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Printed in Great Britain
0268-0033/96 $15.00 + 0.00

0268-0033(95)00068-2

Relationship between vertical ground reaction force and speed during walking, slow jogging, and running

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Abstract

Objective. To obtain descriptive information between vertical ground reaction force (GRF)–time histories and gait speed, running style, and gender.
Design. GRF–time history measurements were obtained from male and female subjects during walking, slow jogging, jogging and running on an indoor platform.
Background. Previous studies have established GRF descriptor variables for male subjects running at speeds from 3 to 6 m s^{-1}, but very little descriptive data exists for slower or faster running, nor have previous studies reported GRF descriptors separately for female subjects.
Methods. GRF–time histories were recorded for 13 male and 10 female recreational athletes during walking and slow jogging at speeds between 1.5 and 3.0 m s^{-1}, and running at speeds between 3.5 and 6.0 m s^{-1}. Vertical GRF–time data for trials with speeds within 0.2 m s^{-1} of the prescribed speed were analysed to determine thrust maximum GRF (F_z) and loading rate (G_z).
Results. In both male and female subjects, F_z increased linearly during walking and running from 1.2 BW to approximately 2.5 BW at 6.0 m s^{-1}, remaining constant during forward lean sprinting at higher speeds. F_z was linearly correlated to G_z, the latter ranging from 8 to 30 BW s^{-1} over this speed range. Slow jogging was associated with a $> 50\%$ higher F_z and G_z in comparison to walking or fast running.
Conclusions. Similar GRF descriptor data and velocity relationships were obtained for male and female subjects. Impact forces were greatest when the subjects adopted a higher, less fixed centre of gravity during slow jogging.

Relevance

These results suggest that vertical GRF norms can be established for male and female subjects alike, and that slow or fast running with a lower, fixed centre of gravity decreases impact forces.

Key words: Gait, ground reaction force, thrust maximum, speed, running, biomechanics

Clin. Biomech. Vol. 11, No. 5, 253–259, 1996

Introduction

The popularity of recreational running has increased dramatically over the past few years, as has the incidence of overuse or repetitive loading injuries. Clinical evidence suggests that workout intensity plays a major role in the development of overuse injuries. In a study conducted by James and associates[1] involving 180 patients, 65% of the chronic injuries occurred among dedicated distance runners logging high mileage on a daily basis. Two-thirds of the chronic injuries were attributed to high mileage, workout intensity, running up hills and on hard surfaces, and/or rapid change in training routine. Other researchers have postulated that impact forces associated with repeated loading are responsible for certain types of overuse injuries of the musculoskeletal system[2,3].

The notion that there may be a positive relationship between impact force and overuse injuries during running, together with the need to assess athlete performance, has prompted numerous experimental studies of ground reaction force (GRF)–time histories during the past 20 years[4]. Ground reaction force–time

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Received: 25 January 1995; *Accepted:* 13 October 1995

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histories provide descriptive information concerning the magnitude, direction and point of application of the impact force. In general the vertical component of the GRF dominates the impact force–time history in comparison to the other two components (backward–forward, medial–lateral), and hence is the easiest to quantify. The vertical GRF also shows the least variability between and within subjects[3,5]. Studies have indicated that the descriptive data characterizing the vertical GRF (loading rate, impact peak, relative minimum, thrust maximum, decay rate) are dependent upon numerous external factors such as subject body mass, loading rate, running speed, running style, area of the foot–ground contact, as well as the mechanical properties of the foot, shoe, and surface involved[2,6–9].

Of the many external factors which influence the GRF, gait speed has been the central focus of many investigations[2,3,5,10–12]. These studies have consistently noted that the magnitude of the vertical GRF increases with increasing speed over the range of speeds examined, but have generally been limited to a narrow range of walking or running speeds and/or a small number of subjects. In an effort to establish reference standards for GRF data as a function of running speed, Munro et al.[5] collected GRF data from 20 adult males at speeds ranging from 3–5 m s^{-1}. At the speeds examined, the majority of the subjects in this study were rear-foot strikers whose GRF–time history was characterized by an initial sharp peak (impact maximum) followed by a second peak at mid-stance (thrust maximum). They noted that the impact maximum increased (about 1.5-fold) in a linear manner from 1.6 bodyweight (BW) to 2.3 BW over this range of speeds. Increases in the thrust maximum and the average vertical GRF exerted throughout the stance phase, however, were less remarkable (1.1-fold and 1.2-fold) over these running speeds, and exhibited a more non-linear relationship with speed (increasing less with increasing running speed). Nigg et al.[7] found similar trends for 14 males running at speeds ranging from 3–6 m s^{-1}. While these results establish useful standards for GRF descriptor variables for male runners, they do not provide descriptive data for women, nor do these results or previous literature consider running at speeds less than 3 m s^{-1} or greater than 6 m s^{-1}.

The objective of this study was to re-examine the relationship between the vertical GRF and speed encompassing a wide range of physiological running speeds. In particular we wished to answer the following questions: (1) does the vertical GRF increase in a linear manner at running speeds greater than 5 m s^{-1}?, (2) does gender influence the vertical GRF?, and (3) what effect does slow jogging as opposed to fast walking have on the vertical GRF?

Table 1. Subject demographics

	Males	*Females*
Age (years)	25.2 (SD 4.3)	28.4 (SD 5.4)
Height (cm)	178.4 (SD 7.0)	168.3 (SD 7.0)
Mass (kg)	75.6 (SD 12.0)	57.6 (SD 5.8)

Methods

Twenty-three subjects (13 males and 10 females) were used in this study (Table 1). All subjects were recreational athletes who participated on a regular basis in a variety of activities including: basketball, squash, cycling, soccer, racquetball, distance running, volleyball, tennis, weight lifting, triathlons, and other sports. All were within the range of normal weight for their height. The majority of subjects surveyed indicated that they run at average speeds of 8–9 minutes/mile for females and 7–8 minutes/mile for males. These speeds correspond approximately to 3.0–3.4 m s^{-1} and 3.4–3.8 m s^{-1} for females and males respectively. During the tests the male and female subjects wore Nike Aircraft running shoes with identical soles and cushioning.

Subjects were asked to walk, jog, and run over a 12-m running platform. This arrangement provided 6 m for the subjects to accelerate and decelerate. Football dummies were placed at the end of the runway as a buffer during deceleration and subjects were encouraged to use them at higher speeds. A 6-channel force platform (Model OR6-3, Advanced Mechanical Technology, Inc., Newton, MA), with a natural frequency of 400 Hz, was located flush in the centre of the platform and was directly connected to a PDP 11/23 computer. A 12-bit A/D converter was used to sample the GRF–time history data at 256 samples per second. This sampling frequency was based upon Nigg's[13] recommendation that the appropriate frequency for data acquisition should be at least five times the maximum frequency content of the analysed signal. During running up to 6 m s^{-1} the frequency content of GRF–time histories is not more than 50 Hz[13].

The force platform surface measured 508 mm × 457 mm and was outlined with a bright yellow, 25-mm wide tape. Subjects were allowed as many practice trials as needed to achieve acceptable foot contact (within the bounds of the force platform minus 25 mm on each side) and were given a rest of at least 1 min between speed trials. A line of 20 LED lights, spaced 0.5 m apart and set to blink in sequence at the desired speeds, was placed on the margin of the running stage in order to guide the subject. Subjects were required to contact the force platform using the same foot (right or left), because the data acquisition program required consistent foot usage throughout. Data from both right and left foot strikers were combined into distinct speed categories according to the method of Munro and associates[5]. An RGB video camera (Hitachi, model KP-C105A, Hitachi Denshi Ltd, Japan) and a 6-head videocassette recorder (Hitachi, model VT-330A, Hitachi Ltd, Japan) were used to film and record (at 30 frames per second) the foot-strike pattern and contact angle during each trial. The camera was located adjacent to the force platform facing either the medial or lateral aspect of the foot, depending upon whether a left or right foot strike occurred, respectively.

A minimum of four walking speeds (1.5, 2.0, 2.5, 3.0 m s^{-1}) and four running speeds (3.5, 4.0, 5.0, 6.0 m s^{-1}) were measured for males. Female subjects were measured at the same walking and running speed intervals up to 4.0 m s^{-1}, after which the speed intervals increased at 0.5 m s^{-1} intervals up to the subjects' maximum speed. In order to obtain GRF–time histories at the subjects' maximum speed, male and female subjects were encouraged to run as fast as possible above 6.0 m s^{-1} and 5.0 m s^{-1} respectively. In a subset of 12 subjects (6 males, 6 females), the subjects were asked to slow jog at speeds of 1.5, 2.0, 2.5, and 3.0 m s^{-1}. Slow jogging was distinguished from walking by the absence of a double support phase. Walking, slow jogging, and running speeds were measured by two photoelectric cells located 1 m from the centre of the force platform, and mounted so that the photoelectric cells were triggered by the subjects' waist. Up to 10 trials at each speed were recorded, and only trials in which there was good foot contact within the perimeter of the tape, a steady stride, and speeds within ±0.2 m s^{-1} of the prescribed speed were analysed.

The six-channel GRF–time history data was later processed on a PDP 11/73 computer using data analysis methods described previously[14]. The main variables reported in this paper are the vertical thrust maximum force (F_z), vertical thrust maximum loading rate (G_z), and speed (v). In order to precisely determine the magnitude and time duration of the vertical thrust maximum force, a four-point interleave filter (3 db cutoff = 15 Hz) was used to smooth the 256 samples/second GRF–time history data. This smoothing process produced data records containing 65 samples/s (256/4 + 1). Thrust maximum loading rates were calculated by dividing F_z by the time interval between initial foot contact and the occurrence of the vertical thrust maximum force. In accordance with Munro et al.[5], F_z and G_z were normalized to the subject's bodyweight (BW). Vertical impact peak forces were not determined from the GRF–time histories, since these short duration peaks were attenuated by of the smoothing scheme used to process the data. The smoothing scheme, however, produced only a small reduction (about 2–5%) in the thrust force values at the highest speeds.

Foot-contact patterns for each trial of each subject were quantified by examining digitized images obtained from the videotape recordings. Originally we had intended to determine both the foot-strike index (rear-foot, mid-foot, fore-foot)[3] and the contact angle from the video recordings of the foot-strike patterns. Both are important parameters which are required for dynamic analysis and modelling of rigid body motion of the lower extremities. Subsequent analysis of digitized images of each foot strike, however, indicated that while this procedure was adequate for determining the foot-strike index, we could not obtain accurate contact angle measurements above 3 m s^{-1} with the frame rate used (30 Hz). This paper, therefore, presents only the former. It should be noted that one can perform centre of pressure measurements to determine contact patterns[2,7], but such measurements cannot be used to compute contact angle measurements.

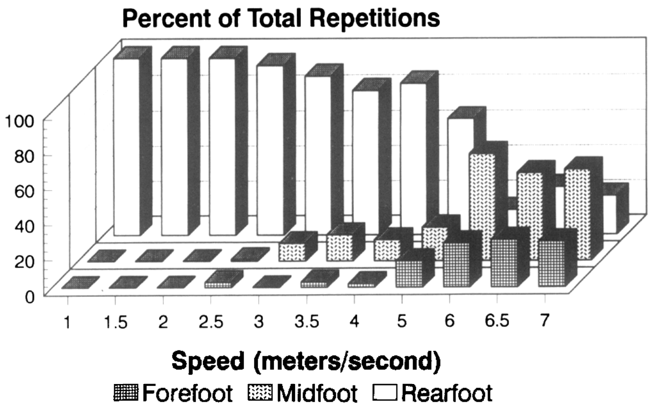

Figure 1. Foot strike indices (rear-foot, mid-foot, fore-foot) versus speed for all subjects. Indices are depicted in terms of the percentage of total walking and running repetitions (n = 879). Foot strike patterns change from predominantly rear-foot to predominantly mid-foot at 6 m s^{-1}.

Means and standard deviations (SD) of the descriptive variables were obtained at each of the fixed walking, slow jogging, and running speeds. Linear regression models were also applied to the force–velocity data, and R^2 values and levels of significance were calculated for the regression equations. An analysis of covariance (ANCOVA, equality of slopes) was also performed to determine if the regression models were significantly different for male and female subjects. GRF descriptor variable differences between men and women, at different speeds, and between slow jogging and walking were assessed using a one-way analysis of variance (ANOVA).

Results

Analysis of the foot strike indices indicated that the majority of subjects were rear-foot strikers at speeds less than 5 m s^{-1} (Figure 1). At speeds above 3 m s^{-1} there was an increasing frequency of mid-foot and fore-foot strikes. Eighty-six percent of the subjects were mid-foot or fore-foot strikers at 6.0 m s^{-1}. Eight females achieved speeds of 5 m s^{-1} and two completed five trials at 6 m s^{-1}. All males achieved speeds of 6 m s^{-1} and four completed four or more trials at 7 m s^{-1}. One male subject completed three trials at a speed of 8 m s^{-1} using a rear-foot strike pattern. Many subjects increased their stride length and assumed a more crouched, forward leaning posture during their high-speed running trials.

The vertical GRF–time histories exhibited a double peak during walking and running below speeds of 2.5–3.0 m s^{-1} (Figure 2). At these speeds the thrust maximum force was generally the first peak recorded and occurred between 15 and 25% of the total stance time. At higher running speeds, the GRF–time histories consisted of a single peak (thrust maximum) located at about 40–50% of the total stance time. The mean values for F_z ranged from 1.15 BW at 1.5 m s^{-1} to 2.54 BW at 4.5 m s^{-1} for females, and from 1.23 BW at 1.5 m s^{-1} to 2.46 BW at 5 m s^{-1} for males (Table 2). The average loading rate increased from 7.77 to 30.0 BW s^{-1} and 8.20 to 29.1 BW s^{-1} in the speed range 1.5–6.0 m s^{-1} for the female and male subjects respectively.

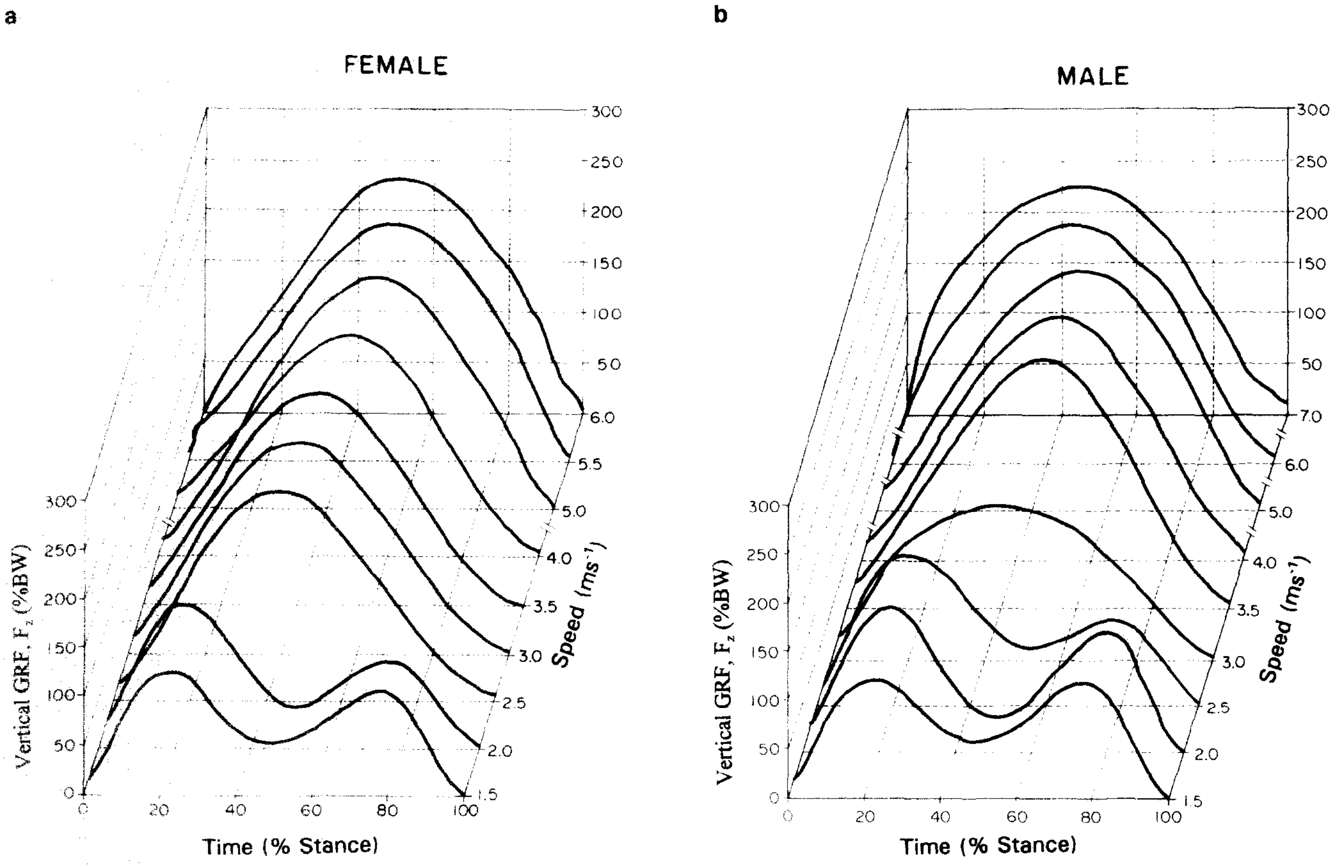

Figure 2. Anterior–posterior vertical GRF–time histories patterns as functions of running speed. Time histories shown were smoothed using a 4-point interleave filter and normalized as a percentage of the total stance time according to the method of Hasan et al.[14]. Impact peaks were not present in the vertical GRF–time histories because of the smoothing procedure used to post-process the data. (a) Female subject (7) for speeds of 1.5–6.0 m s^{-1}. Transition from double to single vertical force peak occurs at 2.5 m s^{-1}. (b) Male subject (9) for speeds of 1.5–7.0 m s^{-1}. Transition from double to single vertical force peak occurs at 3.0 m s^{-1}.

The vertical thrust maximum force increased in a linear manner with increasing speed up to about 3.5 m s^{-1} for both males and females (Figure 3). Variations in F_z were greatest in the speed transition region between walking and running (e.g. 2.5–3.0 m s^{-1}) at which point some subjects walked and some jogged. At 3.5 m s^{-1} the male and female subjects were running at 52.0% (SD 5.2) and 67.5% (SD 6.1) of their maximum speed respectively. Linear regression equations and the coefficient of determination (R^2) for F_z (BW) versus speed (walking and running gaits) in the range of $1.5 \text{ m s}^{-1} < v < 3.5 \text{ m s}^{-1}$ were:

Males (n = 291) $F_z = 0.598\,v + 0.249$, $R^2 = 0.65$ ($P<0.001$)

Females (n = 240) $F_z = 0.634\,v + 0.159$, $R^2 = 0.66$ ($P<0.001$)

where n is the number of trials. Incremental changes in F_z were statistically significant (ANOVA, $P<0.05$) up to 3.5 m s^{-1} for both male and female subjects. At speeds greater than about 3.5 m s^{-1} there were no significant increases in F_z for either group of subjects. In the male subjects there was a slight decrease in F_z at the highest speeds, particularly for the subject who ran up to

Table 2. Summary of vertical GRF variables (mean values) grouped by running speed and sex

Females			*Males*		
Speed ($\pm$0.2 m s^{-1})	*Thrust max. force (F_z, BW)*	*Loading rate (G_z, BW s^{-1})*	*Speed ($\pm$0.2 m s^{-1})*	*Thrust max. force (F_z, BW)*	*Loading rate (G_z, BW s^{-1})*
1.5 (n = 50)	1.15 (0.10)	7.77 (1.78)	1.5 (n = 65)	1.23* (0.10)	8.20 (1.84)
2.0 (n = 50)	1.36 (0.18)	11.5 (2.36)	2.0 (n = 64)	1.42* (0.14)	11.0 (2.29)
2.5 (n = 49)	1.73 (0.43)	14.6 (3.71)	2.5 (n = 65)	1.62 (0.24)	14.6 (2.46)
3.0 (n = 50)	2.11 (0.46)	16.9 (3.97)	3.0 (n = 61)	2.10 (0.50)	16.0 (3.30)
3.5 (n = 41)	2.36 (0.25)	19.1 (3.82)	3.5 (n = 37)	2.45 (0.28)	18.32 (3.36)
4.0 (n = 48)	2.33 (0.32)	19.6 (4.65)	4.0 (n = 58)	2.35 (0.48)	18.9 (4.85)
4.5 (n = 10)	2.54 (0.27)	23.7 (4.91)			
5.0 (n = 38)	2.28 (0.32)	22.3 (4.61)	5.0 (n = 60)	2.46* (0.33)	22.8 (4.51)
5.5 (n = 10)	2.13 (0.32)	22.5 (6.87)			
6.0 (n = 10)	2.45 (0.13)	30.0 (2.63)	6.0 (n = 67)	2.38 (0.28)	29.1 (15.2)
			6.5# (n = 26)	2.34 (0.23)	37.8 (29.3)
			7.0# (n = 17)	2.29 (0.19)	36.5 (22.5)
			8.0# (n = 3)	1.89 (0.49)	58.5 (37.6)

SD in parentheses. n = number of trials.
*Significant difference (ANOVA, $P<0.05$) compared to females.
#Approximate running speed across force platform since subjects were accelerating between 4 and 6 metre speed measurement interval.

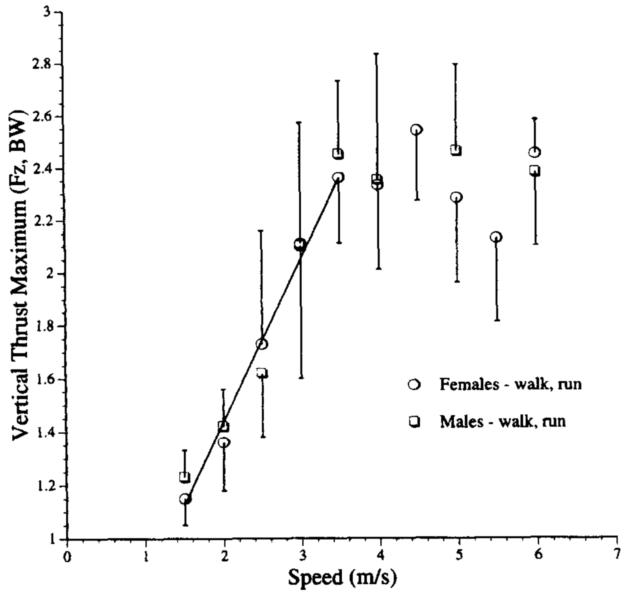

Figure 3. Comparison of male (open squares) and female (open circles) vertical thrust maximum force versus speed (1.5–6.0 m s^{-1}). Mean and standard deviations are shown. Best fit line for combined male and female subjects is also shown for speeds up to 3.5 m s^{-1} (see text for linear regression equation). Differences between male and female subjects were significant (ANOVA, $P<0.05$) at speeds of 1.5, 2.0, and 5.0 m s^{-1}.

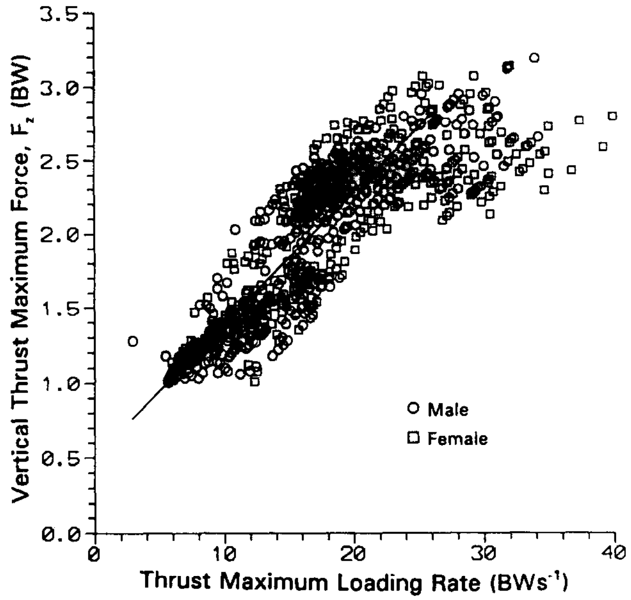

Figure 4. Vertical thrust maximum force (F_z) versus thrust maximum loading rate (G_z) for male (open squares) and female (open circles) during walking and running. Both male and female subjects exhibited a similar positive linear relationship between F_z and G_z. Best fit line for combined male and female subjects is shown in the range $2.9 < G_z < 26$ BW s^{-1} (see text for linear regression).

8 m s^{-1} (F_z = 1.89, SD 0.49 m s^{-1}. Changes in G_z were also linear with regards to speed throughout the range of walking and running speeds examined. However, the relationship between F_z and G_z was most linear only up to about 26 BW s^{-1}, after which F_z remained relatively constant (Figure 4). The following linear regression equation and coefficient of determination (R^2) was obtained for F_z (BW) versus G_z during walking and running:

$$\text{Males } (n = 436) \quad F_z = 0.089G_z + 0.520, \quad R^2 = 0.79\ (P<0.001)$$

$$\text{Females } (n = 356) \quad F_z = 0.090G_z + 0.482, \quad R^2 = 0.77\ (P<0.001)$$

where $G_z < 26$ BW s^{-1}.

An ANOVA indicated that the difference in F_z (BW) between male and female subjects was significant for the following gait speeds: 1.5, 2.0 and 5.0 m s^{-1}, but these differences were small (<8%). There were no significant differences in G_z (BW s^{-1}) between the male and female subjects at any of the speeds examined.

An ANCOVA indicated that there were no significant differences between the force–velocity and loading rate–velocity linear regression equations (equality of slopes) obtained for the male and female groups. Consequently the data for male and female subjects was combined, yielding the following linear regression relationships:

$$\text{Males + females } (n = 531) \quad F_z = 0.614\,v + 0.208, \quad R^2 = 0.65\ (P<0.001)$$

$$\text{Males + females } (n = 753) \quad F_z = 0.089G_z + 0.503, \quad R^2 = 0.78\ (P<0.001)$$

where $1.5 < v < 3.5$ m s^{-1} and $2.9 < G_z < 26$ BW s^{-1}.

Thrust maximum forces and loading rates were as much as 62 and 65% greater, respectively, during slow jogging than during walking at the same speed (Table 3). Differences in F_z and G_z for slow jogging versus walking were statistically significant (ANOVA, $P<0.001$) at speeds ranging from 1.5–2.5 m s^{-1} in female subjects and 1.5–3.0 m s^{-1} in male subjects. Females exhibited a smaller difference in forces between slow jogging and walking than males. Both groups indicated that walking was preferable to slow jogging or 'slogging'.

Discussion

In this study, GRF–time histories and foot-strike indices were analysed for 23 young male and female recreational athletes during walking, slow jogging, and running on a force platform. Normative data for vertical GRF descriptor variables (thrust maximum, average loading rate) were presented and relationships between the GRF descriptors and speed were studied. The notion that altered running gait (slow jogging versus walking) may influence the GRF–time histories was also examined. In order to establish normative GRF data, a relatively large number of subjects wearing shoes with identical soles and cushioning was studied. Over 1100 GRF–time histories and foot contact patterns were collected and analysed for walking, slow jogging, and running at speeds ranging from 1.5 m s^{-1}–8.0 m s^{-1}. Despite limitations in the runway length, most of the male and two of the female recreational athletes examined in this study were able to achieve constant running speeds up to 6 m s^{-1}.

The magnitudes of the vertical thrust maximum forces obtained in this study for walking (less than about 2.5–3.0 m s^{-1}) and running (greater than 2.5–3.0 m s^{-1}) compare favourably with previously published results[2,3,5,9,11,12,15–20]. Results from these studies are summarized graphically in Figure 5 for comparison to the present study. Examination of

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