Factors Affecting Peak Vertical Ground Reaction Forces in Running

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Nine subjects (6 males, 3 females) ranging in body mass from 90.9 to 45.5 kg ran repeated trials across a force platform while being filmed at 50 fps. The subjects ran five barefooted trials at each of three speeds: 3.35, 3.83, and 4.47 m·s⁻¹. Force data were collected on-line and analyzed for the magnitude and temporal characteristics of the initial impact (Fz1) peak and the active (Fz2) peak of vertical ground reaction force (VGRF). Multiple regression and correlation analysis were used to study the relationship between the magnitudes of these kinetic data and kinematic and anthropometric data taken from the film and from measurements of the subjects. The results support the general conclusion that speed and, indirectly, body mass are significant effectors of the magnitudes of Fz1. In addition, other factors that correlate significantly with Fz1 are reciprocal ponderal index (RPI) and stature; half-stride length, step length, leg length, and vertical hip excursion during a half-stride cycle; and hip offset, contact angle, and dorsiflexion angle at contact. Body mass correlates highly with Fz2 (r = 0.95). Other significant factors correlating with Fz2 are RPI, stature, vertical hip excursion, dorsiflexion angle, hip offset, half-stride length, and step length. These data support earlier findings that speed and the effective mass of the leg at contact are important effectors of the magnitude of Fz1. In addition, the kinematic and anthropometric parameters that contribute significantly to the variability in Fz1 and Fz2 are generally cross-correlated with body size and/or running speed.

Cavanagh and LaFortune (1980) and a number of other authors (Bates, Osternig, Sawhill, & James, 1983; Hamill, Bates, Knutzen, & Sawhill, 1983; Miller, 1978; Nigg, Denoth, & Neukomm, 1981) have demonstrated that there are commonly two principle peaks in the typical vertical ground reaction force (VGRF) curve: an “impact” peak (Fz1) occurring shortly after first contact, and an “active” (Nigg, Denoth, & Neukomm, 1981) peak (Fz2) occurring near the middle of stance time. Nigg (1983) has also pointed out that the impact peak may
be absent as noted by Cavanagh and Lafortune (1980), or there may be one, two, or even three peaks during the impact phase.

A number of researchers have presented compelling circumstantial evidence implicating the repeated high-magnitude forces that insult the lower extremity nearly a thousand times in each kilometer of running, in the etiology of many of the chronic injuries that plague distance runners (Clancy, Smith, Drez, & Detmer, 1980; Clancy, 1980; Clement, Taunton, Smart, & McNicol, 1981; James, Bates, & Osternig, 1978; Taunton, Clement, & Weber, 1981). In addition, the literature provides ample evidence that vertical ground reaction forces show considerable interindividual and intraindividual variation (Bates et al., 1983; Cavanagh & Lafortune, 1980; Hamill et al., 1983; Kinoshita, Bates, & DeVita, 1985; Nigg, 1985, 1986). This study attempts to systematically explore the potential contribution of a range of factors to the variability of the initial impact peak and the active peak in VGRF.

Methods

Nine subjects, 6 males and 3 females, ran barefooted across a force platform at each of three speeds: 3.35, 3.83, and 4.47 m • s⁻¹. The subjects were chosen because of their wide range of body masses from 90.9 to 45.5 kg (weight range, 891 to 446 N). The subjects averaged 27 years of age. Eight of them were runners, training at least once a week during the year preceding the study. The ninth subject was not training regularly at the time of the study but had been a runner in previous years. Running was the main sport of all 9 subjects.

Data were collected as the subjects ran barefooted along a raised wooden runway and contacted a Kistler (Kristal) force platform (model 9261A) with the right foot. Speed was maintained by the use of two photocells mounted at head height before and after the force platform. The force platform’s frequency response as mounted was determined to be 700 Hz for the vertical component. Repeated runs were needed to acquire five acceptable trials for each running speed. Three criteria were used to accept a trial: speed had to be within 5% of that specified; there could be no evidence of “targeting,” that is, a pronounced extension or shortening of the stride to hit the force platform; and the plus and minus impulses of the antero-posterior (Fy) force curve as shown on a strip chart record had to appear approximately equal, indicating that the subjects were not accelerating or decelerating during that step.

The output of the force platform for the Fz (vertical), Fx (medio-lateral), and Fy components was sampled on-line at 500 Hz by an EPI minicomputer. In addition, a simultaneous record was taken for reference on a Honeywell Visicorder oscillographic strip chart recorder. The measurement system was calibrated before and after each data collection session by placing known weights on the force platform to give us a precise value with which to set the output of the Visicorder. The force data records were subsequently analyzed to identify the magnitude and time of occurrence of the first and second peaks in the Fz curve for each trial. In those cases in which there was a recognizable second impact peak, only the initial peak was analyzed. Second impact peaks, when present, were almost always lesser in magnitude and occurred roughly 10 msec after the initial peak.
Detailing the characteristics of the second peak goes beyond the scope of this paper. The goals of this study included only the initial impact peak and not the less frequent second impact peaks. In only 7 of the 135 trials was there no impact peak. These 7 trials were excluded from the analysis of $F_{z1}$ but their data were included in the $F_{z2}$ analysis.

During each trial the subjects were filmed from the right side at 50 fps with a Photosonics model 1P cine camera equipped with timing lights. This frame rate was chosen because the film record was to be used to look at relatively gross kinematic parameters. The objective of this study was to see if large changes in the position of the body's major segments just prior to the initial compact peak, as well as the excursion of these segments during the total period of contact, had a statistically significant relationship with the magnitudes of the two peaks under study. The exploratory nature of this study warranted that some precision in the filming technique be sacrificed in exchange for the inclusion of a greater range of variables in the analysis.

After editing to remove excluded trials, the film was analyzed by squarely projecting the image frame by frame onto a smooth surface over which chart paper was taped. A single piece of chart paper was used for each trial, and marks were made on the grid indicating the position, for each frame beginning with first contact, of each of the following anatomical landmarks: the greater trochanter, the lateral femoral condyle, the lateral malleolus, and points marked on the lateral ball and heel of the foot. In addition, the center of foot contact was marked for relevant frames in order to make certain angular measurements described below in more detail. The center of foot contact was taken as the midpoint of the horizontal line formed between the force platform surface and the part of the foot in contact with the surface. Care was taken to ensure registration of each frame by aligning a fixed spot in each frame. Calibration was accomplished by indicating the dimensions of a 60 cm calibration mark shown in each frame.

The frame just prior to the time of occurrence of the first peak ($F_{z1}$) was subsequently analyzed for contact kinematics. In practice this was generally the first frame of foot contact. The following parameters (see Figure 1) were analyzed for this frame: (a) contact angle, the angle to the horizontal of a line from the greater trochanter to the center of foot contact; (b) dorsiflexion angle, the angle of ankle dorsiflexion formed by the shank (lateral malleolus to femoral condyle) and the foot as defined by points on the lateral heel and forefoot; (c) hip height, the vertical height above the floor of the greater trochanter; and (d) hip offset, the horizontal displacement of the greater trochanter from the point of foot contact.

All frames in a half-stride cycle (right foot to left) were analyzed to measure the following half-stride cycle kinematics: (e) step length, the horizontal distance the greater trochanter traveled during the time of foot contact; (f) half-stride length, the horizontal distance along the surface between successive initial foot contacts; (g) vertical hip excursion, the total vertical excursion of the greater trochanter during a half-stride cycle; and (h) horizontal hip displacement, the horizontal distance traveled by the greater trochanter from midstance, as defined by the frame in which the patellae are seen to just pass one another, until the frame in which the greater trochanter reaches its maximum height. Figure 1 shows these parameters in diagrammatic form.
Parameters measured were: (a) contact angle, the angle to the horizontal of a line from the greater trochanter to the center of foot contact; (b) dorsiflexion angle, the angle of ankle dorsiflexion relative to the shank; (c) hip height, the vertical height above the floor of the greater trochanter; (d) hip offset, the horizontal displacement of the hip from the point of foot contact; (e) step length, the horizontal distance the hip traveled during foot contact; (f) half-stride length, the horizontal distance between successive foot contacts; (g) vertical hip excursion, the total vertical excursion of the hip during a half-stride cycle; and (h) horizontal hip displacement, the horizontal distance traveled by the hip from midstance, as defined by the crossing of the patellae, until it reaches maximum height.

The individual values for each trial for these eight variables along with speed, body mass, stature (standing height), the reciprocal ponderal index, 

$$RPI = \frac{\text{stature (inches)}}{\sqrt[3]{\text{body weight (lbs)}}},$$

and standing leg length, taken as the distance from the right greater trochanter to the floor, were analyzed by stepwise multiple regression. In one analysis the magnitude of $F_{z1}$ was used as the dependent variable, and in the second analysis $F_{z2}$ was considered the dependent variable. Stepwise multiple regression was used to develop equations for prediction of the magnitude of $F_{z1}$ and $F_{z2}$. In addition, the individual correlation coefficient of each variable with the two peaks in VGRF was also computed to permit an analysis of the contribution of each variable to the variability in $F_{z1}$ and $F_{z2}$.

**Results**

The data and the resulting statistics show that, on average, peak forces increase in a regular manner with increases in running speed and body mass. Table 1 shows
### Table 1

**Average Force and Temporal Data for the Two Major Peaks in Vertical Ground Reaction Forces (mean data are shown ± SD)**

<table>
<thead>
<tr>
<th>Speed m * s⁻¹</th>
<th>Peak force Absolute N</th>
<th>Relative %BW</th>
<th>Time of occurrence Absolute ms</th>
<th>Relative %CT</th>
<th>Total CT ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F₁</strong>-Impact peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.35</td>
<td>1365 ± 354</td>
<td>203.4 ± 51.6</td>
<td>5.4 ± 4.8</td>
<td>2.4 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>3.83</td>
<td>1590 ± 507</td>
<td>232.9 ± 58.8</td>
<td>7.3 ± 6.6</td>
<td>3.7 ± 3.3</td>
<td></td>
</tr>
<tr>
<td>4.47</td>
<td>1963 ± 546</td>
<td>286.3 ± 46.8</td>
<td>8.2 ± 7.5</td>
<td>4.6 ± 4.2</td>
<td></td>
</tr>
<tr>
<td><strong>F₂</strong>-Active peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.35</td>
<td>1729 ± 373</td>
<td>252.9 ± 54.6</td>
<td>90 ± 8.3</td>
<td>40.1 ± 3.7</td>
<td>224 ± 23</td>
</tr>
<tr>
<td>3.83</td>
<td>1821 ± 420</td>
<td>266.4 ± 61.4</td>
<td>84 ± 6.9</td>
<td>42.3 ± 3.5</td>
<td>198 ± 19</td>
</tr>
<tr>
<td>4.47</td>
<td>1871 ± 476</td>
<td>273.8 ± 69.6</td>
<td>76 ± 7.4</td>
<td>42.1 ± 4.1</td>
<td>180 ± 15</td>
</tr>
</tbody>
</table>

%BW = percentage of body weight; %CT = percentage of total contact time; CT = total contact time of foot with ground

The mean time of occurrence of these peaks is also indicated. Although $F_2$ results are comparable, the relative magnitudes of $F_1$ were greater and occurred much sooner than previously reported for runners wearing shoes (Cavanagh & Lafortune, 1980; Clarke, Frederick, & Cooper, 1983a, b). This is not surprising, because the shock-absorbing properties of running shoe soles would tend to attenuate peak impact forces, shifting them in time.

Figure 2 shows the relative influence of speed and body mass on the two VGRF peaks. For the purpose of comparison, the subjects are divided into three groups of three based on body mass. The three female subjects weighing near 50 kg (45.5, 50.0, and 55.9 kg) are placed in a “light” group. Three of the male subjects are in a “medium” group, weighing near 70 kg (68.2, 70.9, and 73.6 kg), and the remaining three are in a “heavy” group, weighing roughly 90 kg (84.1, 89.1, and 90.9 kg). The pronounced effect of running speed on the average of $F_1$ can readily be seen in Figure 2a. It is also apparent that body mass has a lesser effect on the variation in the absolute magnitude of mean impact peaks for the medium compared with the heavy group. The light group shows much lower impact peaks, however, particularly as speed increases.

Figure 2b shows a different trend for the $F_2$ data. In this figure, body mass has the more pronounced effect on the magnitude of $F_2$. The effect of running speed is less pronounced, but a consistent, albeit slight, trend of increased peak force with increased speed does appear in the mean data for all 9 subjects. This trend is also apparent in the heavy and medium weight groups.

The multiple regression and, in particular, correlation analyses support these observations and point up additional significant findings. To be considered significant, the individual correlation coefficient for a particular variable with
$F_z$ or $F_{z2}$ had to be greater than $r = 0.20$, which is statistically significant at the 0.05 level when $n = 128$ observations (135 total observations less the 7 without $F_z$) (Young, 1962).

![Figure 2a](image_url)  
**Figure 2a** — Average impact peaks in VGRF for light, medium, and heavy weight subjects running at 3.35, 3.83, and 4.47 m·s⁻¹. Mean data for all subjects are also plotted.

![Figure 2b](image_url)  
**Figure 2b** — Average active peaks in VGRF for light, medium, and heavy weight subjects running at 3.35, 3.83, and 4.47 m·s⁻¹. Mean data for all subjects are also plotted, although the curve is difficult to see because it lies almost directly on the curve for the medium weight group.
Speed ($r = 0.34$) and body mass ($r = 0.57$) correlate significantly with the magnitude of $F_{z1}$. And, in order of decreasing correlation with $F_{z1}$, RPI ($r = -0.53$), stature ($0.47$), half-stride length ($0.44$), leg length ($0.38$), vertical hip excursion ($0.34$), hip offset ($0.31$), dorsiflexion angle ($0.31$), step length ($0.29$), and contact angle ($0.24$) also show a significant relationship.

Despite the statistical evidence showing so many significant correlations, none of the variables studied can be considered to dominate the development of $F_{z1}$. Body mass is shown to explain $32\%$ ($0.57^2 = 0.32$) of the variability in $F_{z1}$. This may be arguably a dominant influence, but many other variables are making a contribution as well. The multiple regression analysis revealed that $52\%$ of the variability in $F_{z1}$ can be explained by the combination of body mass, speed, leg length, RPI, stature, and dorsiflexion angle. Adding additional factors to the equation increases the value of $r^2$ by a total of less than $0.01$. This leaves almost half of the variability in $F_{z1}$ unexplained. The situation with $F_{z2}$ is much clearer.

The magnitude of $F_{z2}$ is most influenced by body mass ($r = 0.95$), and three other factors highly cross-correlated with body size also show a significant influence: RPI ($-0.81$), stature ($0.81$), and leg length ($0.52$). Other factors that significantly correlate with $F_{z2}$ are vertical hip excursion ($0.34$), dorsiflexion angle ($0.32$), half-stride length ($0.31$), step length ($0.31$), and hip offset ($0.27$). The correlation coefficient for speed on $F_{z2}$ ($r = 0.15$) is not significant.

The multiple regression analysis shows that $92\%$ of the variability in $F_{z2}$ can be explained by the combination of body mass, stature, RPI, and leg length, with $90\%$ being explained by mass alone.

Discussion

Taken together, these data suggest that body mass has a consistent and pronounced influence on the absolute magnitude of the two major peaks in VGRF. This is not surprising when one considers that the mass contributing to the development of these forces is either the mass of the body itself in the case of $F_{z2}$ or the effective mass of the leg in the case of $F_{z1}$. The effective mass has been shown by Nigg and Denoth (1980) to be, in part, a function of body mass as well as the knee angle at contact. Although the knee angle is not included in this analysis, it would seem that the contact angle and hip offset, which are included and significantly correlated with $F_{z1}$, would also be indicators of effective mass because they are an estimate of the relative extension of the leg ahead of the center of mass at the time of $F_{z1}$. Nigg and Denoth (1980) or Nigg (1986, see chap. 3) provide a more detailed explanation of the role of effective mass in the development of $F_{z1}$.

The other significantly correlated variables of leg length and stature-relative body mass (as estimated by RPI), as well as the highly cross-correlated variables of stature and hip offset, support the significance of the indirect contribution of body mass and the relative mass of the leg to the magnitude of $F_{z1}$.

Increases in running speed result in increases in the magnitude of $F_{z1}$. However, the relatively low correlation coefficient between these two variables ($r = 0.34$) does not reflect the strong relationship between speed and $F_{z1}$ that appears in the plot of the mean data in Figure 2a. This discrepancy probably results
from the high variability in the magnitude of $F_{z1}$. Its coefficient of variability is as high as 27% at 4.47 m/s$^{-1}$, and this decreases the correlation coefficient.

Hamill et al. (1983) have shown a similar relationship between running speed and $F_{z1}$. Their subjects ran trials at 4, 5, 6, and 7 m/s$^{-1}$ and showed progressive increases in body mass specific $F_{z1}$ (N per kg body mass) with speed. In addition, a lesser effect of speed on $F_{z2}$ was observed which is also in agreement with the results of this study.

This relationship between speed and $F_{z1}$ should not be surprising. Nigg and Denoth (1980) have suggested that the biomechanical factors that can affect the magnitude of $F_{z1}$ are effective mass (influenced by knee angle and body mass), the vertical velocity of the effective mass at contact, the area over which the load is distributed, and the compliance and resilience of the surface and shoe. The surface characteristics were controlled and no shoes were worn, so those factors can be eliminated. Of the remaining factors, effective mass, via increased knee angles (Sinning & Forsyth, 1970), and the vertical velocity of the effective mass at contact (given indirect support by the findings of Clarke, Cooper, Clark, & Hamill, 1985) are likely to increase with running speed. Although some increases in contact area are bound to result from increased deformation at higher loads (Cavanagh, Valiant, & Misevich, 1984) and from changes in foot posture, this variable was not assessed. Nigg (1986) presents detailed results on the role of this factor in the development of impact forces.

These data support the general conclusion that body mass and speed are significant effectors of the magnitudes of $F_{z1}$ and $F_{z2}$. In addition, other factors that affect these peak forces are generally cross-correlated with body mass and/or running speed. It should be pointed out that correlation does not prove cause and effect but merely indicates a covariance of the variables being compared. For this reason, the results of this exploratory study should not be construed as proof of any of the ideas they appear to support. Instead, these data should be considered provocative and should be used to promote future research of a more mechanistic and experimental nature.

References


Clarke, T.E., Cooper, L.B., Clark, D., & Hamill, C. (1985). The effect of increased running speed upon peak shank deceleration during ground contact. In D.A. Winter,
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