Foot strike patterns after obstacle clearance during running

Shane D. Scholten

Nicholas Stergiou

Alan Hreljac

Jeremy J. Houser

Daniel Blanke

See next page for additional authors

Authors
Shane D. Scholten, Nicholas Stergiou, Alan Hreljac, Jeremy J. Houser, Daniel Blanke, and L. Russell Alberts

Foot strike patterns after obstacle clearance during running

SHANE D. SCHOLTEN, NICHOLAS STERGIOU, ALAN HRELJAC, JEREMY HOUSER, DANIEL BLANKE, and L. RUSSELL ALBERTS HPER

Biomechanics Laboratory, University of Nebraska at Omaha, Omaha, NE 68182; Orthopaedic Surgery, University of Nebraska Medical Center, Omaha, NE 68198; and Department of Kinesiology and Health Science, California State University, Sacramento, CA 95819

ABSTRACT

SCHOLTEN, S. D., N. STERGIOU, A. HRELJAC, J. HOUSER, D. BLANKE, and L. R. ALBERTS. Foot strike patterns after obstacle clearance during running. Med. Sci. Sports Exerc., Vol. 34, No. 1, 2002, pp. 123–129. **Purpose**: Running over obstacles of sufficient height requires heel strike (HS) runners to make a transition in landing strategy to a forefoot (FF) strike, resulting in similar ground reaction force patterns to those observed while landing from a jump. Identification of the biomechanical variables that distinguish between the landing strategies may offer some insight into the reasons that the transition occurs. The purpose of this study was to investigate the difference in foot strike patterns and kinetic parameters of heel strike runners between level running and running over obstacles of various heights. **Methods**: Ten heel strike subjects ran at their self-selected pace under seven different conditions: unperturbed running (no obstacle) and over obstacles of six different heights (10%, 12.5%, 15%, 17.5%, 20%, and 22.5% of their standing height). The obstacle was placed directly before a Kistler force platform. Repeated measures ANOVAs were performed on the subject means of selected kinetic parameters. **Results**: The statistical analysis revealed significant differences ($P < 0.004$) for all of the parameters analyzed. The evaluation of the center of pressure and the ground reaction forces indicated that the foot strike patterns were affected by the increased obstacle height. Between the 12.5% and 15% obstacle conditions, the group response changed from a heel strike to a forefoot strike pattern. **Conclusions**: At height >15%, the pattern was more closely related to the foot strike patterns found in jumping activities. This strategy change may represent a gait transition effected as a mechanism to protect against increased impact forces. Greater involvement of the ankle and the calf muscles could have assisted in attenuating the increased impact forces while maintaining speed after clearing the obstacle.

Key Words: GROUND REACTION FORCES, GAIT TRANSITIONS, LOCOMOTION

Human beings are capable of producing a number of gait patterns on land, including walking, running, sprinting, bounding, skipping, and jumping. Although there are some clearly defined biomechanical differences between these gait patterns, it is not always clear when one gait pattern ends and another begins. Some researchers (15) believe that various terrestrial gait patterns represent a continuum in terms of biomechanical parameters. Others (1,2,14,16) believe that gait patterns are differentiated between each other only when one or more distinguishing biomechanical characteristics could be identified that change discontinuously at the transition between gaits.

Although running has been described as a series of leaps or jumps (1,21), there are some very clear differences in landing patterns observed between running and jumping. Among the most obvious differences is the portion of the foot that initially contacts the landing surface. At slow to moderate speeds of running ($<4.5\ m\cdot s^{-1}$), a large majority of runners first contact the ground with the heel of the foot (4,24). When landing from a vertical jump, researchers have reported that subjects generally utilize a forefoot landing pattern (12), with similar forefoot landing patterns observed in landings after a basketball rebound (29) and a volleyball block (27). Possibly due to the differences in landing strategies, vertical ground reaction forces have also been shown to differ between running and landing from a jump (13), as well as between moderate speed running and sprinting (19,20).

The landing and force time records of running could be temporarily disrupted when runners are forced to negotiate an obstacle. When subjects run over relatively low obstacles, little difference is observed in the landing pattern compared to that observed during level running (28). However, when obstacles of sufficient height are negotiated, landing strategies change from a heel strike to a forefoot strike pattern, becoming similar to patterns observed while landing from a jump (28). Clearly, there is a difference between the landing mechanics during level running and landing mechanics when jumping over sufficiently high obstacles, but it is not clear whether these differences occur on a continuum scale or whether there is an abrupt discontinuity in some biomechanical factors at a specific height. If an abrupt change could be identified, and if it could be determined that this change is consistent within and between subjects, then these gait patterns could be considered as separate entities (2,14,16). The biomechanical variables that identify this gait change may offer some insight into the reasons that the transition occurs. It has been suggested (2) that the study of gait transitions may be important in understanding the optimization criteria involved in gait selection. The purpose of this study was to investigate the difference in foot strike patterns and kinetic parameters of heel strike runners between level running and running over obstacles of various heights. An attempt was made to determine whether a height existed where there was an abrupt change in the measured parameters or whether differences occurred on a continuum scale. It was hypothesized that the transition in landing strategy would occur at a similar height for each subject and that a small number of variables could be identified that change discontinuously at this transition height.

METHODS

Subjects.

The subjects of this investigation were 10 healthy male (N = 4) and female (N = 6) recreational runners (age = 23.5 $\pm$ 2.5 yr; body mass = 67.5 $\pm$ 15.3 kg; height = 173.9 $\pm$ 9.3 cm). Before the subjects were admitted to this research study, the investigators qualitatively analyzed their running style to ensure they performed at their preferred pace with a heel strike pattern. The study protocol had been previously approved by the Human Subjects Committee of the University of Nebraska. Before testing, each subject read and signed an informed consent form consistent with the University of Nebraska and the American College of Sports Medicine policies.

Instrumentation.

A Kistler force platform (Kistler Model 9281-B11, Amherst, NY) connected to a Kistler signal conditioner/amplifier (Kistler Model 9807) was used to collect the ground reaction forces (GRF) data (900 Hz). The signal condition/amplifier was interfaced to a 16-channel Peak Performance Technologies Analog/Digital Interface Unit (Peak Model 2051, Englewood, CO) containing the analog to digital sampling modules interfaced to a PC. The GRF data were stored on a hard disk during the testing sessions. The vertical (FZ) and the anterior-posterior (FY) GRF components, as well as the coordinates (AX and AY) of the center of pressure (COP), were retained for further analysis.

Protocol.

Subjects wore their regular running shoes to assure the most normal performance. Running speed was monitored over a 3-m interval by using a photoelectronic timing system. This system utilized two infrared timing lights connected to a digital timer. Subjects were given time to accommodate to the experimental set-up and to adequately warm-up before testing. Warm-up consisted of running through the testing area without concern for stepping on the force platform. The testing area was a 40-m runway with a 0.6-m-wide lane. During warm-up, the subject established a comfortable running pace, which was recorded. This speed ($\pm$5%) was used for the subsequent testing. A trial was considered acceptable only when the running speed was within this predetermined range. After this procedure, a foot placement marker was located approximately 7 m before the timed interval to allow for a normal right foot contact on the force platform. Each trial was visually monitored to insure that the stride was normal, and the foot was completely on the force platform. Every subject ran at the previously established comfortable self-selected pace over obstacles of six different heights: 10%, 12.5%, 15%, 17.5%, 20%, and 22.5% of the subject's standing height. In addition, a baseline condition with no obstacle was collected. The obstacle was placed directly before the force platform so that the subject was forced to clear the obstacle with the right leg and land on the force platform. While the subjects performed at their self-selected pace, a marker was positioned one step before the force platform to identify left foot position. When the obstacle was placed on the runway, the subjects were instructed to hit the marker with their left foot before clearing the obstacle with the right leg. This procedure insured that the subjects did not change their stride length when clearing the obstacle. By controlling the stride length and, as mentioned above, the speed, we ensured that the observed changes were due only to the obstacle perturbation. It has been documented in the literature (6,10) that changes in stride length and in speed can affect the mechanics of the leading leg. The obstacles were made of extremely lightweight wood so that when a subject stepped on or hit the obstacle by mistake while running, the obstacle was destroyed. This minimized the risk of the subject tripping and/or falling. Each condition consisted of 10 trials, and the heights of the obstacles were established based upon pilot work and previous literature (28).

Data reduction and analysis.

Based on the literature (7,22,23) regarding the evaluation of GRF, the following parameters were evaluated for each trial using laboratory software: from the anterior-posterior GRF component, the time of the stance (TS) period, the minimum braking peak (Fy1), the maximum propulsion peak (Fy2), the braking impulse (BI), and the propulsive impulse (PI); from the vertical GRF component, the first impact peak (F1), the second impact peak (F2), the active peak (Factive), and the loading rates to the two impact peaks (LR1 and LR2). The loading rates LR1 and LR2 were calculated by dividing F1 with the time to F1 (T1) and F2 with the difference between the time to F2 (T2) and T1, respectively. Subsequently, all force values were normalized to body weight (BW), whereas the loading rates were normalized to $BW \cdot s^{-1}$. The impulses in N·s were normalized by dividing them with the impulse of the individual's body weight over the stance time generating units of body weight impulse (BWI; 22). The means of all parameters were calculated across trials for each condition of each subject. The group means for all parameters were also calculated for each condition.

The second impact peak (F2) appeared predominantly in the high obstacle conditions (Fig. 1). When the vertical GRF plots showed a configuration with two peaks, F2 was selected as the second impact peak. When the plots had only one impact peak, the same value was used for both as F1 and as F2 (Fig. 1). This procedure ensured that for the evaluation of F1, the first impact peak was always used. In addition and for every condition, the number of trials that exhibited two peaks was identified, as well as the ones that had only one peak. The same rationale was used for the evaluation of the LR1 and LR2.

In addition to these parameters, an index of the anterior-posterior (the direction of movement) position of the center of pressure (ICOP) was estimated (Fig. 2). This last parameter was calculated for the entire stance period as follows.

The end and the beginning points of the anterior-posterior coordinate values were subtracted working toward the middle (i.e., if the total number of data points are 100 then subtract 100 – 1 , 99 – 2, 98 – 3 , etc.). Then, the absolute values of the resulting numbers were averaged. This procedure ensured that the location of the foot strike on the platform would not affect the ICOP. Functionally, this parameter assisted in quantifying the foot strike pattern. A large value (above 0.10 m) indicated wide-spread values for the location of COP in the direction of movement (anterior-posterior) and a heel strike pattern, whereas a small value (below 0.07 m) indicated a more concentrated location of the COP and a forefoot strike pattern (Fig. 2). Subject and group means were also calculated for ICOP.

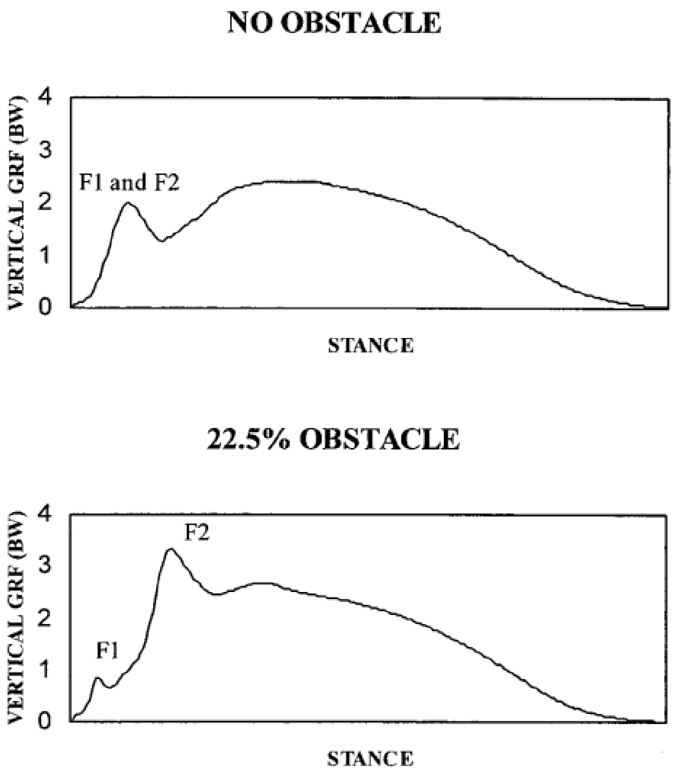

FIGURE 1—Vertical GRF plots from the no obstacle (heel strike) and the 22.5% obstacle (forefoot strike) conditions of a representative subject. The two impact peaks (F1 and F2) are also identified. The second impact peak (F2) appeared predominantly in the high obstacle conditions. When the vertical GRF plots showed a configuration with two peaks, F2 was selected as the second impact peak. When the plots had only one impact peak, the same value was used for both as F1 and as F2.

The method used for the calculation of the ICOP is different than the one recommended in the literature (7,22), where the measure used to quantify COP is the foot strike index. However, the calculation of the foot strike index requires information regarding the exact location of the outline of the foot on the platform. This information is difficult to be acquired based on the procedures described in the literature (7,22), especially for a large number of trials, as was the case in this study. Therefore, the method described above was devised because it does not require such information. In a validation pilot study, a strong correlation (r = 0.99) was found to exist between this method and the procedures described in the literature regarding the identification of the foot strike patterns.

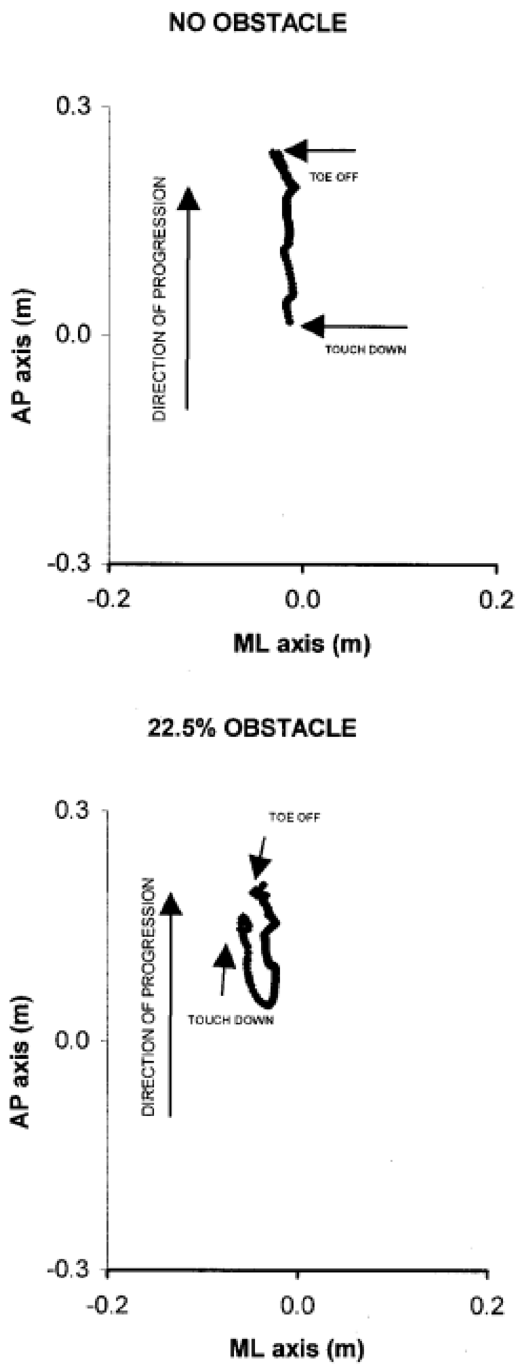

FIGURE 2—Center of pressure plots from the no obstacle (heel strike) and the 22.5% obstacle (forefoot strike) conditions from the same representative subject. The direction of progression, and the occurrences of touchdown and toe-off are identified. The point with coordinates (0.0, 0.0) identifies the center of the force platform, where the AP axis is the anterior-posterior direction and the ML axis is the medial-lateral direction.

Statistical analysis.

Eleven one-way repeated measures ANOVA (obstacle height by subject) were performed on the subject means for all parameters. In tests that resulted in a significant

F-ratio (P < 0.004), a Tukey multiple comparison test was performed to identify the location of the significant differences. A Bonferroni correction was used in this study due to the large number of comparisons conducted.

TABLE 1. Group means and SD for parameters related with the vertical GRF and for the ICOP; condition means that are significantly different ($P < 0.004$) are shown in superscripts; number of trials per condition with one and two impact peaks (IMPs) are included at the end of the table.

Variables	0%	10%	12.5%	15%	17.5%	20%	22.5%
F1 (BW)	1.72 (0.28)	$2.12^{22.5\%}$ (0.57)	1.99 (0.66)	1.66 (0.75)	1.68 (0.81)	1.56 (0.64)	1.43 (0.59)
F2 (BW)	$1.72^{10\%–22.5\%}$ (0.28)	$2.49^{17.5\%–22.5\%}$ (0.54)	$2.48^{17.5\%–22.5\%}$ (0.53)	$2.69^{20\%–22.5\%}$ (0.47)	2.91 (0.51)	3.04 (0.39)	3.10 (0.43)
Factive (BW)	$2.47^{10\%–22.5\%}$ (0.22)	2.62 (0.20)	2.60 (0.20)	2.64 (0.20)	2.67 (0.21)	2.68 (0.23)	2.70 (0.19)
LR1 ($BW{\cdot}s^{-1}$)	$62.27^{10\%–22.5\%}$ (19.12)	118.47 (52.65)	121.75 (55.52)	118.41 (50.83)	130.68 (55.39)	130.96 (49.84)	125.57 (40.60)
LR2 ($BW{\cdot}s^{-1}$)	$62.27^{10\%–22.5\%}$ (19.12)	109.89 (52.20)	115.47 (52.41)	110.51 (53.83)	120.47 (54.39)	118.83 (50.21)	107.69 (32.94)
ICOP (m)	$0.111^{10\%–22.5\%}$ (0.016)	$0.088^{15\%–22.5\%}$ (0.034)	$0.083^{17.5\%–22.5\%}$ (0.033)	0.066 (0.032)	0.062 (0.030)	0.060 (0.030)	0.054 (0.024)
Trials (1 IMPs)	100	87	72	40	38	26	14
Trials (2 IMPs)	0	13	28	60	62	74	86

RESULTS

The group mean values for F1 and F2 were identical only for the no obstacle condition (Table 1). This means that as soon as the obstacle was introduced, some subjects exhibited trials with two peaks. In fact, the categorization of the trials based on the number of their impact peaks (Table 1) showed that 13 of the 100 trials of the smallest (10%) obstacle condition exhibited trials with two peaks. The 15% obstacle was the first condition that showed more trials with two impact peaks (60) in comparison to trials with one (40). Statistically, the group results for the vertical GRF revealed significant differences for all parameters examined (Table 1). The *post hoc* analysis for the F1 group results revealed only one comparison as different. The highest (22.5%) obstacle condition, which had the lowest value, was statistically different from the 10% obstacle condition. The F1 group mean value increased (+0.40 BW) from the no obstacle condition to the 10% obstacle condition where it showed its largest value (2.12 BW). It then decreased between 10% and 12.5% (– 0.13 BW) obstacle conditions and from 12.5% to 15% (– 0.33 BW) obstacle conditions. After the 15% obstacle condition, the F1 group mean value gradually decreased until the 22.5% obstacle condition, where it showed its lowest value (1.43 BW). The vertical GRF plots from a representative subject illustrated that the high obstacle conditions exhibited predominantly two impact peaks (Fig. 1). The first peak was smaller in magnitude and occurred earlier during stance, whereas the second and later peak was larger in magnitude than the first. Because F1 was identified as the first impact peak selected, the change in the configuration of the vertical GRF plots resulted in the decreasing effect on the F1 values, especially starting at the 15% obstacle condition and continuing toward the highest obstacles.

For F2, the *post hoc* analysis revealed several significant differences (Table 1). It can also be observed that F2 increased as the obstacle height increased. It should be noted that the introduction of the obstacle had an immediate effect on this variable. An increase of 0.77 BW was observed between the no-obstacle and the 10% condition. This large increase was not observed between the next two conditions (10% and 12.5%), where the F2 values (2.49 and 2.48 BW) remained almost the same. A nonsignificant increase was observed between the next two conditions (10% and 12.5%), with F2 values of 2.49 and 2.48, respectively. When the 15% obstacle was introduced, F2 increased again (0.21 BW difference from 12.5% to 15%) and eventually reached its largest value (3.10 BW) at the highest (22.5%) obstacle condition. The *post hoc* analysis for the Factive group results revealed significant differences be tween the no obstacle and all the other obstacle conditions. Even though, the Factive values increased with increasing obstacle height, these changes were not significant. For both LR1 and LR2, the *post hoc* analysis showed that all obstacle conditions had significantly larger values than the no obstacle condition.

The ICOP group results revealed that the higher the obstacle, the smaller the ICOP. Smaller values for ICOP indicate a more concentrated path in the anterior-posterior direction (or the direction of the movement) for the center of pressure (Fig. 2). It is interesting to note that the introduction of the obstacle had an immediate and significant effect on this variable (Table 1). A decrease of 0.023 m was observed between the no obstacle and the 10% obstacle condition. No significant decrease was observed between the next two conditions (0.005 m difference from 10% to 12.5%), but when the 15% obstacle was introduced, the ICOP decreased significantly (0.022 m difference from 10% to 15%) and reached its smallest value (0.054 m) at the highest (22.5%) obstacle condition. The differences between the 15% and 22.5% obstacle conditions were nonsignificant.

The group results for the anterior-posterior GRF revealed significant differences for all parameters (Table 2). For Fy1, the *post hoc* analysis indicated that only the no obstacle was significantly different from the 17.5% and 20% obstacle conditions. It is interesting to note that the Fy1 value is consistent between all obstacle conditions and that there was an immediate increase with the introduction of the obstacle. For Fy2, the *post hoc* analysis revealed several significant differences (Table 2), indicating that the increasing obstacle height influenced the maximum propulsive force. Furthermore, it can be observed that the higher the obstacle, the larger the propulsive force. For TS, the *post hoc* analysis indicated that the no obstacle condition was significantly different for all the obstacle conditions. This result indicated that the introduction of the obstacle had an immediate decreasing effect on TS. For the obstacle conditions, TS continued to decrease but this change was not significant. The *post hoc* analysis for BI showed significant decreases with the increasing obstacle height. These decreases were probably due to the decreases in duration of the braking period, since Fy1 actually increased.

TABLE 2. Group means and SD for parameters with the anterior-posterior GRF; condition means that are significantly different ($P < 0.004$) are shown in superscript.

Variables	0%	10%	12.5%	15%	17.5%	20%	22.5%
Fy1 (BW)	$0.42^{17.5\%,20\%}$ (0.07)	0.52 (0.16)	0.51 (0.18)	0.51 (0.17)	0.53 (0.19)	0.53 (0.18)	0.52 (0.22)
Fy2 (BW)	$0.29^{10\%-22.5\%}$ (0.03)	$0.33^{12.5\%-22.5\%}$ (0.04)	$0.34^{15\%-22.5\%}$ (0.06)	$0.35^{20\%,22.5\%}$ (0.05)	$0.35^{20\%,22.5\%}$ (0.07)	$0.37^{22.5\%}$ (0.06)	0.398 (0.06)
TS (s)	$0.27^{10\%-22.5\%}$ (0.04)	0.26 (0.03)	0.26 (0.04)	0.25 (0.04)	0.25 (0.03)	0.25 (0.04)	0.246 (0.035)
BI (BWI)	$0.10^{12.5\%-22.5\%}$ (0.03)	$0.09^{22.5\%}$ (0.02)	0.09 (0.03)	0.08 (0.03)	0.09 (0.03)	0.08 (0.03)	0.06 (0.02)
PI (BWI)	$0.08^{10\%-22.5\%}$ (0.01)	$0.10^{20\%-22.5\%}$ (0.02)	$0.10^{22.5\%}$ (0.02)	0.11 (0.03)	0.11 (0.03)	0.12 (0.03)	0.13 (0.03)

DISCUSSION

The effect of the increased obstacle height was reflected on the force-time plots seen in Figure 1. The higher obstacle conditions exhibited predominantly two impact peaks. The first peak was smaller in magnitude and occurred earlier during stance. This different landing pattern was similar to the foot strike patterns found in jumping activities, where two impact peaks are usually reported (12,13,29). Based on the jumping related literature, the first peak is due to contact of the toes with the ground, whereas the second is due to the subsequent contact of the heel with the ground. Valiant and Cavanagh (29) measured the magnitude of GRF and the patterns of footfall during a simulated basketball rebound activity. Of the 10 male subjects evaluated, 8 exhibited a toe first and then heel landing pattern with average F1 and F2 values of 1.3 and 4.1 BW, respectively. Dufek and Bates (12) studied landing patterns from several heights and with different techniques. They reported average F1 and F2 values of 1.71 and 3.74 BW, respectively. In comparison, in the present study, averages for F1 and F2 of the 22.5% obstacle were 1.43 and 3.10 BW, respectively. Based on the above, it can be suggested that the initial impact peak was associated with a toe impact, whereas the later peak was associated with a heel impact.

The change in the configuration of the vertical GRF plot affected the F1 values. The first impact peak (F1) was associated with the toe impact peak during the high obstacle conditions, whereas in the low obstacles, it was associated with the heel impact peak. Thus, it was anticipated that its value would decrease as soon as the toe impact peak appeared. In fact, up to the 12.5% obstacle, the F1 value remained fairly constant (around 2 BW) with a significant decrease between the 12.5% and 15% obstacle conditions. The F2 value was identified as the second impact peak when the vertical GRF plots showed a configuration with two peaks. Thus, it was always associated with a heel impact. When the plots had only one impact peak, the same value was used both in the evaluation of F1 and F2. This is the reason that in the no obstacle condition F1 and F2 had the same average value (Table 1). Although no differences were found between the 10% and 12.5% obstacles, F2 values tended to increase with increases in obstacle height, with the largest increase occurring between the 12.5% and 15% obstacles.

The F2 results were also similar to results reported by Stergiou et al. (28). In that study, subjects were instructed to run over obstacles of 0%, 5%, 10%, and 15% body height and avoid jumping over them. This resulted in only heel strike type of landings. The authors identified a direct linear relationship between heel impact peak and obstacle height. The same can be observed in the results of the present study, where F2 values increased with increased obstacle height. Stergiou et al. (28) reported values of approximately 2.3 and 2.6 BW for 10% and 15% obstacle conditions, respectively. These results corresponded closely with the mean F2 values of 2.49 and 2.69 BW that were reported at the present study for the same obstacle heights.

Increasing obstacle height resulted in larger vertical (F2 and Factive) forces (Table 1). Combining these results with concurrent decreases in TS with the introduction of the obstacle (Table 2) led to significant increases in loading rates (LR1 and LR2), especially in the higher obstacles. Although vertical forces increased with increasing obstacle height, these changes might have been more dramatic and possibly injurious if the subjects were forced to run over the obstacles and land on their heels. Co et al. (8) and Oakley and Pratt (25) have shown that forefoot strike runners produced lower transient forces than heel strikers. It has also been shown that increased impact forces during initial contact with the ground can deform the heel pad (9). The deformation of the fatty heel tissue is proportional to the force acting on the heel. Thus, landing on the toes first after jumping over obstacles, may have decreased the stress on the heel. In addition, attenuating the increased impact forces could be accomplished by enlarging the contact area and by incorporating additional structures. Thus, the forefoot strike pattern might increase the involvement of other foot structures, especially the ankle joint and the plantarflexors in shock absorption.

Center of pressure patterns from different types of foot strike during distance running have been produced by several researchers (7,26,30). A heel-strike landing pattern is associated with a long, relatively straight line starting from the lateral heel and following the midline of the shoe to the middle of the base of the phalanges. For a forefoot landing pattern, the center of pressure trajectory generally starts at the anterior 1/3 of the shoe and travels to the midfoot area before returning to the anterior 1/3 of the shoe at toe off. These trajectories are similar to the ones depicted in the present study (Fig. 2). Furthermore, the ICOP values decreased with increasing obstacle height, revealing that the higher obstacles showed a more concentrated location of the center of pressure and a forefoot strike pattern. This is also in agreement with the F1 and F2 results.

The ICOP values showed a significant decrease between the 12.5% and 15% obstacles. No significant differences were found for ICOP between the 10% and the 12.5% obstacles or between the 15% and the rest of the high obstacle conditions. Thus, the 15% obstacle condition might be a critical threshold where the subjects as a group altered their landing strategy. Even though there was a significant decrease in the ICOP values between the no obstacle and the smallest (10%) obstacle condition, this was probably not the height at which the subjects changed their landing strategy, because the F1 values showed a nonsignificant increase between these two conditions.

Not all subjects agreed behaviorally with the group response that the 15% obstacle height was the critical threshold. Differential responses between subjects were revealed in terms of an earlier or later transition. In fact, the categorization of the trials based on the number of their impact peaks (Table 1) showed that 13 of the 100 trials even at the smallest (10%) obstacle condition exhibited forefoot strike landings. These results underlined the importance of individual variability as Dufek et al. (12,13) have previously suggested.

The Fy1 and Fy2 values also increased with the increasing obstacle height (Table 2). The Fy1 and Fy2 results were similar to values presented by Williams et al. (30) during running at 5.36 $m{\cdot}s^{-1}$. Their values were 0.67 BW for Fy1 and 0.57 BW for Fy2, whereas in this study, the subjects ran at an average speed of 3 $m{\cdot}s^{-1}$ and showed values of 0.42 BW for Fy1 and 0.28 BW for Fy2 at the no obstacle condition. Using a direct linear extrapolation of the values, it was found that if the subjects were to run at a similar speed as in Williams et al. (30), the current values would have increased to a similar magnitude. TS results from this study were also comparable with the literature (22), where TS was found to be 270 ms at a running speed of 3 $m{\cdot}s^{-1}$. In the present study, TS for the no obstacle condition was also found to be 270 ms for the same speed. The two anterior-posterior impulses indicated that the effect of the obstacle on the braking and the propulsion phases was opposite (Table 2). Although BI decreased, PI increased. Specifically, the differences between BI and PI were at a minimum at the 10% obstacle (0.007 BWI) and at a maximum at the 25% obstacle condition (0.067 BWI). Such differences in BI and PI have been suggested by Miller (22) as indicative of a change in momentum. Furthermore, these differences, along with the decreases in TS and the increases in FY2, may be related to the fact that speed was controlled in this study. Generally, it is expected that an obstacle will have a decreasing effect on the running speed. However, our subjects had to maintain the same speed, and thus, they may have used a mechanism similar to sprinting (3). Sprinters run with a forefoot strike pattern to achieve maximum velocity. One of the primary speed mechanisms is produced by the loading effect on the calcaneal tendon. This type of strategy allows increased speeds that are associated with higher propulsive forces and decreased stance times. Therefore, as obstacle height increased, subjects may have changed to a forefoot strike not only to allow for better shock attenuation but to also minimize the effect of the obstacle on their speed.

The determinants of gait transitions have been identified as variables that increase as speed increases during a particular gait, then fall abruptly to a lower level when a gait transition occurs (2,14,17,18). It has been proposed (5,14) that animals change gaits in response to kinetic factors. Specifically, it was concluded that horses change from a trot to a gallop when critical force levels are reached, demonstrated by the fact that peak forces decreased substantially when changing gaits (14). The gait change was hypothesized to be effected as a protective mechanism. Although no similar response was found in the walk to run transition of humans (17), data from the present study suggest that kinetic factors may trigger the transition from a running to a jumping strategy as obstacle height increases. The impact force peak (F1) increased with increasing height until a height was reached at which the landing strategy changed, then abruptly decreased for all subjects (Table 1). It is possible that subjects changed from running over obstacles to jumping over obstacles to enable them to attenuate increased impact forces. The forefoot strike pattern noted at the higher obstacle levels would likely have increased the involvement of the ankle joint in shock attenuation. However, it should be noted that individual differences regarding the point of transition to a different foot strike pattern do exist.

In conclusion, much research (3,11,16–18,20,24) has been produced on behavioral changes such as the walk-to-run or run-to-sprint transitions. These studies focused on the interaction between the nervous and the musculoskeletal systems under varied conditions in order to improve our understanding of control of locomotion. However, less attention has been directed toward the evaluation of the leading leg mechanics while running over high enough obstacles to cause a heel strike runner to land on the forefoot. In the present study, the results revealed that the foot strike pat terns, as described by the kinetic parameters, were affected by the increased obstacle height. Between 12.5% and 15% obstacle conditions the group response probably changed from heel strike to forefoot strike. This new pattern was more closely related to the foot strike patterns found in jumping activities.

There is no conflict of interest or endorsement of product by the authors. This work was supported by the University Committee on Research of the University of Nebraska at Omaha. The authors gratefully acknowledge the critical reading of this manuscript by Drs. Timothy R. Derrick and Kris E. Berg.

REFERENCES

1. ALEXANDER, R. M. Walking and running. Am. Sci. 72:348–354, 1984.

2. ALEXANDER, R. M. Optimization and gaits in the locomotion of vertebrates. Physiol. Rev. 69:1199–1227, 1989.

3. ARDIGO, L. P., C. LAFORTUNA, A. E. MINETTI, P. MOGNONI, and F. SAIBENE. Metabolic and mechanical aspects of foot landing type, forefoot and rearfoot strike, in human running. Scand. Physiol. Soc. 55:17–22, 1995.

4. BATES, B. T., L. R. OSTERNIG, B. R. MASON, and S. L. JAMES. Lower extremity function during the support phase of running. In: Biomechanics VI-B, E. Asmussen and K. Jorgensen (Eds.). Baltimore: University Park Press, 1978, pp. 30–39.

5. BIEWENER, A. A., and TAYLOR, C. R. Bone strain: a determinant of gait and speed? J. Exp. Biol. 123:383–400, 1986.

6. CAVANAGH, P. R., and R. KRAM. Stride length in distance running: velocity, body dimensions, and added mass effects. In: Biomechanics of Distance Running, P. R. Cavanagh (Ed.). Champaign, IL: Human Kinetics, 1990, pp. 35–64.

7. CAVANAGH, P. R., and M. A. LAFORTUNE. Ground reaction forces in distance running. J. Biomech. 13:397–406, 1980.

8. CO, F. H., H. B. SKINNER, and W. D. CANNON. Effect of reconstruction of the anterior cruciate ligament on proprioception of the knee and the heel strike transient. J. Orthop. Res. 11:696–704, 1993.

9. DE CLERCQ, D., P. AERTS, and M. KUNNEN. The mechanical characteristics of the human heel pad during foot strike in running: an in vivo cineradiographic study. J. Biomech. 27:1213–1222, 1994.

10. DERRICK, T. R., J. HAMILL, and G. E. CALDWELL. Energy absorption of impacts during running at various stride lengths. Med. Sci. Sports Exerc. 30:128–135, 1998.

11. DIEDRICH, F. J., and W. H. Jr. WARREN. Why change gaits? Dynamics of the walk-run transition. J. Exp. Psychol. Hum. Percept. Perform. 21:183–202, 1995.

12. DUFEK, J. S., and B. T. BATES. The evaluation and prediction of impact forces during landings. Med. Sci. Sports Exerc. 22:370– 376, 1990.

13. DUFEK, J. S, B. T. BATES, N. STERGIOU, and C. R. JAMES. Interactive effects between group and single subject response patterns. Hum. Mov. Sci. 14:301–323, 1995.

14. FARLEY, C. T., and C. R. TAYLOR. A mechanical trigger for the trot-gallop transition in horses. Science 253:306–308, 1991.

15. HILDEBRANDT, M. Analysis of tetrapod gaits: general considerations and symmetrical gaits. In: Neural Control of Locomotion, R. Herman, S. Grillner, and P. S. G. Stein (Eds.). New York: Plenum, 1976, pp. 203–236.

16. HRELJAC, A. Preferred and energetically optimal gait transition speeds in human locomotion. Med. Sci. Sports Exerc. 25:1158– 1162, 1993.

17. HRELJAC, A. Determinants of the gait transition speed during human locomotion: kinetic factors. Gait Posture 1:217–223, 1993.

18. HRELJAC, A. Determinants of the gait transition speed during human locomotion: kinematic factors. J. Biomech. 28:669–677, 1995.

19. MANN, R. A. A kinetic analysis of sprinting. Med. Sci. Sports Exerc. 13:325–328, 1981.

20. MANN, R. A., and J. HAGY. Biomechanics of walking, running, and sprinting. Am. J. Sports Med. 8:345–350, 1980.

21. MCMAHON, T. A., and C. G. CHENG. The mechanics of running: how does stiffness couple with speed? J. Biomech. 23:65–78, 1980.

22. MILLER, D. I. Ground reaction forces in distance running. In: Biomechanics of Distance Running, P. R. Cavanagh (Ed.). Champaign, IL: Human Kinetics, 1990, pp. 203–223.

23. NIGG, B. M. Experimental techniques used in running shoe research. In: Biomechanics of Running Shoes, B. M. Nigg (Ed.). Champaign, IL: Human Kinetics, 1986, pp. 27–61.

24. NILSSON, J., and A. THORSTENSSON. Ground reaction forces at different speeds of human walking and running. Acta Physiol. Scand. 136:217–227, 1989.

25. OAKLEY, T., and D. J. PRATT. Skeletal transients during heel and toe strike running and the effectiveness of some materials in their attenuation. Clin. Biomech. 3:159–165, 1988.

26. RODGERS, M. M. Dynamic biomechanics of the normal foot and ankle during walking and running. Phys. Ther. 68:1822–1830, 1988.

27. STACOFF, A., X. KAELIN, and E. STUESSI. Impact in landing after a volleyball block. In: Biomechanics XI-B, G. De Groot, A. Holander, P. Huijing, and G. van Ingen Schenau (Eds.). Amsterdam: Free University Press, 1988, pp. 694–700.

28. STERGIOU, N., B. T., BATES, and S. L. JAMES. Asynchrony between subtalar and knee joint function during running. Med. Sci. Sports Exerc. 31:1645–1655, 1999.

29. VALIANT, G. A., and P. R. CAVANAGH. A study of landing from a jump: implications for the design of a basketball shoe. In: Biomechanics IX-B, D. A. Winter, R. W. Norman, R. P. Wells, and K. C. Hayes (Eds.). Champaign, IL: Human Kinetics, 1985, pp. 117– 122.

30. WILLIAMS, K. R., P. R. CAVANAGH, and J. L. ZIFF. Biomechanical studies of elite female distance runners. Int. J. Sports Med. 8:107– 118, 1987.