INTRODUCTION

Backward running elicits a 30% higher metabolic cost than forward running [4]. Prior research suggests that the greater metabolic cost of backward running results from generating muscle force at a faster rate due to using a faster stride frequency [7]. However, backward running may be energetically more costly as a result of using a more flexed limb posture and thus, a reduction in leg extensor muscle mechanical advantage during the stance phase [3].

In healthy adults, the metabolic cost of running increases with stride frequency [6]. Backward running is associated with a faster stride frequency than forward running [7] and thus, may cause a greater metabolic cost of leg swing. However, the higher metabolic cost of backward running may also be related to an increase in the metabolic cost of supporting body weight as a result of running with a more flexed limb posture that reduces the mechanical advantage of the leg extensor muscles [1]. This study tests the hypothesis that backward running increases metabolic energy consumption due to a greater cost of generating force resulting from a decreased time of ground contact and increased flexion of the legs during the stance phase of running and not due to an increase in stride frequency.

METHODS

Twelve adults (31.4± 11.4 years; six females and six males) ran forward and backward on a treadmill at a speed of 2.24 m/s (5 mph). We examined the effect of stride frequency on metabolic cost and kinematics as subjects performed three seven minute running trials: one forward at preferred stride frequency, one backward at preferred stride frequency and one forward at a prescribed stride frequency matched to the backward stride frequency (Matched SF). Metabolic cost was determined using indirect calorimetry during the last two minutes of each treadmill trial [2]. We calculated the net metabolic cost (W/kg) by subtracting standing metabolic power from gross metabolic power and dividing by body mass. We measured the kinematics of the lower limbs for 10 strides during the last two minutes of each treadmill trial using a 3-D motion capture system (Vicon, Centennial, CO). We calculated maximum joint flexion angle and average joint flexion angle during the stance phase of each step for the hip, knee and ankle joints. We measured the time of foot-ground contact ($T_C$) and then calculated the cost coefficient ($c$) as the ratio of the net metabolic rate ($\dot{E}_{net}$) to $1/T_C$, normalized to body weight ($W_b$). We calculated preferred stride frequency for forward and backward running from the number of steps taken in a 1-minute period.

RESULTS AND DISCUSSION

At preferred stride frequency, backward running elicits a 38% increase in metabolic cost, compared to forward running ($P<0.0001$). Moreover, when using the same stride frequency, backward running elicited a 33% greater metabolic cost than forward running ($P<0.0001$) (Figure 1; Table 1).

Figure 1: Net metabolic power for forward running (preferred stride frequency), backward running (preferred stride frequency), and forward running at a stride frequency matched to backward running.
The cost coefficients of backward and forward running were both 0.26 ($P=0.424$). In backward running, subjects spent approximately 31% less time in contact with the ground ($P<0.0001$) than in forward running ($P<0.0001$). At the same stride frequency, subjects spent an average 26% less time in contact with the ground during backward running ($P<0.0001$). Interestingly, when subjects ran backwards the average knee joint angle during the stance phase was 18% more flexed when compared to forward running ($P=0.009$) (Figure 2; Table 1).

**Figure 2:** Average knee flexion angle as a function of gait cycle for three running conditions: Backward (preferred stride frequency), Forward (preferred stride frequency), and Forward (matched stride frequency).

Whether using preferred or matched stride frequencies, backward running elicits a greater metabolic cost compared to forward running. Thus, in support of our hypothesis, these results suggest the greater metabolic cost of backward running is not the result of using a faster stride frequency. Instead, we found that human runners consume substantially more metabolic energy when running backward primarily due to an increase in the cost of generating force as a result of spending less time in contact with the ground and using greater knee flexion during the stance phase. Using a shorter time of ground contact increases the rate of muscle force generation [5]. Moreover, using greater stance knee flexion decreases the mechanical advantage of the stance limb extensor muscles and thus requires more force to support body weight [1]. Together these factors increase the metabolic cost of generating force in backward running. Further validation of our findings is present in the cost coefficient data of forward and backward running which suggests the difference in metabolic cost between forward and backward running is directly proportional to the rate of ground force application.

**CONCLUSIONS**

In conclusion, the results of our study strongly support the hypothesis that the cost of generating force is a primary determinant of metabolic energy consumption for backward running due to the decreased mechanical advantage of the knee extensor muscles and the increased rate of force generation.

**REFERENCES**


**Table 1:** Metabolic and kinematic data for forward, backward, and forward (matched stride frequency) running

<table>
<thead>
<tr>
<th></th>
<th>Net Cost (Watt/kg)</th>
<th>$T_C$ (seconds)</th>
<th>Cost Coefficient (J/N)</th>
<th>Ave Knee Flexion (deg)</th>
<th>Stride Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>8.23 ± 0.73</td>
<td>0.32 ± 0.04</td>
<td>0.27 ± 0.04</td>
<td>26.2 ± 3.4</td>
<td>1.37 ± 0.08</td>
</tr>
<tr>
<td>Backward</td>
<td>11.40 ± 0.98</td>
<td>0.22 ± 0.04</td>
<td>0.26 ± 0.05</td>
<td>31.0 ± 5.7</td>
<td>1.55 ± 0.14</td>
</tr>
<tr>
<td>Matched SF</td>
<td>8.54 ± 0.65</td>
<td>0.31 ± 0.04</td>
<td>0.26 ± 0.03</td>
<td>26.0 ± 2.6</td>
<td>1.54 ± 0.14</td>
</tr>
</tbody>
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