GROUND REACTION FORCES IN RUNNING: A REEXAMINATION

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Abstract—Ground reaction force (GRF) data were collected on twenty adult males during running stance to establish normative standards to aid in assessment of the gait of atypical runners. Subjects ran between 30 and 40 trials across a Kistler 0.6×0.9 m force platform at self-selected speeds ranging from 2.5 to 5.5 m s^{-1}. Best fit polynomials for a given descriptor variable were constructed for each subject and the polynomials were evaluated as a function of running speed. Predicted means and standard deviations (based on the polynomials) were calculated and multivariate analyses of variance were performed. The descriptor variables: impact peak, loading rate, thrust maximum, decay rate, average vertical GRF, change in vertical velocity, braking impulse, propulsive impulse and stance time were determined to be running speed dependent ($p < 0.001$). Specific patterns associated with the breaking component of the antero-posterior GRF of heel-strikers included single, double and multiple peaks. Three dimensional graphic displays showed that, despite considerable group variability in medial-lateral GRF–time histories, consistency was evident in the patterns of individuals across speeds. Individual right–left asymmetries were clearly shown in these displays.

INTRODUCTION

Ground reaction force–time histories, which reflect the acceleration patterns of the center of gravity, form a part of the descriptive data characterizing the mechanics of running gait. Previous studies have consistently indicated that both the magnitudes and durations of the ground reaction force (GRF) are running speed dependent (Roy, 1981, 1982; Hamill *et al.*, 1983). In general, however, studies have been limited in the number of subjects and/or in the range of running speeds examined (e.g. Payne, 1978, 1983). Further, their values were not reported in a form which could be readily used for comparative purposes (e.g. Bates *et al.*, 1981; Roy, 1981). Consequently, there was a need to develop reference standards for ground reaction data as a function of running speed. Such standards would be useful in assessing performance of atypical runners or in charting the progress of a runner during the recovery process following an injury.

In the course of developing these ground reaction norms, an opportunity was provided to reexamine some of the questions raised in the literature. Specifically, there were conflicting reports as to whether the fore–aft component associated with braking was characterized by a single or a double peak (Cavanagh and Lafortune, 1980; Hamill *et al.*, 1983;

Payne, 1983). It also appeared worthwhile to reexamine the medial-lateral ground reaction force pattern because of the high variability reported within and between subjects (Cavanagh and Lafortune, 1980; Cavanagh, 1982).

MATERIALS AND METHODS

Twenty adult male subjects (Table 1) ran 30 to 40 trials across a Kistler (Type Z4582) 0.6×0.9 m force platform. The platform, installed flush with a 40 m unobstructed running surface, was connected on-line to a PDP 11/34 computer sampling at 1000 Hz per channel. Speeds ranged from 2.5 to 5.5 m s^{-1} and attempts were made to obtain equal numbers of right and left foot contacts. Only trials in which force platform contact was made with a smooth, unbroken running stride were retained for analysis. Running speed was determined utilizing photoelectric cells situated 5 m apart at neck level on either side of the force platform.

Table 1. General characteristics of the subject population

	Age (yr)	Height (m)	Mass (kg)	Running distance per week (km)
Mean	25.4	1.8	77.1	22.8
S.D.	2.4	0.1	12.4	14.8

All subjects wore the shoes they customarily used for jogging. No attempt was made to control for shoe type since the purpose of the study was to establish robust representative values appropriate for application in research and clinical settings in which subjects would be wearing various brands of jogging shoes. Consequently, the standards developed from the current study intentionally incorporated minor variability introduced by differences in shoe construction (Clarke et al., 1983).

After data collection was completed, the change in velocity of the center of gravity in the forward–backward direction during force plate contact was calculated using the linear impulse–momentum relationship. Trials in which the change was greater than $\pm 0.10\ \text{m s}^{-1}$ were rejected.

Foot placement on the force platform was recorded on fabric-backed, moderately textured, lightly colored vinyl wallpaper taped to the force plate. Lines designating the X and Y axes intersecting at the center of the platform were drawn on the paper and served as the coordinate reference system for locating foot position. Before each trial, the subject coated the bottoms of both shoes with blue powdered tempera paint so that an easily distinguishable footprint was left on the platform. A cardboard outline of the subject's shoe aided in recording the midpoints of the heel and toe after each trial. This system allowed approximately twenty trials to be permanently recorded on a single sheet of paper with minimum time delay between trials.

Foot-contact patterns, based on mean foot-strike indices (Cavanagh and Lafortune, 1980) of six trials for each subject, were used to classify the subjects. Initial contacts occurring in the first 1/3 of the total foot length were classified as rear-foot strikes, while the middle 1/3 and last 1/3 were considered midfoot and forefoot strikes, respectively.

Trials for an individual subject which met the criteria for acceptance were combined into a data file containing selected variables characterizing the ground reaction force patterns. Thus a file with an average of 22 ± 5 trials was created for each subject. This file contained information over a running speed range of 2.5 to $5.5\ \text{m s}^{-1}$ for both the right and left feet.

Combining the data of both feet was legitimized by dividing the running speed range into three distinct speed categories (3.5, 4.0 and $4.5\ \text{m s}^{-1} \pm 5\%$ in each case). Five subjects per category were chosen with the criterion for inclusion being a minimum of two observations on each foot in that particular category. A Student's t-test for unequal sample size performed for stance time, average vertical GRF, loading rate, braking impulse and propulsive impulse did not indicate statistically significant differences ($p < 0.05$) for any of these variables between right and left feet. Thus, as a group, right–left asymmetries could not be detected. These findings were in agreement with Hamill et al. (1984) who observed no statistically significant differences between the right and left feet for twenty variables tested. It should be noted, however, that

bilateral asymmetries are reportedly present within individuals (e.g. Cavanagh et al., 1985).

To determine means and standard deviations for a given variable at fixed running speeds, polynomial regression models were generated for each variable of each individual. The polynomial regression models were constructed based on a least squares best-fit in which the partial residual sum of squares of two successive degree polynomials were compared. If there was no improvement, the lesser degree polynomial was chosen. A regression F statistic and an R^2 value were calculated for each regression equation. Analysis of variance for repeated measures was performed to assess the relationship between the dependent variables and running speed. The models were evaluated at speeds from 3.00 to $5.00\ \text{m s}^{-1}$ in $0.25\ \text{m s}^{-1}$ increments. For purposes of standardization, these models were then used to predict the values for the variables at fixed running speeds for each individual. Means and standard deviations for the group were then determined.

The vertical and horizontal GRF–time histories for individuals were also displayed as three dimensional plots with force magnitude, running speed and time being displayed on the axes.

RESULTS AND DISCUSSION

Foot-strike classification

Foot-strike indices from six trials for each subject indicated that seventeen subjects were consistently rear-foot strikers. Two of the subjects, however, had two midfoot strikes and one had four midfoot strikes among the six analyzed. Initial contact was associated with the largest amount of inter-subject variability and consequently no discernible systematic relationship in the group data was noted between the running speeds investigated and the region of initial contact. Following contact, which generally occurred on the lateral border of the foot, the center of pressure pattern continued medially and anteriorly until toe-off and was similar for most of the subjects by the time it reached the midfoot region.

Stance time

It has been well established that stance time is negatively related to running speed. In the present investigation, stance time, defined as the period of time during which the vertical GRF exceeded 16 N, decreased ($p < 0.001$) from 270 to 198 ms as the running speed increased (Table 2). These values were comparable to those reported by Bates et al. (1981) and Roy (1982) but were 10–17 ms longer than reported for ten rear-foot strikers running at $3.8\ \text{m s}^{-1}$ (Clarke et al., 1983) and about 25 ms longer than the average of 188 ms for rear-foot strikers running at $4.5\ \text{m s}^{-1}$ reported by Cavanagh and Lafortune (1980). The latter discrepancy can principally be attributed to the difference in the minimum vertical force used to define

Table 2. Stance time and antero-posterior GRF standards

Speed (m s^{-1})	Stance time (ms)	Braking impulse (BWI)	Zero fore–aft shear (%ST)	Propulsive impulse (BWI)
3.00	270 (20)	−0.15 (0.05)	47.1 (3.1)	0.14 (0.01)
3.25	258 (18)	−0.17 (0.03)	47.2 (2.8)	0.16 (0.01)
3.50	247 (17)	−0.18 (0.02)	47.5 (2.6)	0.17 (0.01)
3.75	238 (15)	−0.20 (0.02)	47.8 (2.1)	0.19 (0.01)
4.00	229 (14)	−0.21 (0.02)	48.0 (1.8)	0.20 (0.01)
4.25	221 (13)	−0.23 (0.02)	48.2 (1.8)	0.21 (0.02)
4.50	214 (13)	−0.24 (0.02)	48.3 (1.8)	0.23 (0.02)
4.75	206 (13)	−0.25 (0.03)	48.2 (2.0)	0.24 (0.02)
5.00	199 (13)	−0.25 (0.03)	47.9 (2.3)	0.25 (0.02)

S.D. indicated in parentheses.

stance. Had we utilized 50 N as did Cavanagh and Lafortune, our times would have been decreased by 2–4 ms at the onset and 10–15 ms at the end of the stance period. This observation underlines the importance of reporting the minimum vertical force accepted as 'signal' if ground contact times are to be compared across studies.

Antero-posterior ground reaction force

The antero-posterior GRF elicited during running typically has been characterized as predominantly biphasic. The initial phase, in which the GRF direction opposes forward movement, is termed braking and the latter phase, in which the force is consistent with the direction of forward motion, is designated propulsion.

Although reasonably constant for a given subject (Fig. 1), the pattern of the braking force in the present investigation was variable across subjects (Fig. 2). Five subjects had braking patterns which peaked at approximately 25% of the total stance time. A second prevalent braking pattern (ten subjects) had two peaks which generally occurred at 7 and 24% of the stance period. A third pattern (five subjects) had multiple braking peaks.

The observation of single, double and multiple braking patterns in a group comprised of rear-foot strikers was contrary to the findings of previous studies. Hamill *et al.* (1983) and Payne (1983) reported that the braking force of rear-foot strikers was characterized by two peaks whereas that of midfoot strikers was single peaked. In contrast, Cavanagh and Lafortune (1980) reported a single peaked curve for rear-foot strikers and a double peaked pattern for the

midfoot strikers. Results of the present investigation indicate that the association of foot-strike classification with specific braking patterns is not as straightforward as previously believed.

Braking and propulsive impulses. The method of trial selection was designed to ensure that the braking and propulsive impulses were nearly equal in magnitude but opposite in direction. This was done so that the assumption that subjects were approximating a constant horizontal velocity as they passed over the force platform could be made. While the design was believed to accomplish its purpose, it did appear that the braking impulses of the trials selected were slightly larger than their corresponding propulsive impulses. The difference noted however would result in a change in horizontal velocity during stance of only −0.02 m s^{-1}. Such a difference was deemed negligible from a functional standpoint and was not considered to detract from the utility of the standards.

The braking and propulsive impulses in Ns were normalized across subjects by dividing each by the impulse of the individual's body weight over the entire stance time (i.e. body weight impulse or BWI). The braking impulse increased ($p < 0.001$) from 0.15 BWI at 3.0 m s^{-1} to 0.25 BWI at 5.0 m s^{-1} while the propulsive impulse increased ($p < 0.001$) from 0.14 BWI to 0.25 BWI (Table 2). The time at which the fore–aft shear changed direction (zero fore–aft shear) from backward (braking) to forward (propulsion) remained at approximately 48% of the stance period. This compared with 50 and 49% for ten males running at 4 and 5 m s^{-1} respectively reported by Hamill *et al.* (1983).
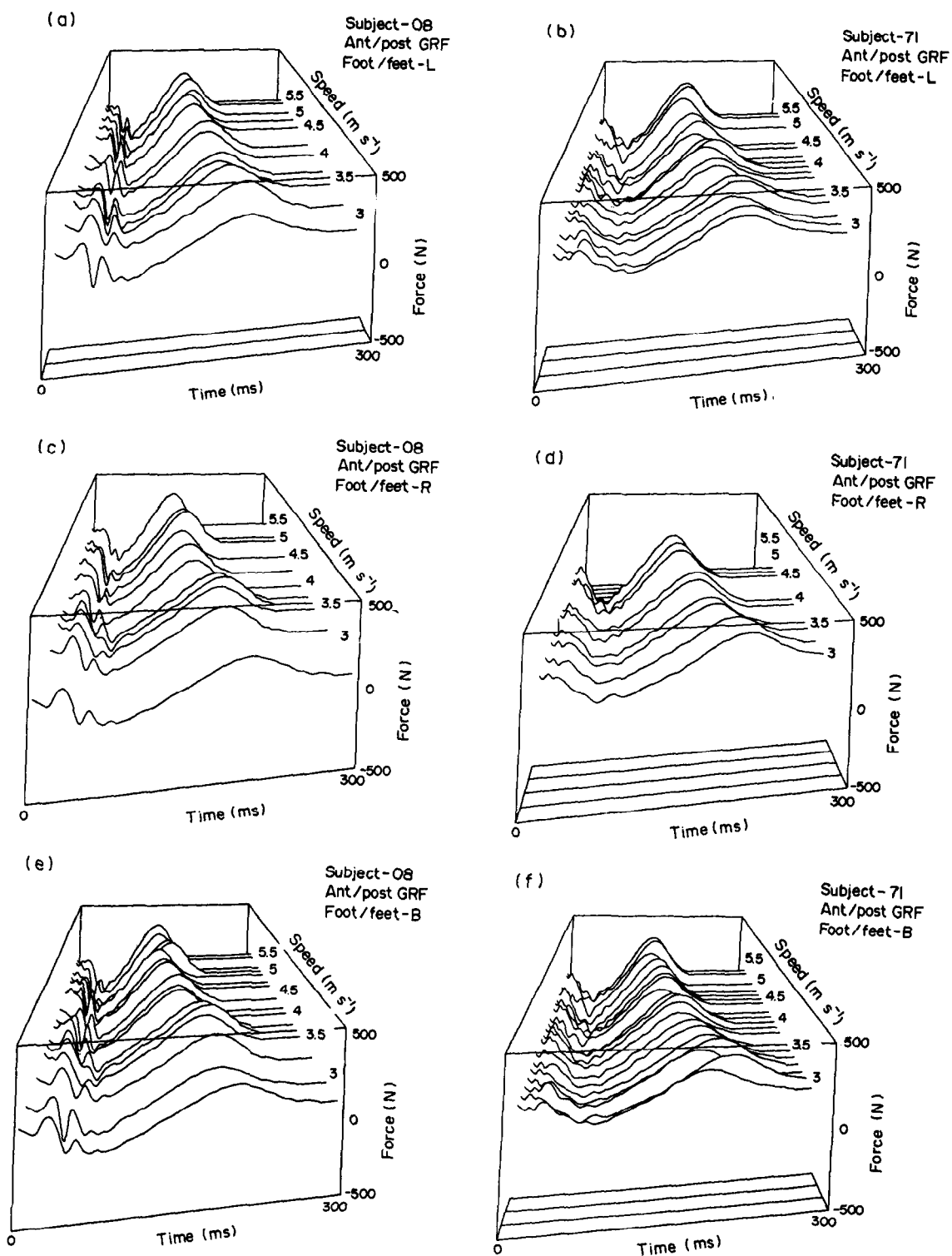
Fig. 1. Antero-posterior GRF patterns as functions of running speed. In this figure, as well as in Figs 3 and 4, the records of two subjects are shown (subject 8 on the left and subject 71 on the right). The upper and middle panels show the GRF–time histories elicited by the left and right feet respectively while the bottom panel combines the data from both feet.

Vertical ground reaction force

The double peaked configuration observed in the vertical component of the GRF was characteristic of those reported in previous literature for heel-strikers (Miller, 1978; Cavanagh and Lafortune, 1980; Hamill *et al.*, 1983, 1984; Payne, 1983). The so-called 'impact' peak was followed by a decrease to a relative minimum and a subsequent rise to a second peak (designated
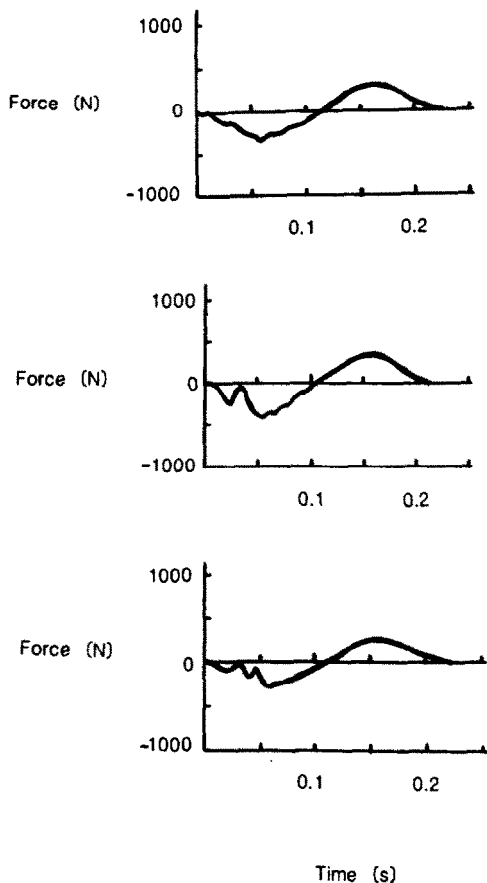
Fig. 2. Variability in braking patterns among heel-strikers. Single, double and multiple peaks are evident in the upper, middle and bottom records. Five, ten and five subjects, respectively displayed these three patterns.

thrust maximum) in the force record (Fig. 3).

Means and standard deviations for the predicted values of loading rate, impact maximum, relative minimum, thrust maximum, average vertical GRF, decay rate and change in vertical velocity are listed in Table 3. Analyses of variance for repeated measures indicated that all vertical GRF descriptor variables increased significantly with running speed ($p < 0.001$).

Impact peak. The initial sharp peak in the vertical GRF associated with heel-strikers has received considerable attention because of its possible implication in running injuries. Nigg et al. (1981) described the so-called impact peak as a high frequency, passive force and noted that ineffective attenuation could result in microtrauma to soft tissue and bone. While it is logical to assume that the magnitude of the impact peak would be more influenced by the type of shoe (i.e. its impact absorbing qualities) than would other GRF variables, unequivocal support for this contention is lacking in the literature (Bates et al., 1983; Clarke et al., 1983; Nigg and Luethi, 1980). The human runner seems to have an extensive adaptive capability such that intra-subject variability often exceeds the variability introduced by different shoe types.

In the present investigation in which the subjects wore their own jogging shoes, the impact peak generally occurred between 6 and 17% of the total stance time and its magnitude increased from 1.6 body weight (BW) at $3.0 \, \mathrm{m \, s^{-1}}$ to 2.3 BW at $5.0 \, \mathrm{m \, s^{-1}}$. These predicted forces were in agreement with values reported previously (Miller, 1978; Clarke et al., 1983; Hamill et al., 1983).

Loading rate. Nigg (1983) presented data on five subjects running at $3 \, \mathrm{m \, s^{-1}}$ in which there was a strong relationship ($r = 0.98$) between the impact peak and loading rate. This correlation suggests that loading rate is a valuable tool in assessing rise to impact. Because of the absence of an impact peak in midfoot strikers (Cavanagh and Lafortune, 1980) and in special populations such as below-knee amputees (Miller et al., 1981), quantification of the initial phase of the vertical GRF may more appropriately be accomplished by reporting the loading rate.

In the present investigation, loading rate was calculated by determining the time required for the vertical force to rise from 50 N to body weight plus 50 N. A significant ($p < 0.001$) increase in the loading rate from $77.2 \, \mathrm{BW \, s^{-1}}$ at $3.0 \, \mathrm{m \, s^{-1}}$ to $113.0 \, \mathrm{BW \, s^{-1}}$ at $5.0 \, \mathrm{m \, s^{-1}}$ was observed.

Thrust maximum. The thrust peak, which is the second peak in the vertical GRF-histories of rear-foot strikers, generally occurred between 35 and 50% of the total stance time and its magnitude increased ($p < 0.001$) from 2.5 BW at $3.0 \, \mathrm{m \, s^{-1}}$ to 2.8 BW at $5.0 \, \mathrm{m \, s^{-1}}$. These data were in agreement with Roy (1982) who presented mean thrust peaks ranging from 2.6 to 3.0 BW for twenty subjects running at 3.4, 3.8, 4.8 and $5.4 \, \mathrm{m \, s^{-1}}$. The values were also similar to the 2.8–2.9 BW reported by Hamill et al. (1983) for running speeds of 4.0 and $5.0 \, \mathrm{m \, s^{-1}}$, respectively.

Decay rate. Following the thrust peak, the force dropped slowly as the stance phase neared its completion. The rate at which this force dropped from $BW + 50 \, N$ down to 50 N increased from 14.6 at $3.0 \, \mathrm{m \, s^{-1}}$ to $23.9 \, \mathrm{BW \, s^{-1}}$ at $5.0 \, \mathrm{m \, s^{-1}}$ ($p < 0.001$). Determination of the rate at which the force approaches zero can provide insight regarding the toeing-off behavior of a runner.

Average vertical GRF. The average vertical GRF is a reflection of the vertical GRF exerted throughout the stance phase and is therefore subject to less intra-individual variance than the other vertical GRF descriptor variables (e.g. loading rate, impact peak, etc.). As such, small differences between two trials at comparable running speeds would be difficult to detect. However, if differences are of sufficient magnitude to be reflected in the average vertical GRF, the investigator or clinician could be reasonably confident that there were functionally significant differences in the running pattern. Consequently, the average vertical GRF can be used to monitor treatment programs which result in changes in the vertical acceleration of the total body center of gravity (e.g. due to prosthesis alterations or changes in weight-bearing following
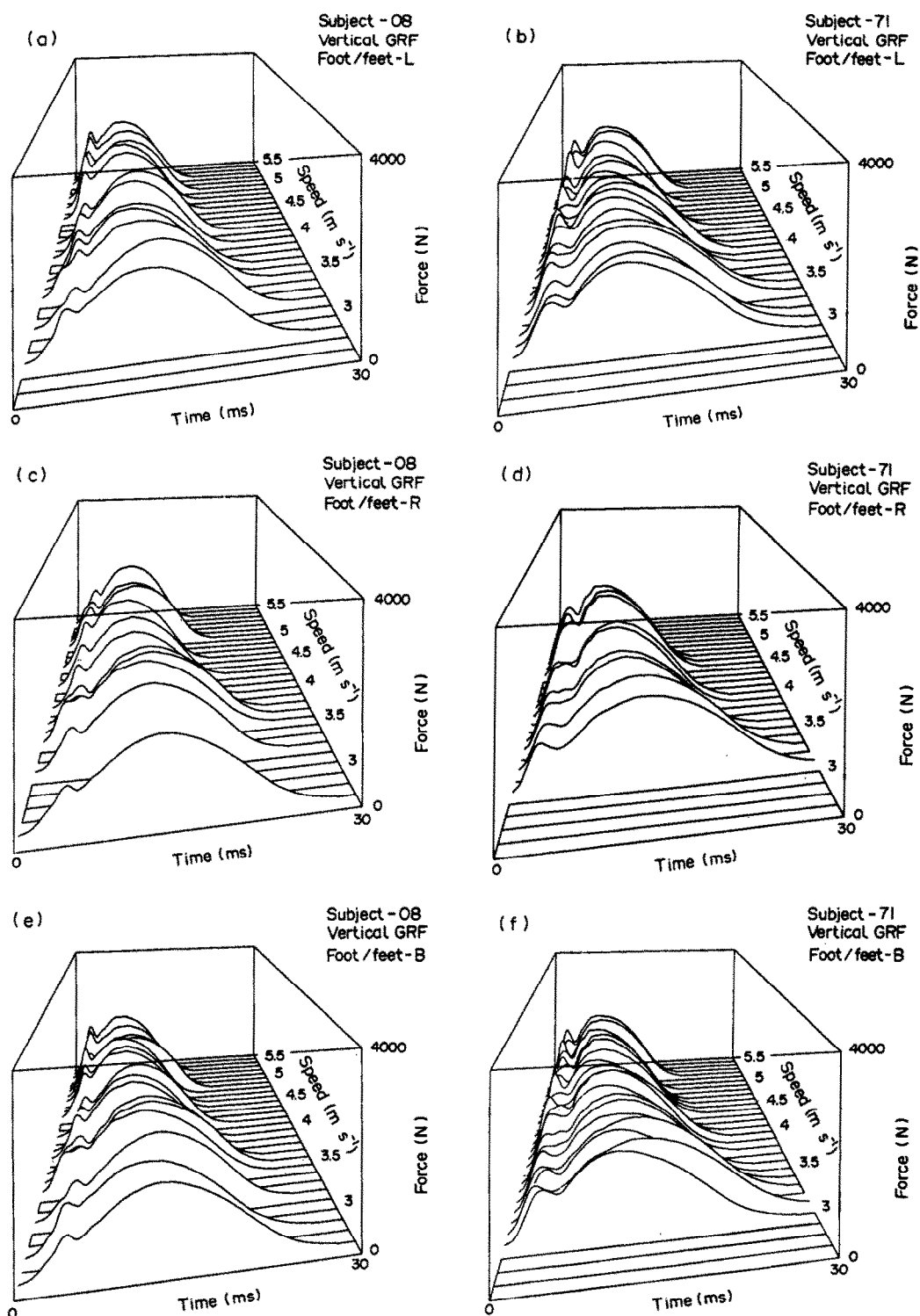
Fig. 3. Vertical GRF patterns as functions of running speed.

injury). The average vertical GRF increased significantly ($p < 0.001$) from 1.40 at 3.0 m s^{-1} to 1.70 BW at 5.0 m s^{-1}.

Change in vertical velocity. Change in vertical velocity gives information regarding a runner's ability to reverse the downward velocity of the center of gravity at touch-down to an upward velocity at take-off. This variable, calculated by subtracting the body weight impulse from the vertical GRF impulse and dividing by the mass of the subject, showed a significant ($p < 0.001$) increase from 1.0 to 1.5 m s^{-1} over the running speed range. This would follow directly from

Table 3. Vertical GRF standards

Speed (m s^{-1})	Loading rate (BW s^{-1})	Impact maximum (BW)	Relative minimum (BW)	Thrust maximum (BW)	Average vertical GRF (BW)	Decay rate (BW s^{-1})	Change in vertical velocity (m s^{-1})
3.00	77.2 (26.7)	1.57 (0.35)	1.28 (0.24)	2.51 (0.21)	1.40 (0.11)	14.6 (2.1)	0.99 (0.21)
3.25	77.4 (19.0)	1.69 (0.21)	1.34 (0.22)	2.56 (0.17)	1.44 (0.08)	15.8 (1.8)	1.01 (0.46)
3.50	80.0 (16.9)	1.76 (0.19)	1.40 (0.22)	2.62 (0.16)	1.49 (0.08)	16.9 (1.8)	1.07 (0.51)
3.75	84.6 (17.1)	1.86 (0.20)	1.46 (0.23)	2.67 (0.16)	1.53 (0.09)	18.0 (1.8)	1.15 (0.42)
4.00	90.5 (18.3)	1.95 (0.21)	1.52 (0.24)	2.72 (0.17)	1.57 (0.09)	19.2 (1.7)	1.23 (0.28)
4.25	97.1 (20.3)	2.05 (0.23)	1.57 (0.25)	2.76 (0.17)	1.61 (0.09)	20.3 (1.6)	1.31 (0.16)
4.50	103.6 (23.0)	2.15 (0.25)	1.63 (0.26)	2.79 (0.18)	1.65 (0.09)	21.5 (1.7)	1.38 (0.17)
4.75	109.2 (26.7)	2.25 (0.27)	1.69 (0.27)	2.81 (0.18)	1.68 (0.08)	22.7 (1.7)	1.43 (0.26)
5.00	113.0 (29.4)	2.32 (0.28)	1.75 (0.27)	2.83 (0.17)	1.70 (0.08)	23.9 (1.9)	1.47 (0.40)

S.D. indicated in parentheses.

the increase in average vertical GRF discussed previously.

The values, however, were considerably lower than those reported by Cavanagh and Lafortune (1980). Their vertical velocity change was 3.2 m s^{-1} for a running speed of 4.5 m s^{-1} compared with our average change for the same speed of 1.4 ± 0.2 m s^{-1}. A rough check of the data provided by Cavanagh and Lafortune indicated that the negative impulse of the body weight was apparently neglected when calculating the vertical velocity change. When such an adjustment was made to their data (assuming an average vertical GRF of 1.8 BW and a stance time of 188 ms), their vertical velocity change during stance of 1.5 m s^{-1} was comparable to those found in the present investigation.

Medial-lateral ground reaction force

Throughout the literature, as in the present investigation, the medial-lateral force has been characterized by extreme variability. Cavanagh (1982), commenting on the GRF–time histories of twelve rear-foot strikers running at 4.5 m s^{-1} stated, 'it is in the medio-lateral shear force direction that runners express their individuality'. Because the purpose of this investigation was to present standards of representative GRF behavior, no medial-lateral GRF descriptor variables were identified due to the large variance associated with this force component.

Although most studies that utilize GRF present graphical representation of the medio-lateral force curve, few report actual force values. However, there does seem to be general consensus that the magnitudes of the peak forces of the medio-lateral GRF component are relatively small by comparison with those of the antero-posterior or vertical components. Cavanagh and Lafortune (1980) cited peak-to-peak amplitudes of 0.12 BW for rear-foot strikers. The diagrams of Hamill *et al.* (1983) show maximum forces in both directions to be in the neighborhood of 0.15 BW while averages shown by Bates *et al.* (1983) appear to range from approximately 0.20 BW medial to 0.35 BW lateral. The subjects in all three of these studies were running at comparable speeds. In the present investigation, no distinct relationship between maximum medial or lateral GRF and running speed between 3.0 and 5.0 m s^{-1} could be discerned. The averages, based on all trials of a given subject, ranged from 0.04 to 0.25 BW for the medial GRF and from 0.06 to 0.31 BW for the lateral GRF. Peak-to-peak amplitudes for individual subjects averaged between 0.20 and 0.50 BW with the mean across all trials of the group being 0.29 BW.

In terms of general configuration, Cavanagh and Lafortune (1980) reported double medial and double lateral GRF peaks. The patterns shown by other investigators and found in the present study (Fig. 4), however, did not appear that clean-cut. In the present investigation, an initial medial GRF was exhibited by 50% of the subjects while 50% elicited an initial lateral GRF.

Although slight differences between the right and left feet for a given individual could be detected in the vertical and braking GRFs, the medial-lateral GRF more readily demonstrated distinct bilateral asymmetries since the variations represented a larger proportion of the force component. This is illustrated by the data of subject 8 and subject 71 (Fig. 4). The
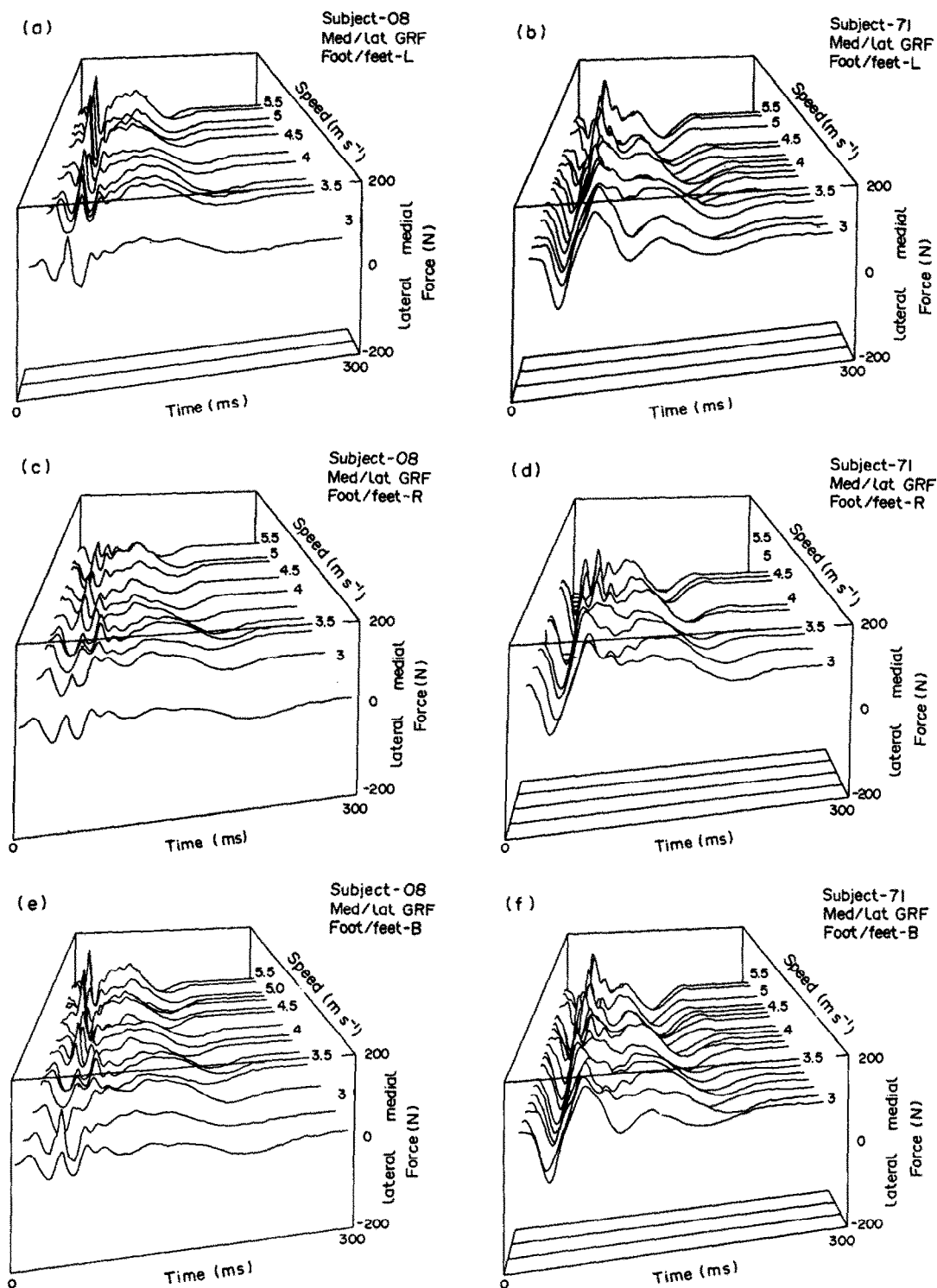
Fig. 4. Medial-lateral GRF patterns as functions of running speed.

medial-lateral GRF elicited during subject 71's left foot stance was fairly consistent although the number of deviations in the second medial GRF impulse increased at the higher end of the running speed range. Subject 71's right stance also developed excursions in the second medial impulse which were greater in number and magnitude than those elicited during left stance. In the case of subject 8, although the general patterns were similar, a difference was detected between the right foot and the left foot in the magnitudes of the second medial GRF impulse.

It must always be kept in mind that the GRF reflects

the acceleration of the total body center of gravity. Consequently, attempts to see and measure changes in the medial-lateral GRF record resulting from changes in shoe-type, orthotic devices or lower extremity bracing would always be difficult to discern even in the absence of the inherent variability of this GRF component.

CONCLUSION

This study has provided vertical and antero-posterior GRF norms as functions of running speed. These norms, in the form of means and standard deviations at $0.25 \, \mathrm{m \, s^{-1}}$ intervals across a speed range of 3.00 to 5.00 $\mathrm{m \, s^{-1}}$, should prove of value in assessing the GRF characteristics of atypical runners. In the case of rehabilitation of lower extremity injuries, as healing progresses the individual's running speed increases. Since almost all GRF descriptor variables are running-speed dependent, it is essential to take this factor into consideration in the assessment. The standards, developed on adult male joggers wearing their customary running shoes, will furnish a frame of reference for this type of evaluation across a speed range typical of recreational runners. Although the medio-lateral component of the GRF was associated with too much variability to establish reliable standards, graphical display of this component across the running speed range proved an effective means of clarifying the nature of right–left asymmetries.

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