Does Running on a Cambered Road Predispose a Runner to Injury?

Kristian M. O' Connor and Joseph Hamill
University of Massachusetts

Roads are generally designed with a camber to facilitate drainage. Running on a cambered road has been suggested as a potential cause of injury. Two possible mechanisms are mediolateral control and impact shock. The purpose of this study was to investigate the effect of a cambered surface on rearfoot motion and impact shock. Twelve runners ran at 3.83 m/s on both a flat and a cambered surface with the left side raised for all of them. Selected rearfoot kinematic and tibial acceleration measures were evaluated using a 2 x 2 repeated-measures ANOVA. The touchdown angle was less supinated on the left (high) side than on the right (low) side on the cambered surface. Maximum pronation was greater on the left (high) high side than on the right (low) side, as was total rearfoot motion. Maximum velocity of pronation was greater under the left (high) limb than under the right (low) limb while running on the cambered road. Time to maximum pronation did not differ, nor were there differences in peak acceleration or time to peak acceleration. The results of this study suggest that running on a cambered road caused changes in rearfoot motion kinematics that may predispose an individual to injury. Also, since the impact shock did not change with changes in rearfoot motion, perhaps the role of pronation on shock attenuation should be reexamined.

Key Words: crowned road, gait, asymmetry, rearfoot motion, shock attenuation

Introduction

Running on a road presents many challenges. Besides the typically hard and unforgiving surface, there is also generally a slight sideways slant to each side of the road. This slant is termed the camber and gives the road a crowned effect. This camber is designed to facilitate drainage. While it may vary from region to region, in Massachusetts the roads are built with a 2% slope. This means that for every 12 ft wide lane, the road drops 3 inches from the center to the edge. Thus, a 2% slope corresponds to a 1.5° angle. This represents a standard value, but the actual camber of roads can be variable.

The authors are with the Biomechanics Laboratory, Dept. of Exercise Science, University of Massachusetts, Amherst, MA 01003.
Running on cambered roads may have deleterious effects on the musculoskeletal system. Bovens, Janssen, Vermeer, et al. (1989) reported significantly more injuries to the left limb in their subject pool, which they attributed to running on crowned roads. Messier and Pittala (1988) found that runners with iliotibial band friction syndrome ran a higher percentage of the time on cambered roads than did a noninjured group. In a follow-up study, Messier, Edwards, Martin, et al. (1995) worked with a larger pool of participants and actually found no differences between injured and noninjured groups, in contrast to their earlier results.

Other epidemiological studies have not been able to discriminate between injured and noninjured runners based on the training surface (Jacobs & Berson, 1986; Marti, Vorder, Minder, & Abelin, 1988). This does not necessarily indicate that running on cambered roads will not cause injury. Since running on roads (most of which are crowned) is so prevalent, these studies may simply be unable to discriminate this as a risk factor.

Some authors suggest that running on one side of a crowned road will lead to increased pronation of the foot landing on the high side (e.g., Brody, 1980). Given the presumed association between excessive pronation and injury (Clement, Taunton, Smart, & McNicoll, 1981), this seems to be a plausible risk factor. Others have argued that running on a cambered surface creates the effect of running with a leg length inequality (du Plessis, 1980; Gudas, 1980). It is believed that this environmental leg length inequality creates consequences similar to those in persons with true inequalities.

This environmental effect likely is small while running on a crowned road, considering that runners tend to place their feet close to the line of travel, resulting in a minimal difference in landing heights. Moreover, the clinical relevance of mild inequalities (< 30 mm) has been debated. Some have argued that small differences are relevant (Blake & Ferguson, 1993; D’Amico, Dinowitz, & Polchaninoff, 1985; Gofton, 1971; Graham, Walker, Redondo, et al., 1997; McCaw, Bates, & Singer, 1989; Schuit, Adrian, & Pidcoke, 1989) while others have argued that they are not (Goel, Loudon, Nazare, Rondinelli, & Hassanein, 1997; Gross, 1984; Kaufman, Miller, & Sutherland, 1996; Song, Halliday, & Little, 1997).

It is possible that running on a cambered road may alter the loading under each limb. Although a differential in landing heights may cause increased loading on the low side (leg length inequality effect), decreased pronation of the foot on the low side may also cause increased shock in that limb. Rearfoot motion has been suggested as a shock absorbing mechanism (Clarke, Frederick, & Hamill, 1984). Pronation is believed to increase the time over which the loading impulse is experienced, leading to a decreased force. This relationship, however, has not been strongly established.

Certainly running injuries are multifactorial in nature, but an activity that has the potential to accentuate motion of the foot and leg and to increase loading may indeed push an individual past his or her injury threshold. The epidemiological studies have not been able to clearly identify this training behavior as a risk, but this may be due to the widespread practice among runners of training on roads. The kinematic and kinetic effects of running on a sloped surface such as a crowned road have not been documented. While not confirming crowned roads as a cause of injury, a study of running on a slanted surface may identify potential mechanisms of injury.
The purpose of this study, therefore, was to investigate the effect of a sloped surface on rearfoot motion and impact shock characteristics. It was hypothesized that the limb on the high side, in this study the left limb, would experience greater pronation and pronation velocity, and that the limb on the low side would experience less pronation and pronation velocity. It was also hypothesized that the change in pronation would lead to greater peak accelerations under the low limb than under the high limb. Further, it was hypothesized that running on a crowned road does not create a relevant leg length inequality.

Methods

Twelve men wearing shoe sizes 9 to 12 were used in this study. They had no history of lower extremity running injuries and were healthy at the time of data collection. Prior to participation, they all signed an informed consent form in accordance with university policy. Mean age, height, and mass were 27.6 ± 5.3 years, 180.8 ± 7.2 cm, and 76.7 ± 6.5 kg, respectively. In order to control for the influence of footwear, all participants wore the same model of running shoes.

Triads of rigidly connected reflective markers were placed on the posterior aspect of the leg and the shoe heel counter of each side of the body (Areblad, Nigg, Ekstrand, Olsson, & Ekstrom, 1990). The shoe triads were aligned with the midline of the shoe in order to use the markers in approximating the shoe midline during filming (Figure 1).

Tibial accelerations were recorded with lightweight (1.7 g) uniaxial accelerometers (model 353B17, PCB Piezoelectronics, Depew, NY) attached to the distal

![Figure 1 — Marker placement and coordinate systems for the right limb. The axes denote the coordinate systems of the room, leg, and foot. Triads of rigidly connected markers were used to track the motion of each leg and foot. The same marker placement and conventions were used for the left limb.](image-url)
anteromedial aspect of each tibia. Each accelerometer was mounted on an aluminum bracket with a mass of 2.1 grams for a total mass of the accelerometer-mount of 3.8 grams. The instruments were secured with elastic straps tightened to the threshold of participant tolerance. This method was similar to that proposed by Valiant, McMahon, and Frederick (1987). It has been found that using a low-mass accelerometer minimizes the effect of soft tissue vibrations (Saha & Lakes, 1977; Ziegert & Lewis, 1979). Foot contact was detected from another lightweight accelerometer mounted on the bed of the treadmill.

Participants ran at 3.8 m/s on a treadmill under a flat and a cambered condition. The cambered condition was implemented by raising the left side of the treadmill to a 3° slope. This slope was utilized to accentuate the effect of running on a cambered road. Although this slope was twice that of the standard in Massachusetts, it represents the net slope of the road. In practice, however, many roads are curved such that the slope is greater toward the edge of the road, where runners normally run. Testing of various roads in the local area with an inclinometer indicated that a 3° slope was common along the edges. It was determined that 3° would maximize the effect while remaining within a reasonable range. If significant effects were documented at a slope of 3°, then further study may be warranted to determine the effect of lesser slopes. If no meaningful effects were found at this slope, however, then any lesser slope would probably also be irrelevant. The order of presentation of the conditions was randomized.

Participants ran for approximately 2 minutes in each condition. Kinematic data were collected using a three-dimensional video system at 200 Hz (Qualisys, Inc., Glastonbury, CT), which simultaneously collected analog data from the three accelerometers at 600 Hz. Three 5-s trials were collected for each condition. The position data were smoothed at 15 Hz with a fourth-order, zero-lag Butterworth filter. This cutoff frequency was considered adequate for rearfoot motion (Hamill, Bates, & Holt, 1992).

Angular kinematic data were calculated using the three-dimensional method described by Areblad et al. (1990). This method defined a separate coordinate system for each foot and leg segment. A right-handed room coordinate system of the right foot was defined with the X-axis pointed laterally, the Y-axis pointed in the direction of travel, and the Z-axis pointed vertically upward (Figure 1). Each segment’s coordinate system with the participant standing facing the direction of travel was defined with the i-axis pointing to the right, the j-axis forward, and the k-axis oriented vertically upward. Prior to the running trials, a standing calibration trial was collected with the participant facing forward and the foot aligned with the direction of travel. This trial was used to determine each segment’s provisional coordinate system relative to the room coordinate system. This relationship was used to calculate transformation matrices that related the provisional coordinate systems to the segment coordinate systems during running.

The major benefit of using a three-dimensional approach as compared to a two-dimensional approach for rearfoot motion is the out-of-plane motion. Areblad et al. (1990) demonstrated that only during midstance does a two-dimensional approach yield accurate joint angles. Eversion/inversion angles were calculated using the convention of Areblad et al. (Equation 1). Pronation velocity was calculated with a first-central difference approximation.

\[ \theta = 90° - \arccos[i_{\text{foot}} \cdot (i_{\text{leg}} \times j_{\text{foot}})] \]  

(1)
Initial rearfoot angle, maximum pronation, time to maximum pronation, total rearfoot motion, and maximum pronation velocity were calculated for each stride. Peak acceleration (reported in g’s) and time to peak acceleration were also determined for each stride. In order to approximate stance width while running, we computed the horizontal position of the shoe midline.

Eleven strides were extracted from the three trials of each condition, which were then averaged to yield representative data for each runner. The data were analyzed using a 2 x 2 (condition x leg) repeated-measures ANOVA ($p < 0.05$). A Tukey’s post hoc pairwise comparison was performed if there were significant effects. Data were analyzed using the SAS statistical software package (v 6.12, Cary, NC).

**Results**

Running on the slanted treadmill surface altered the rearfoot kinematic patterns (Figure 2). There were no significant differences between the angular kinematic data between sides during level running (Figure 3a–3e). In the cambered condition, the touchdown angle was significantly less supinated on the high (left) side than on the low (right) side, although neither value was significantly different from level running (Figure 3a). Similarly, there was greater total rearfoot motion.

![Figure 2](image)

*Figure 2 — Ensemble average rearfoot angle curves for each condition. Thin lines represent the two limbs in the level condition, the thicker lines represent the sloped condition. Solid lines indicate the left side, dashed lines indicate the right side. Vertical bars denote the standard deviations associated with the left foot in the level condition. The other curves demonstrated similar standard deviations. Time is reported in ms with $t = 0$ marking heel contact.*
Figure 3 — Results for rearfoot motion variables:
(a) touchdown angle;
(b) total rearfoot motion;
(c) maximum pronation;
(d) time to maximum pronation;
(e) maximum velocity of pronation.
Black bars indicate the level condition, gray bars indicate the sloped condition.
Vertical lines indicate standard deviations.
Like letters represent values that are not different from each other.
on the high (left) than on the low (right) side, but this was not significantly different from level running (Figure 3b). Maximum pronation was significantly greater on the left (high) side and less on the right (low) side during cambered running than on level running (Figure 3c). There were no differences in the time to maximum pronation (Figure 3d). The maximum velocity of pronation was greater on the high (left) side than for the level condition, and less than the level condition on the low (right) side.

Running on a slanted surface did not alter the impact shock characteristics. The impact accelerations were not different between limbs for either condition (Figure 4a). There was a significantly greater time to peak acceleration on the left side during level running, however, but this difference was not apparent in the cambered condition (Figure 4b).

Running on a slanted surface reduced the stance width, minimizing the disparity between landing heights. During level running, there was a significant difference between the horizontal positions of the left and right legs at foot contact.
(26.3 ± 2.2 cm left vs. 30.6 ± 2.3 cm right). The foot contact positions while running on the slanted treadmill were not different from each other (31.5 ± 2.5 cm left, 31.5 ± 5.3 cm right). These distances are reported relative to the left edge of the treadmill belt.

**Discussion**

The purpose of this study was to investigate the effect of a cambered surface on rearfoot motion and impact shock characteristics. The kinematic data reported for this study reflect values in the literature when running on a flat surface. Areblad et al. (1990) report an initial rearfoot angle of 7°, maximum pronation angle of -10°, and total rearfoot motion of 17°, which correspond well to the values in this study of 6.7°, -8.7°, and 15.4° during level running. The tibial accelerations in this study were on average about 5 g's, which were actually somewhat lower than in other studies. For example, Milani, Schnabel, and Hennig (1995) reported accelerations from 8.2 to 9.4 g's, and Perry and Lafortune (1993) reported values over 10 g's. While the current impact accelerations were less than these previous results, the present study was performed on a treadmill that was more compliant than when running overground.

Regarding the experimental manipulation, participants did demonstrate the predicted kinematic responses with increased pronation on the high side and decreased pronation on the low side. These changes in maximum pronation corresponded to the slope of the treadmill. Interestingly, there were significant changes in the touchdown angle when the treadmill was cambered. The foot on the high side became less supinated at contact than the foot on the low side. This tended to partially offset the differences in maximum pronation. This seems to indicate a kinematic adaptation to minimize the total excursion. Though total rearfoot motion was indeed greater on the high side, the magnitude of the difference was reduced relative to maximum pronation. If there had been no changes in the touchdown angle, the total rearfoot motion would have exactly mirrored the changes in maximum pronation.

The maximum velocity of pronation was greater under the high limb. This result was anticipated given the increased range of motion for the high limb, coupled with the lack of difference in time to maximum pronation. This variable has been linked to various types of injuries. Messier and Pittala (1988) reported greater maximum velocity of pronation for a group of runners with shin splints than for a group of uninjured controls.

The stance width changed between running on a level surface vs. a slanted surface. While running on a level treadmill, the midlines of the shoes landed about 4 cm apart (Figure 4). When running on the cambered treadmill, however, the feet landed along the same line. Considering that the foot generally makes contact with the ground on the lateral edge of the shoe, the points of contact may be as much as 8 cm apart while running on a cambered surface (Figure 5). On a road with a 3° camber, the difference in landing height would be about 4 mm.

Although a 4-mm difference could technically be classified as an environmental leg length inequality, the clinical relevance is questionable. The literature concerning the clinical significance of a leg length inequality on running injury has been mixed. Even quantifying leg length inequality has proven to be difficult (Woerman & Binder-Macleod, 1985). Epidemiological studies have generally found
weak relationships of mild inequalities (< 30 mm) to injuries (Messier & Pittala, 1988; Messier et al., 1995). The literature on leg length inequality has been so varied that some studies have claimed that as little as 6.4 mm can be clinically relevant (Messier & Pittala, 1988), while others have stated that less than a 25-mm difference is not a problem in runners (Gross, 1984). The inequality induced by the slanted surface in this study falls well below these thresholds. Given that the manipulation in this study exceeds many road surfaces, the landing height difference while running may not be a major risk factor for injuries.

Perhaps the most interesting finding was the lack of difference in impact shock between limbs. Several authors (e.g., Clarke et al., 1984) have hypothesized the link between rearfoot motion and shock attenuation. Some studies have performed experimental manipulations in which the midsoles of the shoes were altered to varus and valgus configurations (Milani et al., 1995; Perry & Lafortune, 1993; van Woensel & Cavanagh, 1992). Van Woensel and Cavanagh (1992) showed that wedges of 10° cause significant changes in rearfoot motion but did not create differences in knee range of motion. While their study only reported kinematic variables, the robustness of knee kinematics they reported has implications in later studies in which impact shock was measured.
The knee plays the major role in shock attenuation in the lower extremity (McMahon, Valiant, & Frederick, 1987), and changes in knee kinematics would confound any interpretations of shock attenuation at the ankle. The results of Van Woensel and Cavanagh (1992) would suggest that if this shoe manipulation alters the impact shock characteristics, the shock differences could primarily be attributed to changes in motion of the foot.

Perry and Lafortune (1993) and Milani et al. (1995) both studied the effect of these varus and valgus midsoles on ground reaction forces and tibial accelerations. Interestingly, they reported different results. Perry and Lafortune reported larger impact shock values for the varus wedge (14.3 g’s), which would limit rearfoot motion as compared to the neutral condition (11.5 g’s), but the valgus wedge was not different from neutral (11.7 g’s). They conclude that their results support the hypothesis that rearfoot motion attenuates shock. Milani et al. found that the valgus wedge, which would accentuate pronation, yielded smaller impact shock values (8.2 g’s) than neutral (9.4 g’s). They point to this as potentially supporting the hypothesis, but they also report decreased impact shock with the varus wedge (8.6 g’s) as compared to neutral.

These studies seem to partially support the theory that rearfoot motion is related to shock attenuation, but it is interesting that, even though the experimental manipulations were very similar, the results were not. While one study reported increased shock with the varus configuration as compared to a neutral shoe (Perry & Lafortune, 1993), the other study reported decreased shock (Milani et al., 1995). Perhaps there is a limitation in altering the shoe construction, given its documented effect on impact accelerations (Frederick, Clarke, & Hamill, 1984).

It may also be difficult to compare the results of this study to the shoe manipulation studies since this study used a slope that was much less than those with midsole wedges. Perhaps our study simply did not induce a large enough perturbation to yield changes in impact shock. Although the purpose of this study was to investigate the effect of crowned roads on gait, perhaps further tilting the treadmill could lend insight into the relationship between rearfoot motion and shock attenuation. This type of perturbation would avoid potential limitations in altering shoe geometry (Nigg & Morlock, 1987). In this study, however, a crowned road does not appear to alter impact shock and may not be a factor in inducing impact injuries.

This study utilized a typical camber but it was still comparatively large. The fact that this perturbation did not affect impact shock indicated that the impact shock while running on lesser slopes would also not change. This result would seem to rule out an increased chance of shock related injuries while running on crowned roads. The results of this study suggest that running on a crowned road does create kinematic changes. The increased pronation, coupled with increased pronation velocity experienced on the high side (left limb in this study), has typically been attributed to increased risk for injury. However, we cannot make the claim, based on these results, that running on a cambered road is a risk factor for injury.

Unfortunately, the current state of the literature on running has not identified specific ranges for these parameters that are known to cause injury. Also, the definition of “excessive” as it pertains to pronation and injury may be specific to the
individual in question. Perhaps future epidemiological studies could group their participants according to training history rather than by injury. Comparing a group of runners who rarely run on roads to a group of runners who primarily run on roads may show differences in injury rates. In grouping by injury, the risk from running on cambered roads may be masked by the prevalence of this activity.

References


