GROUND REACTION FORCES IN DISTANCE RUNNING*

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Abstract – Ground reaction forces and center of pressure (C of P) patterns were studied in 17 subjects running at 4.5 ms⁻¹. The subjects were classified as rearfoot or midfoot strikers according to the location of the C of P at the time of first contact between foot and ground. The C of P path in the rearfoot group showed a continuous anterior movement during support while the C of P in most of the midfoot group migrated posteriorly during the first 20 ms of the support phase. Variability in both groups was most marked during early support. The mean peak to peak force components were 3 *BW*, 1 *BW* and 0.3 *BW* in the vertical, anteroposterior and mediolateral directions respectively. Consistent differences between groups were noted in all three components, but individual differences within a given group were also considerable. The C of P patterns are presented in conjunction with ground reaction force data, and the implications of the results in the areas of running mechanics, shoe design and sports injury are discussed.

1. INTRODUCTION

In recent years running has become a popular form of recreational and therapeutic activity. Although several early investigators attempted to study the ground reaction forces during this basic form of locomotion there are few reports in the recent literature where the interaction between the foot and the ground during running has been studied. There are several reasons why the study of the ground reaction forces during running is important beyond providing insight into the basic mechanism of running. Many lower extremity injuries have been associated with 'overuse phenomena' resulting from the repeated impact loading of the foot (James *et al.*, 1978). If the etiology of these injuries is to be fully understood it is clearly important to define the input conditions experienced by the musculo-skeletal system each time the foot strikes the ground during the running cycle. The design of footwear for running should depend on a sound knowledge of the force and pressure environment during ground contact since, on a given surface, the shoe is the major means of attenuating the impacts which the body experiences during running. Also if quantitative laboratory tests to evaluate the performance of running shoes are to be designed, they must closely simulate the conditions which exist in practice.

The present study was designed to document the ground reaction forces which occur during distance running, to examine the changes in the center of pressure distribution (C of P) throughout the support phase, and to gain insight into the changes in velocity of the body center of mass.

2. RELATED LITERATURE

Although a number of investigators have studied various aspects of the ground reaction forces during

walking (Elftman, 1939; Cunningham, 1950; Andriacchi *et al.*, 1977 and Yamashita and Katoh, 1976), there have been fewer studies of the kinetics of running. Amar (1920) reported the first attempt to measure two components of the ground reaction forces during running while the kinematic and kinetic studies of sprint running by Fenn (1930a, b) must be considered classics in the field. Fenn (1930b) used a crude force platform with a first natural frequency of approximately 35 Hz to measure the antero–posterior (A–P) shear component of the ground reaction force at running speeds between 6.4 and 7.7 ms⁻¹. The curves showed a somewhat ragged braking phase followed by a smoother propulsive phase with peak forces of approximately 600 N in both directions. Cavagna *et al.* (1964) presented similar data from a single subject running at 3.61 m s⁻¹. The general characteristics of the curve presented are similar to Fenn's data with smaller peak forces of approximately 280 N during braking and 210 N during propulsion presumably reflecting the slower running speed. Cavagna *et al.* (1964) also investigated the vertical component of force. The single force–time curve presented exhibited an initial peak at 1.2 Body Weight (*BW*) followed by a larger peak of 2.5 *BW*. It is likely that the natural frequency of the device used in these experiments (Cavagna, 1975) was not sufficiently high to provide accurate reconstruction of the force–time curves.

More recently, Miller (1978) presented data for a single subject during a 'slow jog' which indicated vertical forces of approximately 2.1 *BW* 25 ms after ground contact. Later in the support phase (approximately 80 ms after contact) the vertical component exceeded 2.5 *BW* falling slowly thereafter for the remainder of the support phase. Two peaks in the *A–P* force component of approximately 0.4 *BW* occurred during braking with the force falling almost to zero between these peaks. In the propulsive phase, a smoothly rising *A–P* force pattern was recorded with a peak slightly less than 0.4 *BW*. Peaks in the mediolat-

eral force component of approximately 0.2 *BW* were reported.

Several recent investigators have presented data on ground reaction forces during sprint running. Payne (1978) reported data from a single subject showing an initial peak of 5.5 *BW* at ground contact followed by a second peak of 3 *BW* in mid support. The *A–P* component exhibited clear double peaks during braking while the pattern during propulsion was monophasic. The peak braking and propulsive forces were 0.8 *BW* and 0.6 *BW* respectively. Mediolateral force components of 0.7 *BW*, directed both medially and laterally, were reported.

Fukunaga *et al.* (1978) measured two components of ground reaction forces from sprinters using a force platform which had a first natural frequency of 109 Hz. They presented three sets of curves showing vertical and *A–P* components of ground reaction force obtained from a single subject of unspecified body weight running between 5.8 and 9.0 m s⁻¹. The highest peak forces for both components were recorded from an intermediate speed (7.43 m s⁻¹). All three *A–P* curves showed double peaks following foot strike. The first and second peaks of the vertical force component were of similar magnitude on the records from running at 5.8 and 9.03 m s⁻¹ but the first peak was substantially greater than the second at a running speed of 7.43 m s⁻¹.

It is clear from the literature that there is only a limited amount of data from speeds of running which could be considered relevant to distance running. Furthermore, the small number of subjects used in previous experiments do not allow for estimates of between subject variability to be made. Lastly, the authors could not locate any experimental data in the literature describing center of pressure patterns during running.

3. METHODS AND PROCEDURES

3.1 Subjects

Seventeen runners (10 males and 7 females) with a mean age of 24 years were used as subjects in this study. Five subjects of each sex were varsity athletes, the remainder being recreational runners. The weekly running distances within the group ranged from 10 to 160 km. The mean values for height and weight of the group were 174 cm (S.D. 8.9) and 60.85 kg (S.D. 9.7) respectively.

3.2 Data collection

A Kristal Type 9261A force platform was located in the middle of a level 40 m indoor straightaway with photocells at hip height situated 5 m from the center of the platform in both directions. The frequency response of the platform was flat to at least 200 Hz in all three components. The subjects were given as many practice runs as needed to consistently land in the region of the force platform with the right foot and to achieve a steady running speed of approximately

4.5 m s⁻¹. This pace represents a time of 6 min for one mile which would result in a marathon of 2 hr 37 min. Over shorter distances it is a training pace that the average competitive distance runner may use.

Once the subjects were acclimated to the experimental requirements, they were instructed to run at a steady speed through the test area without adjusting their stride to land on the force platform. If the speed was outside the desired range (4.12–4.87 m s⁻¹) or if part of the foot was outside the force platform area during support the data were discarded.

3.3 Determination of foot placement

All subjects wore Etonic Km 505 running shoes with a geometrically similar sole outline despite differences in size. Prior to data collection the functional axis of the foot was approximated by marking the sole of the shoe at the midpoint of the heel width and at the anterior margin of the sole corresponding to the location of the second toe. This line (*aa'* in Fig. 1) is subsequently referred to as the midline of the shoe. Two reference points, *A* and *B*, were located on this line at 90% and 70% of the shoe length from the heel; small holes 3 mm in diameter were drilled into the sole at these points. A reference frame *Bx'y'z'* with origin at the point *B* had axes parallel to the force platform *x* and *y* axes. The reference frame *Bx"y"z"* was fixed in the shoe also with origin at the point *B*. The angle θ between these reference frames gave a measurement of the amount of ad/abduction occurring during contact.

The surface of the force platform was covered with adhesive linen tape. During the steps prior to contact with the platform the subjects ran through powdered chalk and subsequently left an outline of the shoe and the reference points on the platform. The coordinates of the points *A* and *B* were measured to the nearest millimeter following each contact.
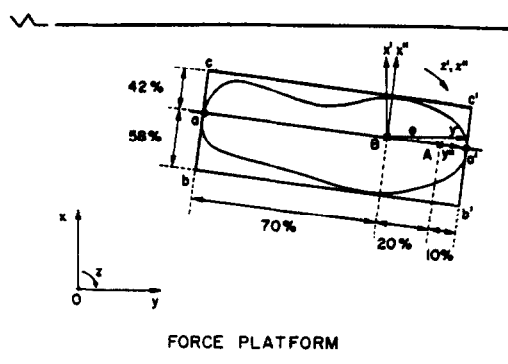

FORCE PLATFORM

Fig. 1. Outline of a typical right shoe used in the experiments shown schematically on the force platform. The reference points *A* and *B* used to locate the shoe position after contact, are on the shoe midline *aa'* at 90% and 70% of shoe length from the heel. See Nomenclature for definition of reference frames.

3.4 Data processing

Data from five right foot contacts for each subject which were within the prescribed limits of running speed and foot placement were recorded at 15 ips on a CEC Model 4020 FM tape recorder. The signals representing Fx, Fy, Fz, Mx and My (Fig. 2) were then replayed at the same speed into the analog to digital converter of a PDP 11/34 computer which sampled the data at 500 Hz per channel. An analog comparator with the Fz signal as input was used to initiate sampling when the force was greater than 50 N; sampling was terminated when the force fell below this value. Examination of galvanometer records indicated that the digital data therefore started approximately 2 ms after foot strike.

The five trials from each subject were averaged in a manner previously described (Cavanagh, 1978). Following classification of the subjects according to the region of first contact between shoe and ground (see Section 4) group averages were calculated. The process of averaging curves of different durations and with asynchronous peaks tends to attenuate peak values considerably. Although the present technique of dilation or compression of the individual curves to the mean time period tended to improve this situation, there was still a reduction in peak values as shown in Fig. 3. For this reason the peak forces reported in Section 4 are averages obtained from peaks of the individual curves irrespective of their time of occurrence.

3.5 Kinematics of the total body center of gravity

If drag is assumed to be negligible, ground reaction and gravity are the only forces acting on the total body center of mass and the impulse–momentum relationship allows the changes in the velocity of the center of mass to be determined. The net velocity change in the mediolateral direction (x-direction in Fig. 2) during the stance phase was calculated as follows:

$$(\dot{x}_{t_2} - \dot{x}_{t_0}) = \frac{1}{m} \int_{t_0}^{t_2} Fx \, dt$$

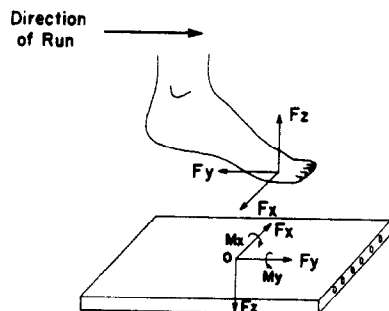with times defined in the list of nomenclature.

Fig. 2. Conventions for positive forces and moments applied to the platform (shown on platform) and positive ground reaction forces acting on the foot. All forces in this paper are in the ground reaction force convention.

Velocity changes in the antero–posterior direction (y-direction in Fig. 2) can be partitioned into braking and propulsion phases and were computed as follows:

Velocity loss during braking:

$$(\dot{y}_{t_1} - \dot{y}_{t_0}) = \frac{1}{m} \int_{t_0}^{t_1} Fy \, dt$$

Velocity gain during propulsion:

$$(\dot{y}_{t_2} - \dot{y}_{t_1}) = \frac{1}{m} \int_{t_1}^{t_2} Fy \, dt.$$

For steady speed running in a straight line the net A–P velocity change during contact is zero since the horizontal components of velocity at take-off and landing are equal if drag is assumed to be negligible.

The changes in vertical velocity of the center of gravity during ground contact can be determined in a similar manner.

$$(\dot{z}_{t_2} - \dot{z}_{t_0}) = \frac{1}{m} \int_{t_0}^{t_2} (Fz - mg) \, dt.$$

The same change in velocity $(\dot{z}_{t_2} - \dot{z}_{t_0})$ will occur during the subsequent flight phase if left/right symmetry is assumed. However, without knowledge of initial conditions, such as velocity at takeoff, solution for the displacement of the total body center of gravity in a complete cycle cannot be obtained.

3.6 Center of pressure

The C of P coordinates were calculated in terms of percentage shoe length relative to the reference frame $Bx'y'z'$ as follows

$$x' = -\frac{My'}{Fz}$$

$$y' = \frac{Mx'}{Fz}$$

where the force and moment values were means from a particular group either within or between subjects (Cavanagh, 1978).

Since the location of the C of P and that of the shoe were known relative to a common reference frame it seemed appropriate to present force and C of P data with respect to the shoe outline. This was achieved by digitizing a shoe outline together with the reference points A and B, and supplying the plotting program with the actual location of the reference points following foot contact on the platform.

4. RESULTS

4.1. Center of pressure patterns

From an examination of the C of P patterns subjects were classified according to the location of the C of P at the time of first contact between foot and ground. The shoe midline was divided into three equal parts and the distinction was made between rearfoot, midfoot and forefoot strikers. In the present sample no subjects
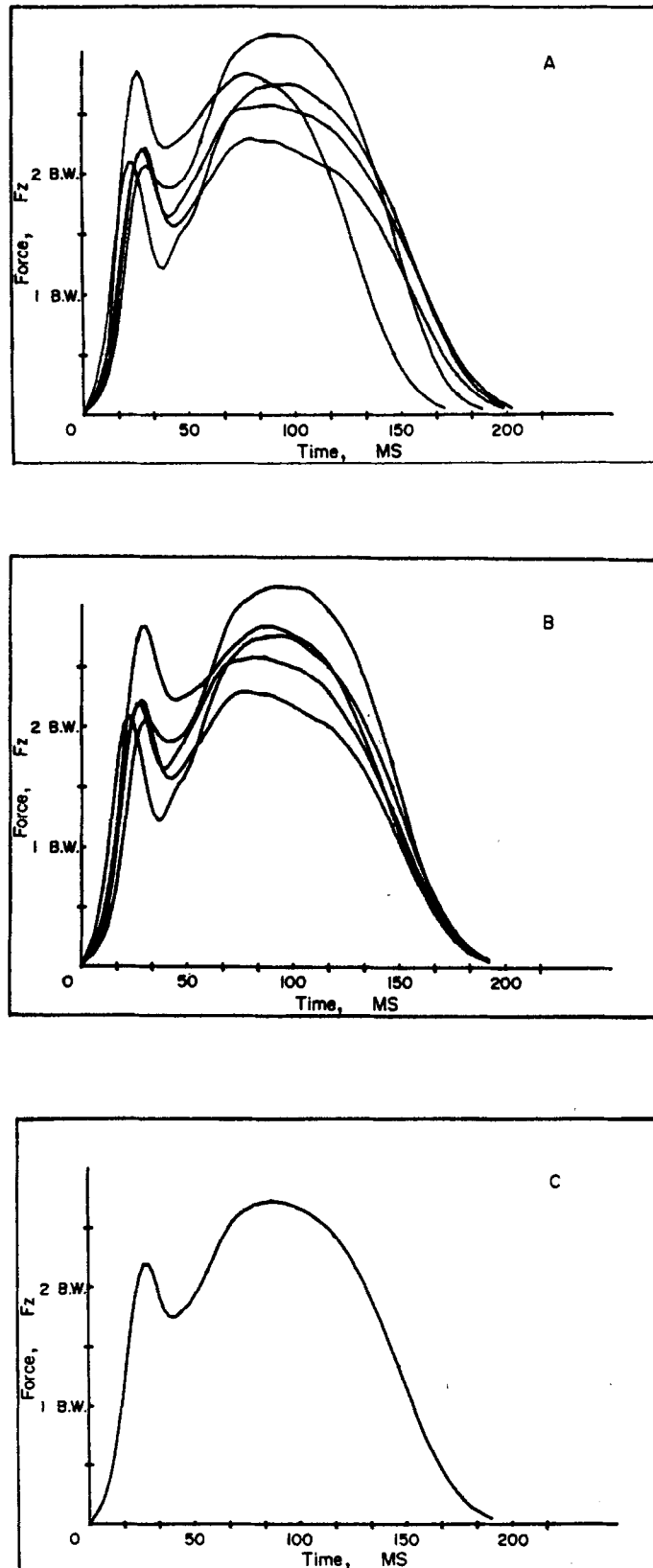
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Fig. 3. (a) *Fz* curves for five different subjects running within the prescribed velocity limits. Note that the curves are of different durations and have asynchronous peaks. (b) Data from the same five individuals following normalization by dilation or compression to the mean contract time. (c) Final mean curve calculated by averaging the time normalized curve.
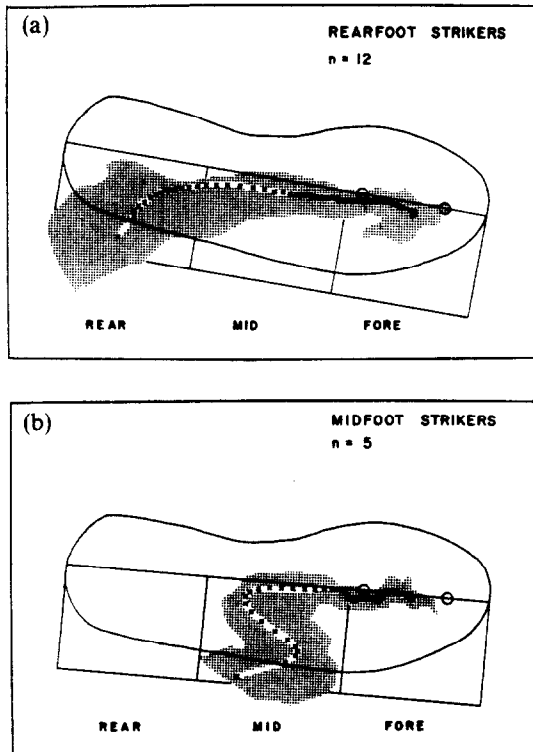
Fig. 4. Mean Center of Pressure locations under the shoe outline at 2 ms intervals during contact. The shaded areas represent the range determined by normalizing all data on the basis of shoe length. The shoe is divided into three equal regions for the purpose of classifying running patterns. (a) Rearfoot strikers — subjects whose first contact with the ground was made in the rear one third of the shoe. (b) Midfoot strikers — subjects whose first contact was in the middle third of the shoe. No subjects in this study were classified as forefoot strikers. See text for further discussion.

were classified as forefoot strikers since all C of P patterns first entered the shoe outline in the posterior two thirds of the shoe.

4.1.1 *Rearfoot strikers.* The mean C of P pattern for the 12 subjects classified as rearfoot strikers is shown together with the range in Fig. 4a. The average placement angle for these subjects was 10.4 degrees of abduction and the shoe outline is drawn with this orientation. The points indicated on the figure are separated in time by 2 ms and thus their distance apart on the shoe outline is an indication of the rate of change of position of the C of P.

The pressure distribution initially had its center on the rear lateral border of the shoe and moved rapidly towards the midline for the first 34 ms after contact. By 42 ms into the contact phase, the C of P had moved anteriorly to 50% of shoe length. It then remained within the limits of 50–80% of shoe length from the heel until the end of the support phase, 146 ms later. Throughout this time, the distribution remained close to the midline of the shoe with a small medial movement in the region of the metatarsal heads which was reversed prior to toe-off. The center of the pressure

distribution was still almost 20% of shoe length from the anterior border of the shoe at the time Fz fell below threshold prior to toe-off.

Of particular interest in Fig. 4a is the variability exhibited in the movement of the center of pressure within this group of subjects. It is clear that individual differences are chiefly expressed by varying pressure distributions in the posterior part of the shoe.

In many of the pressure distributions sampled, the center of pressure fell initially outside the shoe outline. There are two reasons for this; first, placement is preceded by a scuffing phase when forces greater than threshold exist between the foot and the floor but final placement has not been made. A second cause is the 'abductory twist' which is a feature of many running and walking gaits; at the time when the pressure distribution is centered in the forefoot the heel is moved medially by a small amount. The shoe outline has been drawn in its final position but it must be recalled in interpreting all the center of pressure data that the shoe is not fixed during support and this may change the relative position of the center of pressure within the shoe outline.

4.1.2 *Midfoot strikers.* The mean C of P pattern for the 5 subjects classified as midfoot strikers is shown in Fig. 4b. First contact was made, on average, at approximately 50% of shoe length with the midline of the shoe at a 5.3° angle to the y-axis. Following a brief anterior movement, the C of P in each of these subjects migrated posteriorly and medially, the mean pattern reaching its most posterior point 20 ms after first contact. Rapid anterior movement then began as the C of P traversed the middle third of the shoe reaching 65% of shoe length from the heel after 40 ms. A small lateral migration then occurred as the C of P continued a slow anterior movement from 65 to 75% of shoe length. In the later stages of support the path again returned to the midline until the force fell below threshold prior to takeoff. It is again apparent that the variability among subjects in the group occurs during the early phase of contact. From 30 ms after contact until toe-off the patterns follow a remarkably similar path.

4.2 *Force–time data*

The mean force–time curves for the rearfoot and midfoot strikers are shown in Fig. 5. The mean contact times were 188 ms (S.D. 16 ms) and 176 ms (S.D. 14 ms) for the rearfoot and midfoot groups respectively. All of the force components show characteristic differences between the means of the two groups.

4.2.1 *Mediolateral force component* (Fx). The mediolateral force component in both groups (Figs 5a and 5b) showed two positive and two negative peaks, however, the mean peak to peak amplitude was three times greater in the group of midfoot strikers than that for the rearfoot strikers (0.35 BW and 0.12 BW respectively). The shaded areas in Fig. 5 indicate the range of values encountered for the particular group. Subjects in the midfoot group were extremely homo-
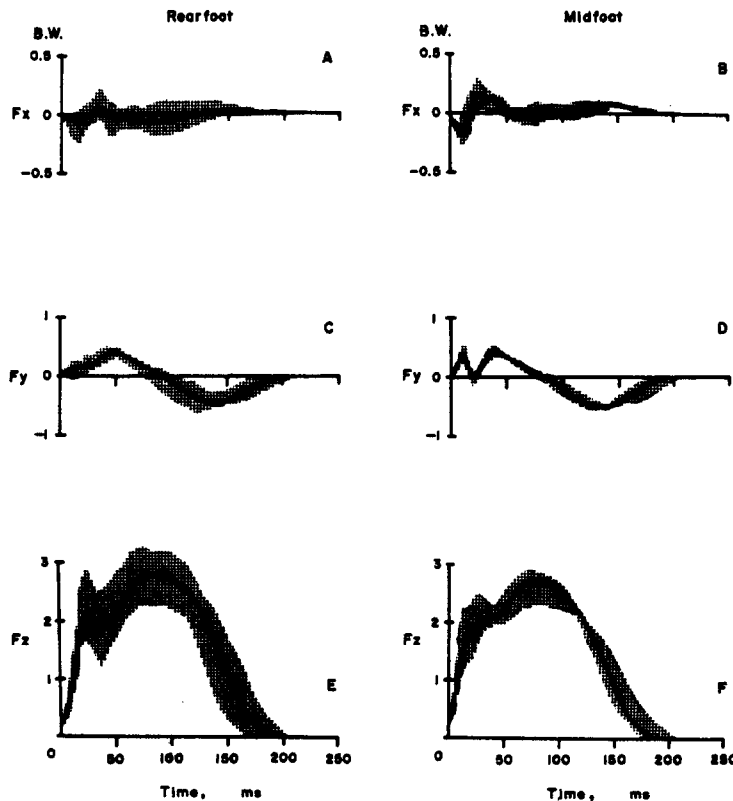
Fig. 5. Mean force–time curves (in units of body weight) and range (shaded area) for the contact phase in both groups of runners. (a, b) mediolateral component. (c, d) anteroposterior component. (e, f) vertical component. Note the characteristic differences between rearfoot and midfoot groups.

geneous in the patterns they displayed while the rearfoot group exhibited considerable variability. In general this force component was found to be small compared to the vertical and anteroposterior components; the mean peak to peak amplitude for all subjects was only 9% of the peak vertical component and 26% of the span in antero–posterior component (note that the scale for Fx in Fig. 5 is double that for Fy and Fz).

4.2.2 *Anteroposterior force component* (Fy). A marked difference in the mean $A–P$ component of the ground reaction forces was found between the rearfoot and midfoot groups during the braking phase of ground contact. The rearfoot group exhibited a mean curve rising gradually to a positive peak of 0.43 BW (S.D. 0.05) at 46 ms (S.D. 5.1) after initial contact (Fig. 5c). The midfoot strikers all exhibited a double peaked braking phase (Fig. 5d); following an average initial peak of 0.45 BW (S.D. 0.09) at 11 ms (S.D. 1.8) the curve fell to or below zero before a second positive peak of almost equal magnitude to the first occurred at 38 ms (S.D. 3.3). The transition from braking to propulsion occurred at approximately 48% of the total support time for both groups, the mean curves falling smoothly to peaks of approximately 0.5 BW at 139 ms

(S.D. 12 ms) and 133 ms (S.D. 9 ms) for the rearfoot and midfoot strikers respectively.

4.2.3 *Vertical force component* (Fz). The mean vertical component of the ground reaction force for rearfoot strikers (Fig. 5e) shows a double peaked curve, the first peak rising to approximately 2.2 times body weight (S.D. 0.4 BW) in 23 ms (S.D. 0.3 ms). The second peak was more slowly rising attaining an average maximum value of 2.8 BW (S.D. 0.3 BW) 83 ms (S.D. 8 ms) after initial contact.

The mean vertical component for the midfoot strikers (Fig. 5f) shows a characteristic absence of the initial peak following contact, although some subjects in this group exhibited a small but recognizable peak. The average peak value of 2.7 times BW (S.D. 0.2 BW) which occurred at 75 ms (S.D. 5 ms) after contact was not significantly different from that found in the rearfoot group ($p \leq 0.05$).

4.3 *Force vectors under the shoe*

The center of the pressure distribution can be considered as the point of application of the resultant force although it is clear that the force is distributed over the sole of the shoe. Since the magnitudes of the force components are known at each of the positions of the center of pressure shown in Fig. 4 it is possible to

represent the resultant force vector beneath the shoe in both magnitude and direction. This has been done in Fig. 6 in an attempt to relate the external forces and the center of the pressure distribution. The force vectors shown in Fig. 6 are the resultants of only the vertical and antero–posterior components since the contribution of Fx to the resultant force was minimal. The significance of these presentations will be discussed in a later section.

4.4 Changes in velocity of the center of gravity

Both groups exhibited changes of approximately $3.15\,\mathrm{m\,s^{-1}}$ (S.D. 0.17) in the vertical component of velocity during the support phase. This change is an absolute value representing the transition from an initial negative velocity, to a zero velocity at the lowest point and then to a positive takeoff velocity. Although the peak vertical force components varied considerably among individuals, the changes in the vertical components of velocity of all the subjects were re-
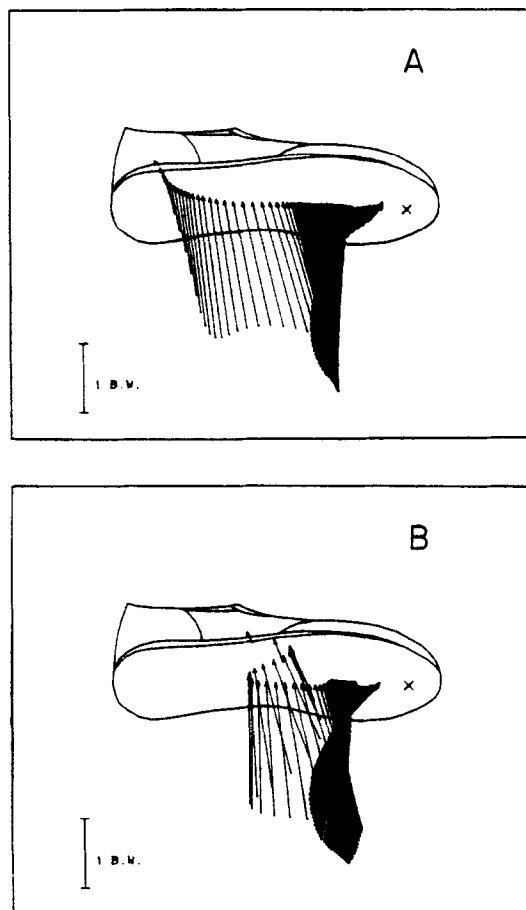

Fig. 6. A computer graphics representation of force vectors beneath the shoe throughout the contact phase. The view is of the right shoe from the lateral aspect with the shoe tilted 30° upwards. The length of the force vectors are proportional to the resultant of Fy and Fz, and the point of application is at the center of pressure corresponding in time to the force value. A scale of 1 body weight is indicated. (A) Rearfoot group. (B) Midfoot group.

markably similar suggesting an interplay between force and contact time to generate the required change in momentum. The correlation between peak vertical force and contact time was -0.67.

The integration of the antero–posterior force component during the braking phase indicated a mean change in velocity of $0.18\,\mathrm{m\,s^{-1}}$ (S.D. 0.026) for all subjects with the two groups showing no significant differences ($p \leqslant 0.05$). This change represents 4.5% of the average running velocity. During the propulsive phase a mean velocity gain of $0.27\,\mathrm{m\,s^{-1}}$ (S.D. 0.04) was calculated. If the assumption of steady speed running is valid, the difference between the braking and propulsion phases indicates that a greater horizontal component of velocity exists at takeoff than at landing due to losses because of drag during flight. It is unlikely that all subjects would display similar asymmetries which would be a further possible explanation for these differences.

The calculation of velocity changes during the support phase in the mediolateral direction revealed that individual subjects in both groups show net velocity changes in both directions. The mean changes were $0.03\,\mathrm{m\,s^{-1}}$ in medial direction for the rearfoot group and $0.03\,\mathrm{m\,s^{-1}}$ in a lateral direction for the midfoot group. This difference between groups was not significant. The largest individual velocity change encountered was $0.13\,\mathrm{m\,s^{-1}}$ in a medial direction by one of the rearfoot strikers, while two subjects in the midfoot group exhibited changes of approximately $0.12\,\mathrm{m\,s^{-1}}$ in a lateral direction.

5. DISCUSSION

It should be stressed at the outset that the results presented in this paper are entirely specific to the conditions of footwear, ground surface, running speed and gradient used in this experiment. A variation in any of the above parameters could be expected to cause changes in both the force–time and center of pressure patterns. A further limitation of the present study is that only the right foot was studied and there is no reason to expect symmetry between the right and left sides.

When interpreting Figs 4 and 6 it is important to realize the limitations of the center of pressure as a description of the interface between the foot and the ground. In the limiting case where there are two discrete and discontinuous areas of contact — such as beneath the ball and heel of the foot — the center of pressure will probably lie between the two areas in a region where there is actually little or no pressure (Cavanagh and Ae, 1980). In the present experiments, this situation is mostly likely to be encountered when the center of pressure is in the middle third of the shoe.

Within the limitations outlined above, the results of these experiments have implications in three separate areas: first, they contribute to basic knowledge in the area of running mechanics; second, the results provide design and testing criteria for running footwear and

third, they identify some of the factors responsible for injury in running. The remainder of the discussion will address these three areas in turn.

5.1 Running mechanics

The traditional concept of 'heel strike' in distance running has been that first contact with the ground is made with the most posterior part of the shoe. The data presented in Fig. 4 show that such is not the case in any of the representative group of runners used as subjects in the present study. In the late stages of the swing phase the feet of most runners are in a supinated position and the hip in adduction, hence initial ground contact is made in almost every case with the lateral border of the shoe.

Many authorities on running have held the view that so-called 'heel–toe' running is characteristic of slower speeds while 'toe' running occurs at higher speeds (Doherty, 1971, p. 365). It is clear from the range shown in Fig. 4, which is from a single speed of running, that there is a continuum of initial contact points which covers the entire posterior 60% of shoe length. There may well be systematic changes in the initial contact point and subsequent pressure distribution as running speed increases, but the individual differences are clearly great enough to make any general statement relating initial contact point and absolute speed invalid. When the C of P is in the midfoot region at the time of initial contact this may represent a 'flat placement' due to the limitations of the C of P mentioned earlier.

A comparison of the Fx force–time component between groups exhibited remarkable differences between the running patterns of different individuals in a given group. This was particularly true for the rearfoot striker group in which there were individuals who had a net zero medio-lateral impulse, subjects who had a net medial impulse and those who exhibited a net lateral impulse. To evaluate this phenomenon completely, one would need to know the medio-lateral component of velocity of the center of gravity at touchdown. However, it is clear that runners differ markedly in the medio-lateral impulse exerted during contact.

The pronounced differences between the groups observed in the antero–posterior component (Fy) of the ground reaction force was reinforced by the uniformity of these patterns within each group. The curves for each subject in the midfoot group showed a fall to zero within 25 ms of contact, a pattern completely absent from the rearfoot group. An examination of Fig. 6b shows that at the time Fy fell to zero, the center of pressure had reached its most posterior location. This is the situation when the force vector in Fig. 6b is vertical. This reinforces the impression of the different nature of the foot strike between the two groups suggested by the center of pressure patterns during early support. Data from many of the subjects in the rearfoot group showed a somewhat fluctuating rise to the positive peak in Fy, representing an

unevenness in the acceptance of weight by the supporting limb. The changes in the anteroposterior component of the velocity of the center of gravity were remarkably similar among all of the runners studied. This variable should be further investigated in runners who have known differences in efficiency since it is clearly related to energy required for forward progression.

The range of peak values for the vertical component of ground reaction force (Fz) was considerable, indicating that some individuals can run at the same speed while exerting forces which are 30% lower than others. The high negative correlation between peak force and duration of contact time indicates that this is an aspect of running style in which the individual is able to choose how the total vertical impulse will be obtained. For each individual, there may be a consistent relationship between stride length and peak force which is not possible to detect from the data presented here.

While the mean pattern for the rearfoot group shows a clear distinction between the first and second peaks of Fz, the tendency amongst the midfoot strikers is for a merging or incomplete separation of the parts of the vertical force component curve associated with impact and upward acceleration of the center of gravity in preparation for takeoff. Figure 6 shows that the fall in vertical force component in the rearfoot group occurs as the center of pressure is moving across the longitudinal arch of the foot while the mean pattern for the midfoot group shows a steady force increase in this region.

Although beyond the scope of the present paper, it is clear that a complete kinematic description of the movements of the body is required for a full understanding of the implications of these results.

5.2 Shoe design and testing

The design of running shoes in the past has often been a joint effort between a runner or coach, who had opinions and empirical evidence concerning the performance of a shoe, and a designer who insured a cosmetically acceptable product. The data provided in this study provide initial information which can assist the design process in a quantitative manner. The wide variation of the point of first contact between shoe and ground and the broad area over which peak impact forces are distributed emphasizes the need for protection of the foot from impact in an area ranging from zero to 60% of shoe length from the heel. The midfoot group, in particular, requires the same kind of attention in the mid region of the shoe that has traditionally been reserved by shoe manufacturers for the heel region. While the rearfoot strikers have two clear peaks in the vertical force component, each with its own characteristic rise time and point of application, the midfoot group requires that the shoe perform all of its functions in a rather small region of the mid and forefoot. Although this dilemma of making one product to suit many users is not uncommon, the data are

strongly suggestive that the two groups would best be served by different shoes designed expressly for their particular running style.

The concentration of design attention to the rear part of the shoe can be further questioned on the basis that the forces under the forepart of the shoe in both groups are the largest that occur during ground contact at this speed of running. The rise time characteristics of the Fz curves during mid support are considerably different from those occurring during the impact phase. In the rearfoot group, for example, the rate of change of force with respect to time is approximately five times smaller during the mid support phase than during the first 25 ms after contact. Since the center of pressure has moved considerably anteriorly by the second rising phase, the use of materials with different characteristics for the two regions would seem to be appropriate.

The backward slope of the force vectors in Fig. 6 indicates that braking is occurring while the pressure distribution is centered as far forward as 70% of shoe length from the heel. While there is certain to be overlap between the regions in which peak braking and propulsive forces exist, the evidence suggests that any modifications to the outsole of the shoe designed to increase traction during braking should extend for most of the rear two-thirds of the shoe. It should again be emphasized that the center of pressure is only the center of what may be an asymmetrical pressure distribution and it is not possible using this technique to unequivocally characterize the function of the various regions of the shoe. Despite this limitation, it is clear that runners in both groups spend most of the contact phase with the center of the pressure distribution between 60 and 80% of shoe length from the heel. The functions of both braking and propulsion are therefore taking place in this region of the shoe which should ideally be capable of adequately resisting slip from forces applied in either an anterior or posterior direction.

The variability that was encountered in the mediolateral component of force between subjects indicates the need for stability in both medial and lateral directions. Different individuals using the same shoe are exerting both net medial and net lateral impulses during the contact phase.

The identification of the loading conditions which the shoe undergoes during ground contact also enable realistic parameters to be selected for laboratory testing of the impact response of both shoes and materials used in the manufacture of shoes. A realistic test must involve the production of forces with magnitude and time characteristics similar to those shown in Fig. 5. Combining the force and center of pressure data suggests that regions 25% and 70% of shoe length from the heel would be appropriate areas to test the different responses required by a typical rearfoot striker. The C of P was situated at these locations when peak Fz forces occurred in the average pattern.

There has been some confusion in the past concern-

ing the reason for wear on the outsole of a shoe (Elftman, 1934). Wear is caused by relative motion between the outsole and the ground, and one would not necessarily expect any relationship between the regions of maximum wear and the regions where maximum forces occur. Wear will occur during the initial scuffing at touchdown and Fig. 4 shows that this region extends along the entire posterior two-thirds of the shoe, if the pattern from all subjects in this study is considered. The second major wear region is likely to be under the forefoot where the center of pressure is located during the abductory twist in late support. Coincidentally, this is the region where maximum vertical forces occur. All of these regions mentioned above should, therefore, receive special attention in design and testing for durability.

5.3. Injury

This study shows that the forces which exist during distance running are 1.5–2 times larger than those occurring in slow walking (Andriacchi et al., 1977). A typical distance runner who may run 130 km/week in training will be subjecting each lower extremity to approximately 40,000 such impacts over a seven-day period. While a limb in normal alignment may withstand this repeated loading, an unusual pattern of foot strike, severe pronation during the support phase or other abnormalities may predispose the individual to one of the 'overuse injuries' that have been shown to be endemic to distance runners (James et al., 1978).

It would seem reasonable to hypothesize that the midfoot strikers are particularly at risk since they are experiencing large forces in a region which has received little attention from shoe designers as far as protection from impact is concerned. This would need to be confirmed by the relevant epidemiological data. There is a clear need for experimental evidence which would specify the tolerance of the human lower extremity to repetitive impact loading of the kind experienced in running. Paul et al. (1978) have made a promising initial attempt to investigate the effects of impact loading on the lower extremity of the rabbit. While such a methodology is not directly applicable to the study of the live human being, similar experiments on cadavers may provide insight into the problem. The absence of human tolerance data makes the establishment of standards for the protective properties of running shoes extremely difficult.

The variability in center of pressure distribution and ground reaction forces between individuals complicates the establishment of 'normal patterns'. It is likely that more powerful techniques for the identification of pathology would be a comparison of the results from the same individual in an injured and uninjured state. It is, at present, an open question as to whether the technique of center of pressure measurement has the required sensitivity to distinguish subtle changes in pressure distribution which may seriously affect the well being of the runner.

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NOMENCLATURE

aa'	Midline of shoe
A, B	Anterior and posterior reference markers on the shoe
$Oxyz$	Inertial reference frame fixed at center point of force platform
$Bx'y'z'$	Inertial reference frame fixed at point B with axes parallel to $Oxyz$
$Bx''y''z''$	Inertial reference frame fixed at point B with By'' parallel to midline of the shoe
θ	Foot placement angle measured between By' and By'' (abduction positive)
t_0	Time of foot strike (when $Fz \geqslant 50\,\mathrm{N}$)
t_1	Time when Fy crosses from positive to negative in mid-support
t_2	Time of toe-off (when $Fz \leqslant 50\,\mathrm{N}$)
F	Net ground reaction force
Fx, Fy, Fz	Component of F in the x, y, z directions
M	Net moment of F about 0
Mx, My, Mz	Component of M about Ox, Oy, Oz
Mx', My', Mz'	Component of M about Ox', Oy', Oz'
$\dot{x}_{t_n}, \dot{y}_{t_n}, \dot{z}_{t_n}$	Velocity of total body center of mass in x, y, z direction at time t_n
g	Acceleration due to gravity
m	Mass of total body
BW	Body weight.