EVALUATING SPORT SHOES USING GROUND REACTION FORCE DATA

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INTRODUCTION

The ground reaction force (GRF) is the most common force acting on the human body. To measure the GRF of the human body involves the use of a force measuring device, most notably, a force platform. The force platform has been one of the most frequently used and most important measuring devices in biomechanics. The use of force platforms to measure GRF's dates back to Marey in the late 1890's. Cavagna (1964) utilized force platforms to measure the vertical component of the GRF. Since the 1970's, GRF data have been used by a number of researchers to quantify external forces during human movements, particularly during walking and running. The information gained from the study of these external forces has been applied to the development of athletic shoes.

The GRF is a force vector consisting of three components; a vertical component and two shear components, the antero-posterior (A/P) and medio-lateral (M/L) components, that act parallel to the force platform surface. In addition, three moments about the corresponding axes are also obtained. The force and moment values can be used to calculate the center of pressure (COP) and the free moment. Using the time histories of the vertical, A/P and M/L components, a number of GRF parameters have been derived to evaluate shoe function during locomotion (Bates et al., 1983a). A description of the path of the COP has also been used in the evaluation of athletic footwear (Cavanagh and Lafortune, 1980). The free moment has been used as a measure of rotational friction and to predict pronation/supination actions of the foot (Holden and Cavanagh, 1991).

FORCES IN RUNNING

The vertical force for heel-toe running usually exhibits two peaks; an initial peak often referred to as the passive or impact peak and a second peak referred to as the active peak (Figure 1). The impact peak can be characterized as a lower magnitude force with a faster rise time whereas the active peak is a higher magnitude force with a slower rise time.

The impact peak is a high frequency peak and generally occurs about 5 to 30 ms after ground contact. Impact forces are the result of the collision of the foot and the ground. The magnitude and the time at which the peak occurs depends on a number of factors including running speed, running style and shoe construction. For example, the peak impact force increases with an increase in running speed; is smaller for a forefoot striker than a rearfoot striker; and occurs earlier in the support phase when wearing a shoe rather than running barefoot and with firm midsole shoes than with soft midsole shoes. For a forefoot striker, the impact peak is generally not obvious on the force-time history compared to a heel-striker although it may still be present.

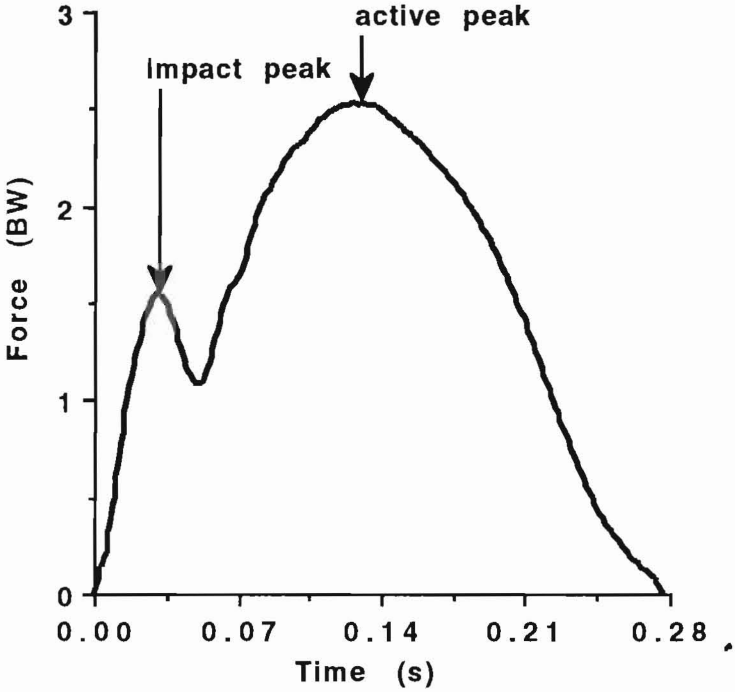

Figure 1. The vertical GRF component for a heel-toe running footfall pattern in units of body weight (BW) showing the impact and active peaks.

The magnitude of the impact peak in running varies greatly depending upon the previously mentioned conditions. For example, Frederick et al. (1981) reported impact peak values ranging from 2.0 to 2.9 BW with increases in running velocity from 3.4 to 4.5 m/s respectively. Both Nigg et al. (1987) and Foti and Hamill (1993) reported little difference in the impact peaks between hard and soft midsole shoes while running at the same speed. Foti and associates (1993) actually reported that the soft midsole shoe had a greater impact peak than the hard midsole shoe.

A key parameter used to evaluate footwear is the loading rate of the initial portion of the vertical GRF component. This parameter describes the initial slope of the vertical component. Nigg et al. (1987) reported that loading rate was dependent on running velocity. It is an important variable when evaluating footwear worn by runners who are forefoot strikers since they generally do not exhibit an impact peak. The unit for this parameter is N/s or BW/s. Exactly when to determine the slope is important since the foot may undergo some re-positioning during the first part of support. Generally it is recommended that a magnitude of 50 N be achieved before the computation is made. It has been reported that loading rate varies inversely as shoe hardness increases.

The primary portion of the shoe that influences the impact peak, the time to the impact peak and the loading rate is the midsole. Midsoles are constructed of many types of materials. Various densities of materials such as ethyl vinyl acetate (EVA) and polyeurethane (PU) are used in the midsole for cushioning.

The active peak is a low frequency peak that generally occurs in the middle of the support phase between 100 and 250 ms after ground contact. This peak is generated by movements that are controlled by muscular activity (Nigg, 1986a). The magnitude and time of occurrence for this peak is not generally affected by footwear construction but is affected mainly by running speed. However, it has been suggested than attention to the forefoot region of the shoe may be critical for runners who do not employ a heel-toe footfall pattern.

The A/P component describes the braking and propulsion of the runner during the support phase. By integrating the A/P component, the velocity of the center of mass of the runner can be determined. Comparing the braking velocity with the propulsion velocity is critical in shoe evaluation because the ratio of these velocities determines if the subject is running at a constant velocity. Cavanagh and Lafortune (1980) suggested that the functions of braking and propulsion take place in the region of the shoe between 60 and 80% of the shoe length from the heel. They further stated that this region of the shoe should be capable of resisting slip from forces applied in either the posterior or anterior direction.

The M/L GRF is the side-to-side component. While it has been possible to determine a number of identifiable characteristics of the vertical and A/P components, the same cannot be said for the M/L component. The most identifiable feature of this component is its high variability. That is, there appears to be no discernible, consistent pattern. Cavanagh and Lafortune (1980) suggested that the variability in the M/L component indicates the need for stability in both the medial and lateral directions. Statements such as this lead to the idea that the M/L component can be linked to the pronation and supination actions of the foot. Bates et al. (1983b) reported significant differences in the M/L impulse between running shoes and suggested these differences were related to pronation. Attempts to make this connection have not proven particularly fruitful. Theoretically, it is probably not appropriate to make this link.

CENTER OF PRESSURE

The COP is the point of application of the of the resultant GRF and its location changes during the support phase of running. For the most part, COP patterns have been used to identify the footfall pattern of runners. Therefore, combining the COP pattern with the force information is important for shoe design for runners with specific footfall patterns. COP data should be linked to kinematic data in order to determine the find the COP location relative to the foot. Attempts to directly relate the COP pattern to characteristic behavior of footwear in order to differentiate footwear has been unsuccessful. Williams (1985) suggested that this was because the COP is a global measurement and does not account for subtle changes that might have occurred during the support period.

FREE MOMENT

The free moment acts in a plane parallel to the running surface and results from the action of the shear forces that produce a force couple. The profile of the free moment generally is consistent within a subject/condition but shows great variability across footwear conditions. The free moment is often to calculate a friction coefficient to evaluate the resistance of a shoe to rotation (Holden and Cavanagh, 1991). However, it has also been related to the pronation action of the foot. Holden and Cavanagh (1991) used the free moment to evaluate shoes that were specifically constructed to place the foot in a pronated, supinated or neutral position. They reported that the pronation/supination actions in these various footwear conditions could be differentiated using this technique in that greater the maximum free moment the greater the degree of pronation.

EVALUATING FOOTWEAR FRICTION CHARACTRISTICS USING GRF DATA

The friction characteristics of athletic footwear include the evaluation of both translational friction and rotational friction. Translational friction determines how much horizontal force will be needed to cause the shoe to slide over the surface. The resultant shear component is this force. However, the coefficient of friction is the parameter that is required to compare the translational friction characteristics of both footwear and surfaces. Stucke et al. (1984), using GRF information, used the following formula to calculate the translational coefficient of friction (μ):

$$\mu \leq \frac{F_{A/P}}{F_{vertical}}$$

This calculation, however, assumes that the movement is only in the sagittal plane. This coefficient can be measured using a physical test or by performing a carefully controlled experiment using human subjects. However, Stuke et al. (1984) reported that physical tests generally yield higher coefficients than human subject tests. It was suggested that humans probably try to adjust their movements to compensate for the friction force. Valiant et al. (1987) suggested that a coefficient of friction of 0.8 provides sufficient translation friction for most athletic movements. It should be noted that too much friction can have very negative results.

Rotational friction determines how much force must be applied as a moment of force to cause the shoe to rotate on a surface. However, there is no coefficient of rotational friction. Generally, researchers have used the peak free moment of the GRF to describe rotational friction. A greater peak free moment indicates a greater rotational friction. Valiant et al. (1986) reported a peak free moment of 3 N•m when completing a 180° pivot while wearing gym socks and 13 N•m when accomplishing the same task in basketball shoes. Rotational friction can be measured using both physical and human subject tests but physical tests are generally preferred. However, physical tests of rotational friction generally result in a greater peak free moment than in human subject tests.

It should be noted that the two aspects of friction, the translational and rotational, are not independent parameters. Schlaepfer et al. (1983) derived an equation based on Coulomb's Law that illustrates that pressure and the translational coefficient of friction influence the moment of rotation.

PROBLEMS IN EVALUATING FOOTWEAR WITH GRF DATA

Cavanagh (1987) suggested that footwear can affect the GRF patterns recorded although not as drastically as one might have imagined. The key GRF parameters that are often referred to in footwear evaluation are the vertical impact peak, the time to this peak and the loading rate of impact will be used to illustrate this point. Studies by Nigg et al. (1987) and Foti and Hamill (1993) produced what may seem to be counterintuitive results. In both of these studies, GRF measures were collected on individuals running at the same speed in footwear of differing midsole density. In the former study, there were no differences in the peak impact force across midsole hardness conditions. In the latter study, the results showed that the impact peaks were greater and the time to the impact peak was longer in the soft midsole shoes than in the firm midsole shoes. In addition, the loading rate was greater in the soft midsole shoe. These results are not what one would predict. In both studies, the explanation for this phenomena was that the soft midsole shoes "bottomed" out.

Further evidence that it is difficult to evaluate athletic footwear using GRF data is present when materials test result are compared to *in vivo* data. To determine the cushioning properties of footwear, impact data on midsole materials, collected using an instrumented impact tester, generally reveals linear relationships in midsoles of differing hardnesses. Figure 2 illustrates the peak g and time to peak g values for three midsoles (25, 35 and 50 durometers respectively on a Shore A scale). It would be expected that, with material hardness, the peak g would increase and the time to peak g would decrease.

When footwear such as these are tested with subjects running across the force platform, the results are generally not like this at all. With human subjects, the impact peak of the vertical GRF component does not follow the linear impact pattern of the materials test. Therefore, there is a lack of correlation between physical tests of cushioning and performance tests. Nigg et al. (1986b) reported no differences in impact peak when a mass was added to the tibia of runners. Nigg and associates suggested that there are a number of strategies that the runner may use to influence the impact forces. One solution that was documented was a change in knee angle to a more flexed position. The implication is that a human subject is not simply a mass that drops on the ground but they can adjust their kinematics to help attenuate the impact force. The strategy chosen, however, is subject dependent. This results in trends in impact peaks, time to impact peak and loading rates that are not consistent from subject to subject or from shoe to shoe.

This subject by footwear interaction becomes a problem in the statistical analysis of GRF parameters. For example, if, in a study of footwear with different midsole hardnesses, some subjects may radically alter their kinematics while other do not. The analysis of the group means in the various footwear conditions may not represent what truly occurred in the experiment. The impact peak for those subjects that alter their kinematics would be much less than those that did not. The group mean does not reflect either strategy. The possibility of achieving statistical differences among footwear types then becomes difficult. Therefore, the differences in footwear types may be masked resulting in inaccurate interpretation of the data.

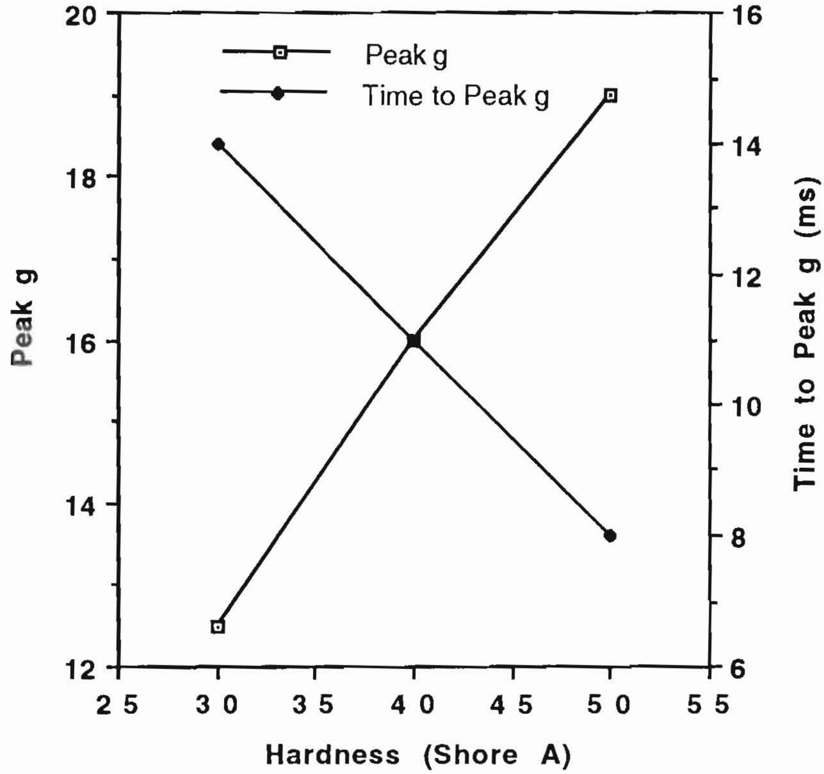

Figure 2. Material impact test results on midsoles of different hardnesses.

To alleviate the problem of subject by footwear interaction, Bates et al. (1983b) developed a model in which the GRF parameters of individual subjects in different footwear conditions could be evaluated. Using this approach, each subject's GRF data were evaluated independently. This method takes into account inter-individual variability and dismisses between subject differences. Trends in the data across subjects can be investigated on a *post hoc* basis. However, the drawback to this approach is that a significant number of trials, usually about 25, is necessary for each subject in each condition.

INTERPRETATION OF THE GROUND REACTION FORCE

With the difficulty in linking GRF data directly to foot function, it would be appropriate to discuss exactly what a GRF profile is. From Newton's second law of motion, a force is the product of the mass of an object and its acceleration. In terms of the vertical component of the GRF, the mass is the total body mass and the acceleration is the change in velocity of the center of mass. Bobbert et al. (1991) calculated an estimation of the vertical GRF component from the positional data of the center of mass of each body segment. These researchers calculated the vertical GRF component as:

$$F_{vertical} = \sum_{i=1}^{n} m_i(a_{zi} - g)$$

where m_i is the mass of the *i*th segment, a_{zi} is the vertical acceleration of the *i*th segment and g is the acceleration due to gravity. The vertical GRF component may be constructed by summing the products of the masses of each segment and the acceleration of the center of mass of each segment. This equation may be re-written as:

$$F_{vertical} = M(a_{cm} - g)$$

where M is the total body mass, a_{cm} is the vertical acceleration of the total body center of mass and g is the acceleration due to gravity. Thus, GRF data reflect the motion of the center of mass of the runner and not necessarily the motion of the foot at the foot-ground interface.

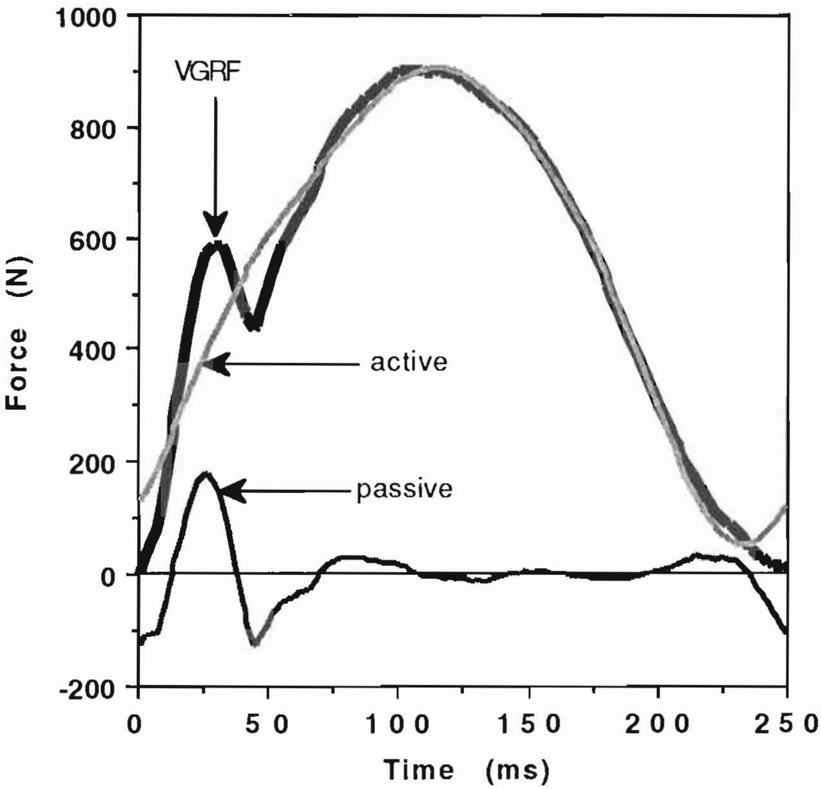

Figure 3. A decomposed vertical GRF component illustrating the total vertical GRF curve (VGRF), the passive (impact) component and the active component.

The work of Bobbert and his associates further illustrated the origin of the vertical impact peak and determined the variables that contributed to its magnitude. By decomposing the vertical component into the contributions of the various body segments, these researchers illustrated that the impact peak results primarily from the acceleration of the support leg. This decomposition of the vertical GRF component may also be accomplished by investigating the frequency components of the GRF profile. Using this method, the low and high frequency components of vertical GRF curve are determined using an FFT. An inverse transform is then performed twice - once on the low frequency component (below 3 Hz) and once on the high frequency component (above 3 Hz). The results of this technique are comparable to those of Bobbert et al. (1991). Figure 3 illustrates a vertical GRF profile that was decomposed using this technique.

Investigating segmental contributions to the vertical GRF component may lead to a more suitable method for evaluating the effects of athletic footwear using GRF data. For example, in evaluating footwear with hard and soft midsoles, the impact peak oftentimes does not illustrate differences because the impact portion of the force-time curve is summed with the active portion. The impact peak measured from the vertical GRF component therefore is obscured by the active peak resulting in virtually no change in the impact peak characteristics. Decomposing the GRF component, therefore, may present a more complete picture.

CONCLUSIONS

It is evident, therefore, that attempts to differentiate between footwear types using GRF data is extremely difficult. In some studies, the difficulty in differentiating footwear is a result of an inappropriate number of trials (Bates et al., 1983b). However, given appropriate methods and statistical procedures, the data still must be viewed with caution. Most of the problem concerns the fact that GRF data are not a direct measure of the forces at the foot. That is, GRF data represents the force acting on the center of mass, although it is applied at the foot/ground interface. Thus the difficulty in interpretation of shoe differences is that GRF data are a "remote" measure of lower extremity action.

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