What Is the Influence of Cambered Running Surface on Lower Extremity Muscle Activity?

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Running on a road for fitness, sport, or recreation poses unique challenges to the runner, one of which is the camber of the surface. Few studies have examined the effects of camber on running, namely, kinematic studies of the knee and ankle. There is currently no information available regarding muscle response to running on a cambered road surface. The purpose of this study was to investigate the effects of a cambered road on lower extremity muscle activity, as measured by electromyography in recreational runners. In addition, this study examined a true outdoor road surface, as opposed to a treadmill surface. The mean muscle activity of the tibialis anterior, lateral gastrocnemius, vastus medialis oblique, biceps femoris, and gluteus medius were studied. Fifteen runners completed multiple running trials on cambered and level surfaces. During the stance phase, mean activities of tibialis anterior, lateral gastrocnemius, and vastus medialis oblique were greater on the gutter side than the crown side. There were no differences in mean muscle activity during the swing phase. The findings of this study suggest that running on a road camber alters the activity of select lower extremity muscles possibly in response to lower extremity compensations to the cambered condition.

**Keywords:** crowned road, gait, electromyography, injury

Running is a popular fitness pastime as evidenced by the 10–20% of Americans who run regularly. However, approximately 50% of runners experience injury yearly and 25% can be injured at any given time.1 The incidence of running injury reported by the literature varies between 2.5 and 12.1 injuries per 1000 h of running, with most injuries occurring in the lower extremities due to overuse.2

The etiology of running-related injuries is multifactorial in nature and comprises both intrinsic and extrinsic factors. Anthropometric variables linked to a higher predisposition for injury consist of high longitudinal arches, leg length discrepancy, ankle range of motion, and lower extremity alignment abnormalities.3–5 Biomechanical variables associated with higher risk for running-related injuries involve vertical impact force, impact loading rate, pronation velocity, muscle weakness, rearfoot eversion, as well as joint forces and moments.3,5,6 These intrinsic factors may be influenced by the running surface, particularly the camber. Running on a lateral slope such as a road camber has been argued to create an environmental leg length inequality7–11 resulting in long leg (crown side) and short leg (gutter side) conditions. In addition to an environmental leg length inequality, road camber has been suggested to predispose a runner to higher risk for injury by altering motion at the subtalar joint3,12,13 and shifting the point of force application at the knee joint.14

There has been little investigation into how real-world training surfaces can impact a runner’s predisposition to biomechanical variables associated with injury. Prior research has focused on quantifying the biomechanical differences between treadmill and overground running in the level15–17 and inclined conditions18,19 as well as between surfaces of differing firmness20 and varying vertical perturbations.21 The findings of these studies demonstrate that training surfaces affect gait patterns; however, level/inclined treadmill or laboratory surfaces do not accurately represent real-world running conditions such as the cambered road.

**Camber** is the term given to the sideways slant to each side of the road, used to facilitate rainwater drainage, which gives the road a crowned effect. Recreational and competitive runners alike are often forced to run on a cambered surface, whether running with traffic or against traffic. However, minimal research has been done investigating the effects of cambered running with the few studies focusing on kinematics of rearfoot motion12 and the knee joint.14 O’Connor and Hamill12 reported significantly greater total rearfoot motion and decreased supinated touchdown angle on the high side when compared with the low side when running on a laterally sloped treadmill. Maximum pronation and maximum velocity of...
pronation values were significantly greater on the high side and reduced on the low side when compared with level running. The kinematic changes at the subtalar joint suggest adaptations to accommodate for the sloped surface and to possibly decrease total excursion (while in turn increasing maximum pronation velocity). Gehlsen et al\textsuperscript{14} observed kinematic changes at the knee joint during the support phase including a decreased range of flexion-extension on the high side compared with both the low side and level running as well as an increase in knee valgus-varus on the low side compared with the high side. During swing phase, the knee joint on the high side exhibited greater flexion-extension and valgus-varus range of motion compared with the low side. Based on these findings, Gehlsen et al\textsuperscript{14} postulated that when on the high side of a camber runners have shorter step lengths and use more than normal knee flexion to maintain a level trunk. In addition, the knee joint becomes compromised when the subtalar joint can no longer adjust to the degree of camber, which in turn can relate to a change in the point of force application at the knee joint. In these two studies, the motions at the subtalar joint and at the knee joint were observed to be influenced by road camber. However, it is not known if these kinematic changes result in compensatory neuromuscular changes from the lower limb musculature.

During level running, lower extremity kinematic and kinetic data in conjunction with electromyography (EMG) have provided a comprehensive picture as to the contributions of each muscle’s activity throughout the gait cycle.\textsuperscript{22–25} Functional muscle groups in healthy individuals have been examined via EMG to create a normative database of muscle activity profiles during running at different speeds.\textsuperscript{22,24,25} These studies provide insight into the firing patterns and functions of lower extremity muscles but are limited to controlled, level treadmill and laboratory runway surfaces. When comparing treadmill versus overground running, runners have been shown to adopt surface-dependent movement patterns which directly impact the lower extremity EMG amplitudes and activation schemes.\textsuperscript{16,17} Due to differences in neuromuscular control mechanisms seen at the hip, knee, and ankle joints, Baur et al\textsuperscript{15} recommended that overground surfaces be used when examining muscle activity during running. It can be ascertained that cambered running surfaces can also influence muscle activity patterns and that these effects would be best realized on a true cambered surface.

It is unclear how muscle activity is affected by running on a nonlevel, cambered surface, which is typical of road running. Given that two studies have demonstrated that the camber surface alters knee and foot kinematics,\textsuperscript{12,14} and that the camber surface has been postulated to create an artificial leg length discrepancy,\textsuperscript{7–11} it is important to determine if a cambered surface also contributes to muscle function alterations as a possible compensation to these changes. This study attempted to begin the process of analyzing EMG of select lower extremity muscles of runners on an actual cambered road condition. Therefore, the purpose of this study was to investigate the effects of a cambered running surface on lower extremity muscle activity as measured by EMG in recreational runners. It was hypothesized that running on either the crown or gutter side of a cambered road would alter the mean muscle activities of lower extremity muscles during the stance and swing phases of the running gait cycle, in response to the reported kinematic changes observed by prior studies. More specifically, muscle activity on the gutter side during the stance phase was predicted to increase to allow for better shock attenuation and stabilization of the limb, in response to the reported changes at the rear foot and knee. During the swing phase, to facilitate ground clearance, it was anticipated that the tibialis anterior, lateral gastrocnemius, and biceps femoris would increase in the swing limb to assure sufficient ankle dorsiflexion and knee flexion on the crown side.

**Methods**

**Subjects**

Fifteen recreational runners (6 male, 9 female) participated in this study; an a priori power analysis (\(P = .80\), G-Power v3.1.2, Germany) suggested a sample size of 10 subjects, based on an expected moderate effect size, when comparing mean EMG values). A recreational runner was defined as one who jogs a minimum of 10 miles per week or two to three times per week. All subjects had no current (within past 3 months) lower extremity injuries and were healthy at the time of data collection. Before participation, all subjects signed an informed consent form approved by the university human subjects committee and in accordance with university policy. Mean age, height, mass, weekly running mileage, and runs per week were 27.6 ± 6.6 y, 174.1 ± 9.6 cm, 71.2 ± 13.7 kg, 18.0 ± 14.3 miles/wk, and 3.9 ± 0.9 runs/wk, respectively.

**Instrumentation**

An inclinometer (Noraxon, USA, Inc, Scottsdale, Arizona; 25 mV/° sensitivity, ± 2° accuracy) was used to measure, in degrees, the range of camber of the road where testing took place as well as roads in the local area. Following an offset bias reading on the level surface of the curb, the investigator measured the incline of the road next to the curb, moving away toward the crown at 2 cm increments. The range of road camber on the test road was recorded as 5–7°. This degree of camber was consistent with measures taken from the surrounding roads as well as with the degree of camber used in previous treadmill simulated studies (5° and 10° tested by Gehlsen et al;\textsuperscript{14} 3° tested by O’Connor and Hamill\textsuperscript{13}).

The EMG data were collected from five lower extremity muscles of the right leg: tibialis anterior (TA), lateral gastrocnemius (LG), vastus medialis oblique (VMO), biceps femoris (BF), and gluteus medius (GM). The right leg of all subjects was measured for consistency. A certified athletic trainer (ATC) experienced with EMG prepared the skin and placed the surface electrodes...
lengthwise according to the surface electromyography for the non-invasive assessment of muscles (SENIAM) recommendations. A common ground electrode was placed over the lateral femoral epicondyle. The skin was shaved and then cleaned with isopropyl wipes before 3.8 cm diameter (1 cm diameter conductive area) self-adhesive Ag/AgCl surface electrodes (Noraxon USA, Inc) were placed over the muscles with an interelectrode distance of 10 mm. Foot switch sensors were placed on the base of the heel and first metatarsal of the right foot to detect ground contact and toe-off. The Noraxon Telemyo System comprising of the Telemyo 2400T and 2400R (Noraxon USA, Inc) was used to process the EMG and footswitch signals.

The electrodes and foot switches were connected to a battery-operated, 8 channel FM wireless transmitter (8th order Butterworth/Bessel low-pass antialias filters with 500 Hz cutoff frequency; CMRR > 100 dB; input impedance > 100 MΩ; base gain 500) via preamplified active leads (1st order high-pass filter with 10 Hz cutoff frequency). The signals were converted from analog to digital within the Telemyo 2400R receiver, which was connected via USB to a laptop computer (Vostro 3700; Dell Inc, Round Rock, Texas), and sampled at a frequency of 1500 Hz before being processed with MyoResearch software (Noraxon USA, Inc).

**Experimental Procedure**

Subjects reported to the University Biomechanics Laboratory. The University Institutional Review Board approved all study procedures. Each subject signed the informed consent form and answered questions regarding lower extremity injury history, weekly running mileage, and runs per week to ensure that they met the inclusion criteria at the time of the study.

The ATC applied the surface electrodes to the right leg. To decrease movement artifact, the sensors and leads were secured to the subject with prewrap and athletic tape. The transmitter was secured to the dorsal aspect of the subject’s torso with a belt and Ace wrap. Each subject was led outdoors to the traffic-free road where the EMG receiver and laptop were setup. The ATC instructed the subject through manual muscle tests for each of the five muscles to verify correct electrode placement. To ensure that the equipment was secure and did not inhibit the subject’s gait, the subject was asked to jog at a comfortable pace, and, if necessary, adjustments were made to lead placements or lengths.

Using standard manual muscle test procedures, the maximal voluntary contraction (MVC) for each muscle was recorded. Subjects were allowed a 1 min warm-up jog to familiarize themselves with the road conditions. Data were collected for three surface conditions (level, gutter side, crown side). For the level condition, the subjects were instructed to run on the double yellow lines located on the crown of the road. For the crown and gutter side conditions, the subjects were instructed to run on the side of the road nearest the curb, eastward or westward respectively. The order of conditions was randomized to protect against order effects.

The investigator instructed subjects to begin at the “start” marker on the road and jog through the “finish” marker (a distance of 50 m) while maintaining a self-selected, comfortable pace. EMG and running speed were recorded 10 m into the 50 m distance to allow for subjects to attain a self-selected pace. Subjects were instructed to maintain a consistent pace for each trial. A trial was discarded if subjects were not within ±5% of their self-selected pace.13,19

Between each condition, subjects were allowed a 1 min active recovery of walking. Two to five trials per condition (minimum of five to seven successful gait cycles) were recorded for each subject. The investigator and ATC determined that a trial was successful if the raw EMG and foot switch signals were clear and the self-selected pace was maintained.

**Data Processing**

The raw EMG signals were full-wave rectified and filtered (FIR, 40–450 Hz bandpass). The amplitude of muscle activity for each subject was normalized to the muscle’s peak amplitude obtained from the MVC trial. Amplitude normalization allowed the EMG data to be expressed as a percentage of peak MVC and was calculated using the MyoResearch software.

Five complete gait cycles per surface condition were analyzed for each subject. The gait cycles were divided into swing and stance phases based on the foot switch signal. The mean EMG values were extracted for the stance and swing phases separately. The reliability of the mean measures of the gait cycles selected was ensured by computing the Intraclass Correlation Coefficient (ICC) for each muscle in each road condition. ICC values greater than 0.90 were considered high (97% of means), and ICC values greater than 0.80 were considered acceptable (3% of means).26 The five gait cycles for each subject were ensemble averaged and added to a normative database (for each road surface condition) of 101 points (0–100% of the gait cycle) in the MyoResearch software.

**Statistical Analysis**

For each muscle, a one-way repeated-measures analysis of variance (RM ANOVA) with post hoc paired t tests (P < .10) was used to examine the effects of level, gutter side, and crown side running surface conditions on mean muscle activity (SPSS, Inc., Chicago, IL). Assumptions of sphericity were examined using Mauchly’s test and violations prompted the use of Greenhouse-Geisser or Huynh-Feldt estimates of degrees of freedom. One subject’s GM data were revealed to be an outlier (z score > ±2) and was removed from the statistical analysis of this muscle. An alpha level of .10 was selected a priori because this is an exploratory study intended to obtain additional information about the neuromuscular demands associated with running on a cambered surface, and the added risk of a Type I error would not be detrimental.27
Results

During the stance phase of the running gait cycle, the TA, LG, and VMO all demonstrated significant differences in mean EMG activity across the three road conditions (TA \([P < .10, \eta^2 = .250]\), LG \([P < .10, \eta^2 = .343]\), and VMO \([P < .10, \eta^2 = .269]\)) (Table 1). No significant road condition effects were observed for the BF \((P > .10)\) or the GM \((P > .10)\) during the stance phase. The results of the paired t tests revealed that the mean TA EMG activity on the gutter side was significantly greater \((P < .10, \eta^2 = .450)\) than on the crown side. The mean LG EMG activity on the gutter and level side was significantly greater than on the crown side \((P < .10, \eta^2 = .333\) and \(P < .10, \eta^2 = .733\) respectively). Finally, the mean VMO activity was significantly greater \((P < .10, \eta^2 = .309)\) on the gutter side compared with the crown side. During the swing phase of the running gait cycle, no significant road condition effects were observed for any of the five muscles’ mean EMG activity \((P > .10)\) (Table 1).

Discussion

The aim of this study was to evaluate lower extremity muscle activity during cambered running in an outdoor real-world setting. The EMG data collected for the level running conditions are consistent with findings reported in the literature.\(^1\) The hypotheses of increased muscle activity running on a road camber, when compared with a level surface, during the stance phase were generally supported. Changes were observed during the stance phase of running on the cambered surface, while no differences were observed during the swing phase of running on a cambered surface.

As expected, running on the gutter side of a road camber caused an increase, relative to the crown side, in mean TA activity during stance (Table 1). Functioning as an ankle dorsiflexor as well as an inverter at the subtalar joint, which can serve to lengthen the limb in the short leg (gutter side) condition, this increase in TA activity supports the findings of reduced pronation evidenced in the gutter side foot.\(^1\) Looking at Figure 1, during the late portion of stance, it appears that the activity of the TA on the crown side is greater than that of the gutter or level side. This time point was not tested statistically; however, it might be inferred that this rise in TA activity on the crown side is in anticipation of greater ankle dorsiflexion necessary for ground clearance during swing.\(^1\) Without both time-matched kinematic data and extrapolation of this specific time point, this is only speculation.

In addition to the TA, the LG functions to assist resisting pronation in early to midstance and to also resist the motion of ankle dorsiflexion in the early stance portion of running. The increase in mean EMG of the level and gutter side LG during stance when compared with that of the crown side condition (Figure 1) supports the kinematic rearfoot motion findings reported by O’Connor and Hamill.\(^1\) The increase in mean LG activity on the gutter side during stance may serve to minimize ankle dorsiflexion which helps maintain knee extension and control supination. It can be ascertained that these functions assist ground clearance of the contralateral limb by “lengthening” the gutter side leg and contributing to its lower limb stability. Decreased mean LG activity during stance of the crown side condition supports Gehlsen et al.’s\(^1\) findings of greater flexion-extension ROM at the knee joint. The crown side limb contacts the ground

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level Condition</th>
<th>GS (Short Leg) Condition</th>
<th>CS (Long Leg) Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stance Phase</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tibialis Anterior</td>
<td>30.92 ± 13.87</td>
<td>32.90 ± 14.23(^a)</td>
<td>27.81 ± 10.17(^a)</td>
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<tr>
<td>Lateral Gastrocnemius</td>
<td>111.99 ± 44.89(b)</td>
<td>111.92 ± 30.79(a)</td>
<td>89.39 ± 32.38(b)</td>
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<tr>
<td>Vastus Medialis</td>
<td>107.74 ± 69.39(b)</td>
<td>106.75 ± 66.02(a,b)</td>
<td>88.06 ± 45.09(a)</td>
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<tr>
<td>Biceps Femoris</td>
<td>57.61 ± 50.97</td>
<td>56.48 ± 45.16</td>
<td>52.28 ± 45.69</td>
</tr>
<tr>
<td>Gluteus Medius</td>
<td>61.45 ± 77.56</td>
<td>66.85 ± 70.92</td>
<td>54.94 ± 43.86</td>
</tr>
<tr>
<td>Swing Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibialis Anterior</td>
<td>47.44 ± 24.62</td>
<td>48.19 ± 22.82</td>
<td>45.80 ± 21.61</td>
</tr>
<tr>
<td>Lateral Gastrocnemius</td>
<td>35.27 ± 22.60</td>
<td>33.60 ± 21.68</td>
<td>36.60 ± 19.14</td>
</tr>
<tr>
<td>Vastus Medialis</td>
<td>43.36 ± 30.10</td>
<td>41.92 ± 29.11</td>
<td>41.58 ± 21.48</td>
</tr>
<tr>
<td>Biceps Femoris</td>
<td>56.53 ± 39.10</td>
<td>53.81 ± 43.61</td>
<td>51.41 ± 36.18</td>
</tr>
<tr>
<td>Gluteus Medius</td>
<td>60.96 ± 94.57</td>
<td>69.23 ± 107.42</td>
<td>58.11 ± 65.57</td>
</tr>
</tbody>
</table>

Note. Mean (± standard deviation) EMG, expressed as percentage MVC, for TA, LG, VMO, BF, and GM during each surface condition tested (level, gutter side [GS], crown side [CS]) during stance (top table) and swing (bottom table) phases of the running gait cycle.

\(^a\) \(P < .10\), significant difference between gutter and crown sides.

\(^b\) \(P < .10\), significant difference between level and crown sides.
with increased knee flexion and pushes off with less than normal knee extension to maintain a level upright trunk position.

The increased mean VMO activity observed in the gutter side condition during stance when compared with the crown side leg (Figure 1) suggests greater control of knee flexion during loading response on the gutter side to absorb the impact of the body at foot contact. Activity of the gutter side’s VMO is also believed to aid in maintaining the gutter side limb in knee extension, to assist with ground clearance of the contralateral limb.

Two muscles (GM and BF) did not demonstrate any significant changes during stance or swing (Figure 2). This was particularly surprising for the GM. Based on the theory that running on a road camber creates an environmental leg length inequality\(^7\) the GM was expected to be affected by the gutter side of the road camber during stance. A trend was observed in the data relative to the GM; however, there was insufficient power to support this trend. The trend of greater mean EMG on the gutter side limb (ie, the short limb) could be in response to an increased demand to elevate the pelvis on the side of the contralateral swing limb, to assist with ground clearance of the crown side limb during swing. Due to the high standard deviations in the gutter and crown side GM data, and the absence of concurrent kinematic data, this finding should be interpreted with caution.

It was also expected that the BF would increase activity, particularly during swing, in response to the reported increase in knee flexion on the crown side.\(^14\) However, this was not observed, and it is assumed that the kinematic changes at the knee are accomplished through some other mechanism. Perhaps the gastrocnemius, which showed a tendency for greater activity during swing on the crown side (Figure 1), is responsible for the increased knee flexion reported during swing.

The findings of this exploratory study indicate that road camber alters the mean muscle activity of the lower extremities and show potential trends in hip joint muscles during the stance phase of the gait cycle. The EMG data

**Figure 1** — Normative mean EMG activity, expressed as % MVC, of the TA (top), LG (middle), and VMO (bottom) during the level (solid line), gutter side (GS; dotted line), and crown side (CS; dashed line) conditions plotted from 0% to 100% of the gait cycle. Solid vertical line indicates toe-off.

**Figure 2** — Normative mean EMG activity, expressed as % MVC, of the BF (top) and GM (bottom) during the level (solid line), gutter side (GS; dotted line), and crown side (CS; dashed line) conditions plotted from 0% to 100% of the gait cycle. Solid vertical line indicates toe-off.
support previous kinematic findings of altered motion at the knee and ankle joints as a result of running on a camber. However, it must be noted that prior studies involved the use of treadmills and laboratory runways whereas this study used a cambered road. Although this study cannot conclude that road camber is the cause of lower extremity injury, the differences in muscle activity across cambered conditions, coupled with the kinematic and kinetic differences identified in the literature (ie, knee and rearfoot motion changes) suggest that the increased muscle activity may play a role in injury risk for road runners. However, without concurrent kinematic and kinetic data, these EMG data simply provide additional insight of the neuromuscular demands incurred on a cambered running surface. It should be noted that the sample size of this study was small and included only healthy, uninjured runners. Further, the EMG instruments available were not ideal for outdoor testing and the use of surface electromyography, versus fine wire electrodes, introduced the possibility of cross-talk in the recorded muscle activity.

This study has contributed to an understanding of the neuromuscular adaptations required of select lower extremity muscles during the stance and swing phases of gait when running on a cambered road surface. The increased mean muscle activity of the TA, LG, and VMO in the gutter side limb compared with the crown side limb supports previously reported findings of kinematic adaptations at the knee and ankle joints during stance.

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