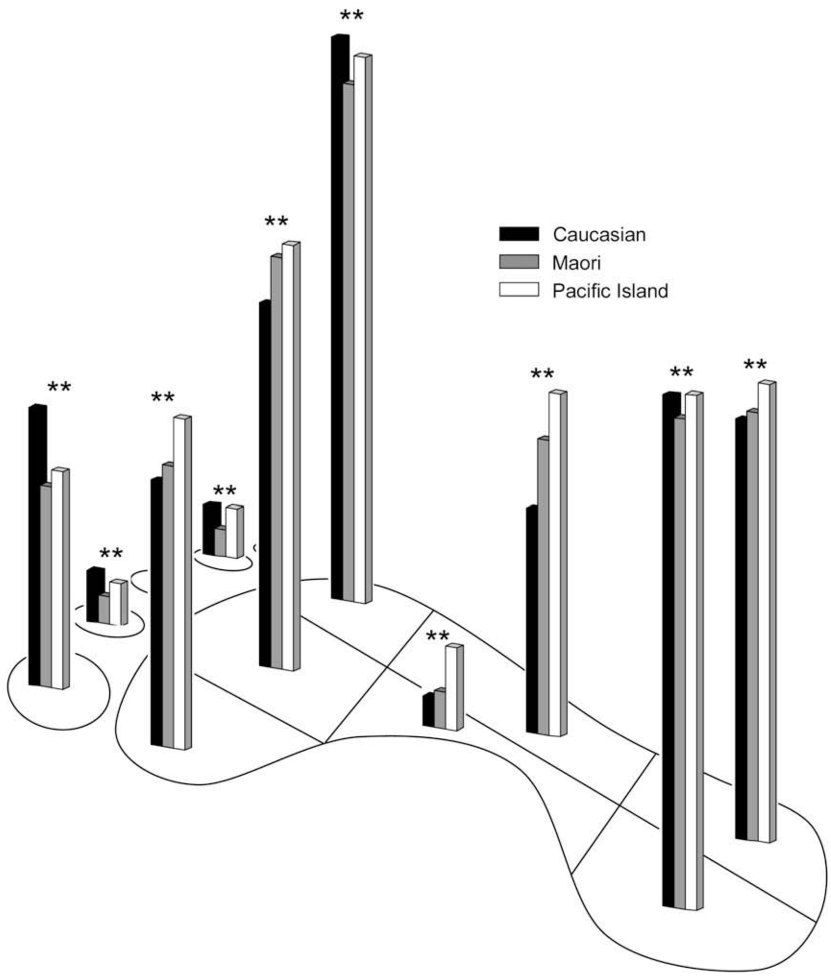

Fig. 3. Maximum force results presented by region; $^{**}p < 0.01$; $^{*}p < 0.05$.

diverse sample of subjects would be required in order to prove such a claim.

A point for consideration is how the presence of hallux valgus relates to plantar loading. Loading of the hallux has been shown to decrease with increases in hallux valgus angle (Saro et al., 2007). In combination with the different toe-off strategy discussed above, this may explain the significantly decreased plantar loading of the hallux in Maori and PI subjects compared to Caucasian subjects. In order to quantify this relationship, a correlation analysis was conducted between hallux angle and both peak pressure and maximum force at the hallux. The result of this correlation analysis, however, does not support the findings of Saro et al.; the Pearson correlation coefficients were $r = -0.153$ and $r = -0.229$ for peak pressure and maximum force, respectively. While this is a negative correlation, supporting the claim that hallux loading decreases with increases in hallux valgus, the correlation coefficients are simply too low to suggest anything but a supporting role in the attainment of this result. This may be due to the large within-ethnicity variation in hallux angle (Table 1). It is likely that the inconsistency of hallux angle data obtained is due to this parameter being measured dynamically, as opposed to statically.

4.1. Footwear

The results of the current study may have consequences in terms of footwear modalities and design. As previously mentioned, Maori and Pacific Islanders regularly report that finding athletic shoes with a proper fit can prove to be quite difficult. In fact, several subjects informed us that they have their shoes custom-built at local cobblers to overcome this problem. This study has shown that not only can ethnicity affect foot shape, but also that the loading characteristics during gait are significantly altered between ethnicities. This has significance for the design of footwear, particularly sports footwear, regarding shoe shape and the placement of shoe technologies such as cushioning elements. For example, the shift in peak loading tendencies from the toes to the forefoot exhibited by Maori and Pacific Islanders compared to Caucasians suggests that optimal design of athletic footwear for this population would incorporate greater cushioning support at the forefoot. Also the availability of width options for athletic footwear could be highly beneficial considering the significantly greater absolute width of the Pacific Island foot compared to the other two ethnicities.

Hawes et al. (1994) stated that since shoe comfort is dictated by the interaction between foot shape and shoe shape, it is necessary to gain a normative database on foot shape from the target population. This has never been conducted for the Maori and Pacific Island population. Most footwear purchased in New Zealand is designed and manufactured overseas – and it seems likely that this practice will continue for the foreseeable future.

4.2. Confounding variables

It should be emphasized that foot geometry measures were taken from data obtained during a dynamic trial, not a static, quiet standing trial. Additional anatomical measures such as static foot width, foot length and soft tissue measures could have further explained the significant differences in loading strategy observed between ethnicities but was not available.

In this study, sample diversity could also be considered as a confounding variable. It should be noted that any findings relate to a specific population, namely professional rugby league players, and therefore any conclusions cannot be generalised to either an entire ethnic population, or even to other athletic populations. Rugby league players are generally large in stature – as evidenced by their anthropometric status (Table 1) – and therefore not representative of all athletic populations, who may vary in their anthropometry depending on their specific athletic pursuit. However this is an interesting topic and the current study serves as a starting point.

The differences in peak pressures for the total foot discerned between ethnicities may have been related to the weight of subjects, since the PI group was found to have a larger BMI than the Caucasian subjects but not the Maori ($C = 29.2$, $M = 29.6$, $PI = 30.8$). Hills et al. (2001) showed differences in plantar pressures when comparing obese ($BMI = 38.8 \pm 6$) and non-obese ($BMI = 24.3 \pm 3$) subjects, where the obese subjects showed higher mean and peak pressures. However, the difference in BMI between the two groups examined in their study was far greater than the difference between the Caucasian and PI groups examined in this study. Also, it has been shown that BMI may not be an adequate measure of body shape when examining elite highly trained athletes as in the present study (Nindl et al., 1998).

5. Conclusions

This study demonstrated that different ethnicities show functional differences in foot loading and morphology during gait. Pacific Island foot tends to be wider throughout the length of the foot. Differences were observed in loading strategies between ethnicities; while the Caucasian subjects seem to load their toes to a greater extent, the Maori and PI participants were more inclined to load the mid and forefoot regions. Pacific Island subjects demonstrated a significantly greater hallux valgus angle than both the Caucasian and Maori subjects, which may have altered plantar loading at this region. In order to further quantify differences in foot morphology and function between ethnicities in a more comprehensive manner, future studies should incorporate several more static foot measurements, including three-dimensional foot analysis, as well as EMG and strength analysis of the small intrinsic foot muscles.

Acknowledgements

We would like to thank the athletes for their participation in this study.

References

Abbott, C., Morris, J., Garrow, A., Van Ross, E., Carrington, A., Boulton, A., 2005. Foot ulcer risk is lower in South-Asian and African-Caribbean compared with European diabetic patients in the U.K. Diabetes Care 28 (8), 1869–1875.

Bryant, V., Wilson, A., Jones, T., Hague, R., 1999. A high uptake eye and foot screening service for an urban population. Diabetic Medicine 16, 609–613.

Gottschalk, F., Sallis, J., Beighton, P., Solomon, L., 1980. A comparison of the prevalence of hallux valgus in three South African populations. South African Medical Journal 57 (10), 355–357.

Gottschalk, F., Solomon, L., Beighton, P., 1984. The prevalence of hallux valgus in South African males. South African Medical Journal 65 (18), 725–726.

Gurney, J.K., Kersting, U.G., Rosenbaum, D., 2008. Between-day reliability of repeated plantar pressure distribution measurements in a normal population. Gait and Posture 27, 706–709.

Hayafune, N., Hayafune, Y., Jacob, H., 1999. Pressure and force distribution characteristics under the normal foot during the push-off phase in gait. The Foot 9, 88–92.

Hawes, M., Sovak, D., Miyashita, M., Kang, S., Yoshihuku, Y., Tanaka, S., 1994. Ethnic differences in forefoot shape and the determination of shoe comfort. Ergonomics 37 (1), 187–196.

Hills, A., Hennig, E., McDonald, M., Bar-Or, O., 2001. Plantar pressure differences between obese and non-obese adults: a biomechanical analysis. International Journal of Obesity 25, 1674–1679.

Hughes, J., Pratt, L., Linge, K., Clark, P., Klenerman, L., 1991. Reliability of pressure measurements: the EMED F system. Clinical Biomechanics 6, 14–18.

Murphy, D., Beynnon, B., Michelson, J., Vacek, P., 2005. Efficacy of plantar loading parameters during gait in terms of reliability, variability, effect of gender and relationship between contact area and plantar pressure. Foot and Ankle International 26 (2), 171–179.

Nindl, B., Kraemer, W., Emmert, W., Mazzetti, S., Gotshalk, L., Putukian, M., Sebastianelli, W., Patton, J., 1998. Comparison of body composition assessment among lean black and while male collegiate athletes. Medicine and Science in Sports and Exercise 30 (5), 769–776.

Razeghi, M., Batt, M., 2002. Foot type classification: a critical review of current methods. Gait and Posture 15, 282–291.

Rosenbaum, D., Becker, H., 1997. Plantar pressure distribution measurements. Technical background and clinical applications. Foot and Ankle Surgery 3, 1–14.

Saro, C., Andren, B., Fellander-Tsai, L., Lindgren, U., Arndt, A., 2007. Plantar pressure distribution and pain after distal osteotomy for hallux vagus: a prospective study of 22 patients with 12-month follow-up. The Foot 17, 84–93.

Taranto, J., Taranto, M., Bryant, A., Singer, K., 2005. Angle of gait: a comparative reliability study using footprints and the EMED-SF. The Foot 15, 7–13.

Veves, A., Sarnow, M., Giurini, J., Rosenblum, B., Lyons, T., Chrzan, J., Habershaw, G., 1995. Differences in joint mobility and foot pressures between black and white diabetic patients. Diabetic Medicine 12 (7), 585–589.