THE EFFECT OF POSTURE ON RUNNING ECONOMY, KINEMATICS, AND MUSCLE ACTIVATION

By

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ABSTRACT

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Running is a common form of exercise with a high incidence of injury. However, there is little evidence for how changes to running posture may influence running economy (energy consumed), kinematics (joint motion), and muscle activation. This study sought to investigate the effect of postural alterations (magnitude of forward lean and strategy) on running economy, kinematics, and muscle activity. Methods: 16 healthy young adult runners (23±4.89 years, 8M/8F) who participated in running for fitness or competition, with a 5k time ≤22 minutes, ran on a motorized treadmill at 8.0 mph (3.576 m/s) in five different running posture conditions. Metabolic energy consumption (metabolic power), kinematics, and muscle activation data were recorded for all trials. Results: Running with a large lean resulted in a decrease in running economy (p=0.001) and increased hip flexion (p=0.002) such that the body increases its reliance on the less efficient proximal hip muscles. Specifically, leaning forward increased gluteus maximus (p=0.017) and biceps femoris (p=0.033) activation during stance phase. In addition, gluteus maximus activation increased by 45% when accepting body weight in landing (p=0.005). Conclusion: These findings suggest that running with an upright posture or more moderate forward lean may be more energetically optimal.
ACKNOWLEDGEMENTS

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INTRODUCTION

The interest in running as a form of exercise and for competition has grown significantly over the last quarter century (31). Despite increases in popularity, researchers have yet to determine if there is an optimal running posture for maximizing efficiency, decreasing injury and promoting longevity. Of the many factors investigated, running economy (metabolic cost) is often utilized to predict performance. Some of the key influences in running economy include contact time duration, stride frequency, and hip flexion. These kinematic variables provide insight into the energy conservation of running.

When evaluating running economy, many look at joint motion (kinematics) as indicators of change in metabolic cost. From evaluations on joint kinematics, researchers have determined that contact time duration influences the elastic properties of the lower extremities (7). Furthermore, shorter ground contact time duration contributes to higher running economy and that this decreased cost is primarily due to the attenuation of braking in the first half of stance when accepting body weight (11, 12, 14, 19, 25, 26, 33). Contact time duration also influences stride frequency and the highest running economy occurs at an intermediate stride frequency, slightly above preferred (4, 24, 28). Variations in preferred stride frequency have shown that increasing stride frequency by 10% contributes to decreased loading at the hip and knee joints during running, meaning that less force is traveling through the joints that may contribute to injury (16, 18, 21, 22, 27). Stride frequency also influences neuromuscular input to the lower extremities.
Increasing stride frequency from preferred corresponds to increased gluteus maximus activation (3). This increase in neuromuscular activity may help to reduce anterior knee pain in runners (3). These changes have implications for runners training for fitness or competition. To demonstrate the importance, runners have been shown to decrease stride frequency from preferred during prolonged high intensity running (18, 27). If runners are taught to maintain stride frequency with prolonged high intensity training or racing, they may experience decreased likelihood of injury.

Due to the influence of kinematics on running economy, some coaches prescribe postural changes for runners looking to improve performance, decrease injury, or when recovering from injury. Some coaches that changing posture with a forward lean improves running mechanics and improves running economy (29). The forward lean is taught in a popular technique, Chi running, that claims to mitigate injury occurrences and require less energy (8). There is little evidence for how Chi running technique influence muscle activation as well as how different degrees of lean and strategy differ. Researchers have found that running with a forward lean from the trunk results in decreased patellofemoral joint stress compared to upright running posture (2, 15, 29, 30, 33). These studies on running economy and trunk flexion displayed the highest running economy in runners with a mean trunk flexion angle of 5.9 degrees (33). Unfortunately, these studies did not also evaluate running with a posture similar to Chi running style, where runners lean forward in a column from the ankle to the ear (8).

In addition to evaluating running with kinematics, energetic data is often
evaluated to determine efficiency as metabolic power (8). Lower metabolic power (higher running economy) has been correlated with higher energy generation at the knees in stance phase running mechanics (17). Furthermore, running economy is also influenced by the reliance upon the hip for energy dissipation in stance. When there is lower reliance upon the hip musculature for power generation, the running economy increases (17, 20, 23).

Although researchers have looked at running with a forward lean from the trunk, there is limited research on how these alterations in addition to Chi running posture will influence running performance, injury prevention, and longevity in the sport (7, 16, 29, 32). Current research does not describe how altering posture via Chi running influences metabolic energy requirements (29). The claims made by running coaches and Chi running advocates that running with an increased postural lean can prevent injury have yet to be evaluated by observations of muscle activation patterns, metabolic cost, and kinematic data. Therefore, the purpose of this study was to investigate the effect of postural alterations (degree of forward lean and strategy) on running economy, kinematics, and muscle activation. This study sought to evaluate the null hypothesis, that there would be no effect of posture on running economy, kinematics, or muscle activation.
METHODS

Participants included 16 healthy young adult runners (23±4.89 years, 8M/8F) who participate in running for fitness or competition, with a 5k time ≤ 22 minutes. Adequate sample size was determined from a priori power analysis with the program G*Power from studies on kinematics and metabolics (α=0.05, β=0.80) (13). All participants met inclusion criteria and were given informed consent. Prior to data collection all participants were given a five-minute familiarization trial. A counter balance design was used for all experimental trials to reduce the influence of an order effect. Real time video feedback was used while subjects ran at three lean angles ran on a motorized treadmill at 8.0 mph (3.576 m/s). These angles included upright (0°), maximal forward lean (8.34°±1.35), and moderate forward lean (4.18°±0.68). For both the maximal forward lean and the moderate forward lean subjects were instructed to “lean from their ankle.” Additionally, subjects repeated the maximal forward lean and moderate forward lean while being instructed to “lean from the torso.” During all trials participants were given a target degree of lean through the real time video feedback of their sagittal plane. Participants were provided a minimum of five minutes rest between each condition.

For each of the five trials, running economy was quantified as metabolic power (W kg⁻¹) using indirect calorimetry. Average metabolic rate per kilogram body mass (W kg⁻¹) was calculated using the average VO₂ (ml O₂ min⁻¹) and VCO₂ (ml CO₂ min⁻¹) for a two minute time period between minutes 3 and 5 when the real-time plot of VO₂ indicates
that metabolic steady-state had been achieved (1). The standing metabolic rate was subtracted from running metabolic rate to calculate net metabolic power (J kg$^{-1}$ s$^{-1}$) for each running trial. A two way repeated measures ANOVA was used to determine the effect of postural lean and postural strategy (ankle vs. torso) on running economy.

Kinematic data were collected for 15 seconds in the last two minutes of each trial (sampling rate = 200 Hz, Vicon Nexus, Centenial, CO). Kinematic data were processed using Visual 3D (C-Motion, Rockville, MD). A low pass butterworth filter (6Hz) was used for marker data. Ten consecutive strides were used to calculate averages for peak hip flexion during stance, peak knee flexion during stance, peak dorsiflexion during stance, average stride length relative height, and average time of foot-ground contact for each participant. A repeated measures MANOVA with simple first pairwise comparisons strategy was used to determine the effect of lean magnitude and lean strategy (ankle vs. torso) on running economy. A discriminant function analysis was done to determine the influence of each dependent variable.

Muscle activity (EMG) data were collected for the gluteus maximus (GM), biceps femoris (BF), rectus femoris (RF), vastus medialis (VM), tibialis anterior (TA), medial gastrocnemius (MG), and soleus (SOL) (sampling rate = 2000 Hz). Using a custom Visual 3D analysis program, the normalized root mean square (40 ms window) EMG amplitude ($\text{EMG}^{\text{RMS}}$) was calculated. $\text{EMG}^{\text{RMS}}$ amplitude of each muscle was normalized relative to its peak $\text{EMG}^{\text{RMS}}$ amplitude during the participant’s natural running posture. A Teager-Kaiser Energy Operator method was used for temporal muscle activity analysis. Average muscle activation magnitude was calculated across the entire gait
cycle. A repeated measures MANOVA was used to determine the effect of lean magnitude and lean strategy (ankle vs. torso) on muscle activity to determine the interaction of lean magnitude and lean strategy on average muscle activation throughout the gait cycle. Post hoc tests were done on stance and swing phase for each muscle; these tests helped to determine if condition influenced muscle activation during the loading response and propulsion phase of stance in addition to pre-activation in terminal swing.
RESULTS

Running Economy

In contrast to our hypothesis, postural lean significantly influences running economy (p=0.001). Specifically, results showed that running economy was reduced by 4-6% when running with maximal forward lean as compared to running upright (p=0.005). However, running economy did not change when running with a moderate forward lean, as compared to running upright (Figure 1, p=0.148). Postural strategy (leaning from ankle vs. torso) had no effect on the metabolic cost of running across the range of postural lean conditions (p=0.993). Although differences in lean strategy were not significant, metabolic cost for the large lean conditions were greater than either the upright or moderate lean conditions. Within the ankle conditions, there was more than a 5% increase in net metabolic power when changing from moderate ankle to large ankle. Furthermore, from upright to large ankle there was approximately a 6% increase in net metabolic power. Within the trunk conditions, net metabolic power increased by about 3% from moderate trunk to large trunk strategy, and about 5% from upright to large trunk strategy. There were minimal differences between the upright condition and either moderate ankle or moderate trunk strategies (Table 1).

Kinematics
In addition to running economy changes, postural lean influenced stride kinematics (p=0.002). Peak hip flexion during the stance phase was an average 28% greater for the large lean condition than for the upright condition (p<0.001). However, there was no other effect of lean magnitude on knee flexion, dorsiflexion, stride length relative height, or time of foot-ground contact (p>0.05, Table 2). Moreover, there was no main effect of lean strategy (ankle vs. torso) or interaction effect of lean magnitude and lean strategy on running kinematics (p=0.894 and p=0.914, respectively). A discriminate function analysis explained that 99% of the difference in running kinematics between lean conditions were due to changes in hip flexion. Furthermore, no difference was found in stride length and stride width variability related to lean magnitude or lean strategy (p=0.653).

Muscle Activity

Throughout trials, select muscle activation patterns were influenced by running posture. With regards to lean magnitude, total muscle activation resulted in lower activation for the large lean in the RF, SOL, MG, AT, BF, and VM (Table 3). In the upper leg muscles, muscle activation decreased by 4% for the RF, 5% for the BF, and 14% for the VM from the upright to large lean condition. To contrast, the large lean conditions resulted in higher GM activation; GM activation increased by 10% from the upright to large lean condition (Figure 4). However, due to the large variability within the muscle activation data these trends were not significant and there was no main effect of either lean magnitude or lean strategy on muscle activation across the entire gait cycle.
(p>0.05). Furthermore, there was no interaction between lean magnitude and strategy for the upper leg (GM, VM, BF, RF) or lower leg (TA, SOL, MG) average muscle activation across the gait cycle (p>0.05).

Interestingly, when broken down into specific phases of the gait cycle, GM activation increased by ~35% from the upright to large lean condition during the stance phase (p= 0.017). Specifically within the first 10% of the gait cycle (loading response), GM activation increased by 45% from the upright to large lean conditions (p=0.005). As lean increased for both strategies (ankle and torso), GM activation increased in the loading portion of the stance phase. Additionally, the large lean condition displayed a delay in activation during 55-65% of the gait cycle (Figure 6).

Lean magnitude influenced BF activation in the stance phase (p=0.033). Most notably, during the first 10% of the gait cycle (loading response) BF activation was 30-50% higher for the moderate and large lean strategies as compared to the upright lean condition (p=0.012). Furthermore, lean magnitude resulted in changes to BF activation in the second half of swing, from 75-95% of the gait cycle (p=0.031). This difference was particularly noted from 75-85% of the gait cycle where BF activation increased by 40-51% from the large lean to the upright and moderate lean conditions (p=0.014), (Figure 6).

During the stance phase, an increase in ankle lean resulted in a decrease in RF activity, particularly during the loading response. However, during the swing phase, increasing lean appeared to have little to no effect on RF activation. Although the change in RF activity was not significant, RF activation decreased an average of 50% during the
late loading response of running from the upright to the large lean condition (p=0.636). Moreover, as participants leaned farther forward, there was a corresponding decrease in RF activation during mid-stance (15-25% of the gait cycle) and late stance (25-35% of the gait cycle); (Figure 6). Furthermore, at 55% of the gait cycle, RF activation increased by 18% from upright to the large lean condition and 10% from upright to the moderate lean condition (Figure 6).

Finally, there was no change in VM, TA, SOL, or MG activation due to lean magnitude and lean strategy across the gait cycle (p>0.05, Figure 6, Figure 7). Additional tests were conducted to determine if there was a covariate effect of mass on our finding for running economy, kinematic and muscle activation. Results showed no influence of body mass on running economy, kinematic or muscle activation (p>0.05).
DISCUSSION

The purpose of this study was to evaluate the effect of posture on running economy, kinematics, and muscle activation. This study rejected the null hypothesis and found posture to influence running economy. Secondary, kinematic changes associated with a forward lean were found to support our purpose in furthering knowledge on running posture. Although no differences were found in muscle activity across the entire gait cycle for the upper and lower leg, changes did occur to gluteus maximus and biceps femoris activation with regard to lean magnitude (Figure 6). These findings provide insight for the running community and researchers on the interaction of kinematics and muscle activation with running economy.

The results of this study suggest an interaction between metabolic cost, GM activation, and hip kinematics. There was an effect of posture on hip flexion during stance and the increased hip flexion during the large forward lean conditions was associated with decreased running economy (Table 1, Table 2). The corresponding decrease in running economy with increased activation of the GM in stance is supported by previous studies that have shown that proximal hip musculature tend to be less efficient at generating force in running (3, 9, 12, 17, 20), (Figure 6). Our results show that when hip flexion increased during stance, GM activation increased, and resulted in a decrease in running economy. These findings suggest that increased hip flexion may not be an effective postural strategy for long distance running when the goal is maximal efficiency over a given distance.
The postural changes observed in stance may influence how the body responds to loading and conservation of energy as represented by the spring mass model (11). According to the spring mass model of running and cost of generating force hypothesis, running economy is related to stride length and time of ground contact. However, in the present study we found that while running economy decreased with greater lean, stride length and ground contact duration did not change (Table 2). These result suggest that the energy conservation of the spring mass system associated with the cost of generating force was not altered by lean magnitude or strategy. In addition, these kinematic findings do not support the claims of many Chi running advocates that running with a forward lean decreases stride length (8). Thus, the lack of change in contact time duration, stride length, knee flexion, and dorsiflexion do not support in the claims that spring mass energy conservation of the legs improve with forward lean (11).

Despite the lack of an effect of improved running economy via spring mass energy conservation, the increase in BF activation during late swing and pre-activation suggests that participants may have adjusted leg stiffness in response to lean magnitude; this increase in muscle activity may have influenced the attenuation of braking in the loading response phase (3); (Figure 6). However, no change in contact time duration suggested that braking during the first half of stance and propulsive impulses during the second half of stance remained constant across conditions. These findings suggest that participants did not alter leg stiffness in response to lean magnitude or strategy, or that changes were too minimal to detect. The primary determinant for the increased activation of BF and GM may have resulted from a change in torque applied at the hip.
With increased lean, the torque across the hip increased, resulting in an increased need for activation of the BF and GM.

Although no changes to stride frequency occurred, the change in GM activation during stance may correspond with a reduction in ground reaction forces transferred to the hip and knee (3). Despite the decrease in running economy, if a forward lean corresponds to a decrease in joint stress, coaches may choose to prescribe this technique. These findings are further supported by studies on upright posture in running and increased patellofemoral joint stress (29, 30, 33). Further studies should investigate the kinetics associated with different postural strategies for running to fully understand the interaction of patellofemoral joint stress and running posture.

In addition to major running economy and kinematic findings, the data from this study support the use of concurrent feedback as an effective tool for gait retraining during running (5). Participants were able to effectively use the concurrent feedback to adjust magnitude of lean in the sagittal plane. These findings support the use of sagittal plane posture feedback in conjunction with verbal cues for gait retraining for runners recovering from injury or undergoing training to alter posture while running (10, 21, 34).

A limitation of our study may be the specificity of participants tested. Due to the demographics of runners tested based upon fitness requirements, some participants may have already developed a stride frequency close to optimal for the speed tested (3.58 m/s); (16, 22). As a result, experienced runners may be less prone to kinematic variability when compared to novice runners (6). As a consequence, these findings may
not prove generalizable to a population of novice runners. Furthermore, the lack of significant findings in muscle activation across the entire gait cycle may be attributed to the large variability within the inter-subject muscle activation data.
CONCLUSIONS

Despite claims that running with a large forward lean will improve running economy, results from this study suggest that running with an upright posture or more moderate forward lean, either from the ankles or torso, may be more energetically optimal. The results of our study showed that running with a large lean changes hip kinematics such that the body increases its reliance on the less efficient gluteus maximus muscle (3). Based on the results of this research, our understanding of running may benefit from future studies examining the effect of lean on the kinematics, muscle activation, and metabolic cost of running across a range of incline slopes and speeds. Additional kinetic data may also provide insight into the loading of joints across different postural alterations that occur in conjunction with muscle activation changes.
REFERENCES


Figure 1: Net metabolic power (Watts/kg) for upright (■), moderate lean (■■), and large lean (■■■) conditions averaged from the final two minutes of each trial ± standard error of the mean. Asterisk indicates significant differences (p=0.005), (N=16).
Figure 2: Model representing measurements for joint angles (degrees) in stance for hip flexion (180-α), knee flexion (0-β) and dorsiflexion (θ).

Figure 3: Peak hip flexion at stance (degrees) for upright (■), moderate lean ( ), and large lean ( ) conditions ± standard error (N=16). Asterisk indicates significant differences (p<0.001).
Figure 4: Normalized EMG<sub>RMS</sub> activation of the upper leg muscles for upright (black), moderate lean (light grey), and large lean (dark grey) conditions ± SEM (N=14).

Figure 5: Normalized EMG<sub>RMS</sub> activation of the lower leg muscles for the no lean (black), moderate lean (light grey), and large lean (dark grey) conditions ± SEM (N=14).
Figure 6: Normalized EMG$_{RMS}$ of the gluteus maximus, rectus femoris, biceps femoris, and vastus medialis for the upright (▼), moderate ankle lean (O), and large ankle lean (●) conditions (N=14). Asterisk indicates significant differences in degree of activation (p<0.05).
Figure 7: Normalized EMG\textsubscript{RMS} of the tibialis anterior, soleus, and medial gastrocnemius for the upright (▼), moderate ankle lean (O), and large ankle lean (●) conditions (N=14).
TABLES

Table 1: Net metabolic power (Watts/kg) for conditions averaged from the final two minutes of each trial ± standard error of the mean (N=16). Asterisk indicates significant difference from upright (p<0.05).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic Power (Watts/kg)</td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>11.60 ± .26</td>
</tr>
<tr>
<td>Moderate ankle</td>
<td>11.69 ± .28</td>
</tr>
<tr>
<td>Moderate torso</td>
<td>11.80 ± .24</td>
</tr>
<tr>
<td>Average moderate lean</td>
<td>11.74 ± .26</td>
</tr>
<tr>
<td>Large ankle</td>
<td>12.31 ± .35</td>
</tr>
<tr>
<td>Large torso</td>
<td>12.20 ± .40</td>
</tr>
<tr>
<td>Average large lean*</td>
<td>12.25 ± .36</td>
</tr>
</tbody>
</table>
Table 2: Mean values for kinematic variables ± standard error of the mean (N=16).

Asterisk indicates significant difference for magnitude of lean (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>Magnitude of lean</th>
<th>Mean±SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact time (sec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>0.25 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>0.25 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>0.26 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Stride length (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>1.42 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>1.41 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>1.43 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>Hip flexion (deg)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>28.56 ± 1.20</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>32.34 ± 1.20</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>36.53 ± 1.20</td>
<td></td>
</tr>
<tr>
<td>Knee flexion (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>-40.61 ± 1.03</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>-41.25 ± 1.03</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>-41.56 ± 1.03</td>
<td></td>
</tr>
<tr>
<td>Dorsiflexion (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>24.95 ± 0.73</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>24.85 ± 0.73</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>25.14 ± 0.73</td>
<td></td>
</tr>
</tbody>
</table>
Table 3: Mean values for muscle activation across the gait cycle ± standard error of the mean (N=14).

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Magnitude of lean</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus Maximus (GM)</td>
<td>Upright</td>
<td>0.24±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.26±0.02</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.27±0.02</td>
</tr>
<tr>
<td>Biceps Femoris (BF)</td>
<td>Upright</td>
<td>0.31±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.33±0.03</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.30±0.02</td>
</tr>
<tr>
<td>Vastus Medialis (VM)</td>
<td>Upright</td>
<td>0.25±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.25±0.02</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.22±0.02</td>
</tr>
<tr>
<td>Rectus Femoris (RF)</td>
<td>Upright</td>
<td>0.32±0.03</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.31±0.03</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.31±0.03</td>
</tr>
<tr>
<td>Tibialis Anterior (TA)</td>
<td>Upright</td>
<td>0.31±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.34±0.02</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>Soleus (SOL)</td>
<td>Upright</td>
<td>0.26±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.22±0.02</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.22±0.02</td>
</tr>
<tr>
<td>Medial Gastroc. (MG)</td>
<td>Upright</td>
<td>0.23±0.02</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>0.23±0.02</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>0.22±0.02</td>
</tr>
</tbody>
</table>