Effect of Step Platform Height on Stepping Efficiency in Children

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This study was conducted to determine if VO$_2$ of stepping in children is affected by altering the step platform height based on leg length. The effect of leg length on VO$_2$ and heart rate (HR) during stepping was examined in 19 children, ages 8–17, who stepped onto 5 different bench heights that corresponded to hip angles of 65°, 73°, 82°, 90°, or 98°. VO$_2$ and HR response to a work load of 8 m · min$^{-1}$ assumed a U-shaped curve with 82° assuming the lowest point of the curve. Efficiency of stepping was significantly higher at 82° when compared to the other hip angles. It was concluded that VO$_2$ and HR in children is influenced by leg length during stepping, and there is an optimum step height for stepping that can be determined from the ratio of leg length to stature.

The development of valid and reliable tests of cardiorespiratory fitness for children is an area of importance for physical fitness and exercise specialists. Over the past decade, much emphasis has been devoted to the study, measurement, and development of cardiorespiratory fitness (aerobic power) in adults (16, 17). Recently the need for valid field tests of aerobic power, specifically in children, has been identified in order to accurately assess cardiorespiratory fitness levels in this population (1, 9).

One traditional test that has commanded favorable acceptance has been the step ergometer. Because of the economy, mechanical simplicity, and administrative ease of this device, it has been extensively employed in both submaximal and maximal tests of cardiorespiratory fitness in adults (13, 17, 18). However, one issue that is commonly raised in connection with the use of traditional fixed height step tests is that taller subjects are favored and that the test results of stepping might be influenced by limb length (4, 10, 14, 15, 31, 34). Elbel et al. (14, 15) and Cooke (10) determined that leg length significantly influences the cardiorespiratory fitness index scores of the Harvard Step Test. Similarly, Ariel (4) reported that the angle of the knee joint created while stepping on the bench of the Harvard Step Test had a significant effect on the fitness index score.

Shahnawaz (31) was the first to conclude that mean VO$_2$ was significantly related to limb length in a height-adjusted stepping exercise in adults. Likewise,
Stanforth et al. (34), in a study of the aerobic requirement of bench stepping, found that leg length significantly affected oxygen uptake. More recently, Francis et al. (20) reported that a more accurate prediction of VO\textsubscript{max} in adults is achieved in stepping when a fixed ratio of step height to leg length is used.

Whereas the effect of leg length has been shown to significantly affect VO\textsubscript{2} of stepping in adults, the influence of leg length on stepping performance could be potentially greater in children in whom anthropometric characteristics can vary greatly even among children of the same chronological age (26, 27). The adjustment of the step height using leg length measurements has the potential for normalizing the prescribed work and the more precise estimation of VO\textsubscript{2}max from submaximal stepping.

In addition, the adjustment of the step height to leg length might be beneficial to youth activities that utilize the bench for performing aerobic exercise. For example, many step aerobics classes that use heart rate to monitor intensity of stepping assume that the same VO\textsubscript{2}-HR relationship holds true regardless of stature (34). The normalization of work of stepping will better facilitate the use of HR as an accurate predictor of exercise intensity. Therefore, the following study was conducted in order to determine if VO\textsubscript{2} of stepping in children is affected by altering the step platform height based on leg length, and if so, the optimum step height for stepping.

**Methods**

**Subjects**

Nineteen healthy, nonsmoking, non-obese children, ranging in age from 8 to 17 years, were utilized in this study. A broad age range of subjects of varying stature was utilized to increase the external validity of the study. Subjects were recruited from the adolescent clinic at the University of Alabama at Birmingham, area YMCAs, Jewish Community Centers, church youth groups, and colleagues. Healthy, as defined in this study, was any subject who was free from any physical or physiological contraindication to exercise. Each participant completed a medical history form prior to any testing to determine if he or she had any contraindications to exercise. A signed informed consent was also obtained from all participants and-or their guardians prior to any testing. The study received approval from the Institutional Review Board for the use of pediatric human subjects.

**Test Procedures**

The platform height used for testing each subject was based on the height of the foot when the hip was flexed at a given angle (11). This was determined from the geometric relationship of an individual’s stature and femur length as shown in Figure 1. Using the following equation, the platform height was calculated:

\[ H_f = (h)(1 - \cos \theta) \]  

where \( H_f \) = foot height (cm); \( h \) = length of femur (cm); and \( \theta \) = hip angle.

In order to calculate the height of the foot when the hip is flexed (\( H_f \)) the length of the femur (\( h \)) and the hip angle \( \theta \) must be determined. The length of the
Figure 1 — The height that the foot will rise ($H_f$) when the hip is flexed at angle $\Theta$ can be determined using the relationship: $H_f = (h)(1 - \cos \Theta)$, where $h$ is the length of the femur.

femur is a function of the stature, and the numerical relationship is best determined using orthoroentgenograms. Anderson and Green (2, 3), through careful measurements of orthoroentgenograms, reported standards for length of the femur and tibia and their relationship to stature throughout the growth period of children and youth. Using these established relationships, the length of the femur ($h$) for each age was determined to be $L_f$ times the stature ($lh$). The corresponding value of each $L_f$ categorized by age and sex is shown in Table 1. Therefore, where $lh$ was the stature in cm, the platform height (cm) was determined to be:

$$H_f = (L_f \times lh)(1 - \cos \theta)$$

(2)

It should be noted that even though subjects were selected by chronological age (ages 8–17) with broad range in stature, the stability of the ratio of the femur length to stature (less than 2% variability over the entire age range) allowed for the precise establishment of the bench height without concern for maturational differences (2, 3).

To determine the resultant step height for stepping, the platform heights were calculated using Equation 2 at hip angles of 65°, 73°, 82°, 90°, and 98°. These five hip angles (separated by approximately equal increments of 8°) were chosen because previous step test designs resulted in minimal and maximal platform heights that produced hip angles ranging from 65° to 98° (11, 16, 31). In order to insure the correct angle for stepping, the subject’s hip angle was measured using a goniometer with his or her back flat against the wall with the right hip flexed and right foot placed onto the platform with the heel of the foot even with the edge of the step. In order to standardize knee extension when placing the foot onto the platform, the platform was placed such that the distance from the wall to the step was equal to the length of two of the subject’s feet placed heel to toe. The subject placed the right heel in front of the left foot, and the step was placed in front of the subject’s right toes. The average hip angle of three readings at each height was used as the angle measurement. The step platform could be raised or lowered to within ±0.5 cm of the desired bench height.

To minimize the number of visits, two sessions were used to collect the data set. Each session was separated by 24–48 hours. Three randomly assigned step
Table 1  Ratio of Femur Length to Stature in Children and Adolescents, Ages 8 to 17 Years

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Gender</th>
<th>$L_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>M</td>
<td>0.257</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.258</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>0.259</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.262</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>0.263</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.264</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>0.266</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.267</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>0.269</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.268</td>
</tr>
<tr>
<td>13</td>
<td>M</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.267</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.268</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.266</td>
</tr>
<tr>
<td>16</td>
<td>M</td>
<td>0.269</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.265</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>0.268</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.264</td>
</tr>
</tbody>
</table>

tests were administered during Session 1, and two randomly assigned tests were administered during the second session. Sufficient time was allowed between tests to allow the subject’s heart rates to return to pre-exercise levels.

A pilot study using four subjects was conducted prior to implementing the actual study to determine if a stepping workload of $10 \text{ m} \cdot \text{min}^{-1}$ could be utilized in this study. This workload was initially selected as the workload of choice because Shahnawaz (31) had utilized this workload in demonstrating VO$_2$ of stepping was influenced by leg length. Workloads of $6 \text{ m} \cdot \text{min}^{-1}$ had previously been shown not to distinguish differences in VO$_2$ of stepping with different leg lengths (9). However, the pilot study revealed that a workload of $10 \text{ m} \cdot \text{min}^{-1}$ produced VO$_2$ and heart rate values close to maximal levels and that a $10 \text{ m} \cdot \text{min}^{-1}$ workload combined with a small hip angle of $65^\circ$ was such that the step cadence could not be maintained accurately, especially with shorter stature subjects. Therefore, the mean difference between the two workloads of $8 \text{ m} \cdot \text{min}^{-1}$ was used for each of the five tests.

Power was held constant across all five work conditions. Frequency of stepping (cycles $\cdot \text{min}^{-1}$) was determined by dividing the $8 \text{ m} \cdot \text{min}^{-1}$ work load by bench height. The cadence was assisted by adherence to a mechanical metronome. Each subject was allowed to stretch to warm-up before commencement of testing and was instructed on the stepping technique. A stepping demonstration was also performed by the test administrator. Subjects performed all trials in shorts and running shoes.
Subjects stepped for a 5-min period. The stepping cycle consisted of stepping up to full extension of both legs (lifting the center of mass up onto the bench step) and stepping down with both legs to a count of four (up, up, down, down) set by a metronome. Subjects were allowed to alternate their lead stepping leg to avoid fatigue.

**Instrumentation**

During the step test, oxygen consumption ($\text{VO}_2$) and heart rate (HR) were measured continuously. An EKG (Physiocontrol Lifepak Cardiac Monitor) was used to record HR. $\text{VO}_2$ was measured using open circuit spirometry. Each subject breathed through a Hans Rudolph two-way breathing mask. The expired air passed into a mixing chamber before passing through a volume-meter. Samples of expired air were extracted from the chamber to be analyzed by a PK Morgan oxygen and carbon dioxide analyzer. The analyzers were calibrated using standard gases. $\text{VO}_2$ was recorded every 15 s. Percent body fat was determined from skinfold measurements taken at the triceps and subscapular using the equation of Boileau (7).

**Determination of Efficiency**

For the purposes of this study, the relationship between work output and energy consumption is called efficiency. $\text{VO}_2$ data used for the energy expenditure calculations were obtained during the last 2 min of stepping at which time all subject’s metabolic rates had settled to a steady state ($\text{VO}_2$ values $\pm$ 0.05 liters $\cdot$ min$^{-1}$ for four readings). Net efficiency of stepping was calculated using the steady state $\text{VO}_2$ and the procedure described by Oksa et al. (28) and Seidl et al. (30). External work was first expressed as force acting through a distance (Equation 3) and then converted to kcal $\cdot$ min$^{-1}$ (Equation 4).

\[
\text{External work output (kg} \cdot \text{m} \cdot \text{min}^{-1}) = \text{mass (kg)} \times \text{step height (m)} \times \text{frequency (step cycles} \cdot \text{min}^{-1})
\]  

(3)

\[
\text{Energy output (kcal} \cdot \text{min}^{-1}) = \frac{\text{External work output (kg} \cdot \text{m} \cdot \text{min}^{-1})}{427 (\text{kg} \cdot \text{m} \cdot \text{min}^{-1})}
\]  

(4)

Net energy expenditure was determined as the gross energy expenditure adjusted for basal energy expenditure (Equation 5).

\[
\text{Net energy expenditure (kcal} \cdot \text{min}^{-1}) = \left[\frac{\text{Gross } \text{VO}_2 (L} \cdot \text{min}^{-1})}{[\text{Resting } \text{VO}_2 (L} \cdot \text{min}^{-1)]) \times \text{calorie equivalent (kcal} \cdot \text{L}^{-1})}\right]
\]  

(5)

Net efficiency (Equation 6) is given by the ratio of external work output (Equation 4) to the gross energy expenditure adjusted for basal energy expenditure (Equation 5).

\[
\text{Net efficiency (\%) = } \frac{\text{Energy output}}{\text{Net energy expenditure}}
\]  

(6)

Calorie equivalent of oxygen for non-protein RQ was derived from Shephard (33).
Test-Retest Reliability

A test-retest reliability was determined with five of the subjects chosen at random. These subjects repeated a test using a randomly chosen hip angle. VO₂ was compared with data collected from the two tests.

Statistical Analysis

Data were entered into a microcomputer SPSS for Windows Release 6.1.2 Standard Version statistical program. A repeated measures analysis of variance (ANOVA) was performed on VO₂, HR, and efficiency versus the hip angle of stepping to examine the effects of stature height relative to stepping height. The significance level was set at \( p < .01 \), and a Newman-Keuls test was used to probe significant differences. An intraclass correlation coefficient was used to test the statistical relationship between the tests and retests (12).

Results

The mean (SD) of the physical and physiological characteristics of the 19 children (12 males, 7 females) used in this study were: age (years) 13.9 ± 2.8, stature (cm) 163.5 ± 16.2, body weight (N) 5.65 ± 1.72, and body fat (%) 17.6 ± 4.9.

The mean VO₂ uptake at each of the respective hip angles of stepping are shown in Figure 2. At a hip angle of 82°, the mean VO₂ uptake was 30.46 ± 2.56 ml \( \cdot \) kg\(^{-1} \) \cdot \) min\(^{-1} \) which was lower than values recorded at the other hip angles. VO₂ uptake data assumed a U-shaped curve with 82° resulting in a VO₂ at the lowest point of the curve and 65° and 98° representing the highest VO₂ values.

![Figure 2 — Relationship between VO₂, ml \( \cdot \) kg\(^{-1} \) \cdot \) min\(^{-1} \) (± SD) and heart rate, beats \( \cdot \) min\(^{-1} \) (± SD) at the five different hip angles of testing. Means with different superscripts are significantly different at \( p < .01 \) level.](image-url)
The mean HR responses at each hip angle of stepping are also shown in Figure 2. At a hip angle of 82°, the mean HR response was 152.0 ± 15.9 beats · min⁻¹ which was lower than values recorded at the other hip angles. HR response data assumed a U-shaped curve similar to that of VO₂ uptake with 82° resulting in an HR at the lowest point of the curve and 65° and 98° resulting in HRs at the highest values.

The mean stepping efficiencies at each hip angle of stepping are shown in Figure 3. The efficiency rating demonstrates an inverted U-shaped curve that mirrors the VO₂ utilization curve. At a hip angle of 82°, the mean stepping efficiency was 12.4 ± 0.9% which was higher than at the hip angles of 65° and 98°. An intraclass correlation coefficient (Kappa = 0.95, \( p < .01 \)) was determined for the five subjects' test-retest measurements of VO₂ and HR (12).

**Discussion**

The rationale for adjusting the step height to leg length is supported by a number of studies on adults (4, 11, 13, 14, 18, 31). For example, in the study by Shahnawaz (31), a constant workload of 10 m · min⁻¹ was maintained while the bench height was adjusted to accommodate the limb length of the test subject. He found that the calculated hip angle of 86° resulted in the lowest mean VO₂ (i.e., greatest efficiency). Similarly, Folsom and Minard (20) found that the highest efficiency and lowest VO₂ in adults were recorded at a hip angle of 82° while working at workload of 10 m · min⁻¹. These studies and the results shown in Figure 1 and 2 suggest that leg length does influence efficiency of stepping.

![Graph](image-url)  
**Figure 3** — Relationship between stepping efficiency (±SD) at the five different hip angles of testing. Means with different superscripts are significantly different at \( p < .01 \) level.
These results are in conflict with the results reported by Cicutti et al. (9). Cicutti et al. (9) found that in young boys 10 years of age, there was no significant difference between VO$_2$ and HR when stepping at calculated hip angles of 68°, 80°, and 92°. The difference between the results found in this study and those reported by Cicutti et al. (9) may be related to the limited age and leg length of subjects used by Cicutti et al. Whereas Cicutti et al. (9) did not report the range of subjects’ age or leg length used in his study, the mean age was 10.1 ± 1.2 and mean leg length was 72 ± 4.7. The age of subjects used in the present study ranged from 8 to 17 with corresponding leg lengths that ranged from 59 to 87 cm ($M = 76.8 ± 7.4$). The differences between the results of Cicutti and those found in the present study were probably not related to maturational differences due to the narrow age range used by Cicutti because the ratio of femur length to stature used to determine step height varies less than 2% over the ages 8–17 (2, 3). Therefore the more heterogeneous group of subjects used in the present study apparently allowed for distinguishing changes in VO$_2$ that were not detectable with the more homogeneous group of 10-year-olds with a similar stature used by Cicutti (9).

The U-shaped energy curve of Figure 1 showing a minimal metabolic cost of stepping when a fixed ratio of step height to leg length is similar to energy curves reported by others for walking. For example, Zarrugh et al. (39), Zarrugh and Radcliffe (38), and Holt et al. (23, 24) have shown a U-shaped energy curve with a minimum energy expenditure occurring at the preferred period-stride length combination for a particular speed. Holt et al. (24) showed that the preferred period-stride length frequency of walking can be modeled as the resonant period of a force-driven harmonic oscillator when speed is held constant. Holt et al. (23) concluded while factors such as strength and the resistance of connective tissue might provide a marginal improvement in the predictive value of the model, the most powerful single determinant of minimal metabolic cost appears to be resonance. The optimal stride frequency of walking produces an optimal metabolic cost as an a posteriori fact of the leg oscillating at resonance (23, 24). The similarities of the U-shaped energy curves for preferred stride length as shown by Holt et al. (23) and the U-shaped curve for stepping shown in Figure 1 supports the claim that preferred behaviors are lawfully generated by the relationship between body-scaled (in this case leg length) and environmental (gravity) parameters (8,37).

On the basis of this investigation, it can be concluded that VO$_2$ and HR in children is influenced by leg length when working at a work load of 8 m · min$^{-1}$ and that, of the five hip angles tested in this study, stepping efficiency is maximal at a hip angle of 82°. The practical implication of these findings suggest that the validity of any form of a step test should be enhanced if bench height is related to a child’s stature rather than using a fixed bench height. The determination of the optimal hip angle of 82° provides for the initial development of an algorithm for a height-adjustable step test that can be used to assess cardiorespiratory fitness in normal healthy children.

References


