Mechanical efficiencies of lower-limb amputees rehabilitated with crutches and prostheses*

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Abstract—An investigation of the mechanical efficiencies of stair climbing by a group of below-knee amputees fitted with p.t.b. prostheses and another group of lower-limb amputees using crutches was made, and the values were compared with the mechanical efficiency of a group of normal individuals performing the same exercise. The mechanical efficiencies of the first and second group of rehabilitees were, respectively, 20.5% and 48.5% lower than those of normal persons. An attempted comparison of mechanical efficiencies between the p.t.b.-fitted below-knee amputees and normal persons in the performance of a step test failed to reveal any significant differences. The measurement of mechanical efficiency requires a careful choice of the test activity, but shows promise of providing an objective basis for assessments of functional rehabilitation of amputees fitted with different types of prostheses.

Keywords—Mechanical efficiency of lower-limb amputees

Introduction

The ability to convert chemical or heat energy into mechanical work makes an analogy between a machine and the living body a practical one. This comparison has culminated in measurements of ‘mechanical efficiency’ in man—a method that has been, for long, exclusively used by physical scientists, engineers and technologists—as an index of performance of useful work by him in the physical sense of the word. However, instances of extending this approach to assessing the degree of normality restored in the rehabilitated physically handicapped are perhaps rare.

This paper describes a study in which ‘mechanical efficiency’ has been used as a tool to derive the standards of performance of two kinds of handicapped-appliance systems, namely the below-knee amputee–p.t.b. (patellar tendon-bearing) prosthesis and the leg amputee–crutches combinations.

Materials and methods

Subjects: The test group comprised ten below-knee amputees fitted with p.t.b. (patellar tendon-bearing) prostheses and ten other leg amputees using crutches. The control group included 16 normal healthy adult males of sedentary habits. The personal data of all the subjects are presented in Table 1.

Environment: The environmental conditions which prevailed during the experiment are also presented in Table 1.

Tests: During this study, the tests selected according to their suitability of application in the subjects tested were:

(a) Ascending stairs: HILL (1965) pointed out that the gross efficiency has little significance unless the metabolic work load is substantially greater than the resting value. From this point of view, ascending stairs, being the most strenuous of the common activities of daily living and working (ASMUSSen and POUlSEN, 1963), is ideally appropriate for the measurement of mechanical efficiency of human subjects.

The present test involved climbing 127 steps, each 142 mm high, the total vertical height ascended being 18 m. The rate of vertical ascent was 7.48, 7.37 and 5.68 m/min for the control-group subjects, the below-knee rehabilitees and the crutch-using amputees, respectively.

(b) Step test: It involved stepping up and down a 200 mm-high stool at the rate of 15 steps/min for a period of 10 min. Although this test does not represent any common activity for daily living and working, it was chosen because it is also substantially strenuous and moreover is a standard test for the measurement of exercise tolerance, where the performance can be controlled so as to make valid comparisons between different groups possible. Besides, it also allows the quantum of positive work to be directly computed. This test was administered to the control-group subjects and the below-knee rehabilitees only, as the crutch users were not in a position to perform it.

For each test, data were collected on the energy cost of performing it, and the corresponding cardio-pulmonary responses of the subjects were also measured. Energy expenditure was determined by collecting expired air in a Douglas bag, followed by its analysis in a Haldane gas-analysis apparatus, according to standard procedures (CONSOLAZIO et al., 1963). Peak heart rates were counted by noting the time for 30 heat beats during the last minute of the tests.

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Table 1. Personal data of subjects and environmental conditions

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Personal data</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Age</td>
<td>Height</td>
<td>Body weight</td>
<td>B.S.A.</td>
</tr>
<tr>
<td></td>
<td>yrs</td>
<td>m</td>
<td>kg</td>
<td>m²</td>
</tr>
<tr>
<td>Controls</td>
<td>28.40 ± 7.05</td>
<td>1.6430</td>
<td>51.00 ± 6.56</td>
<td>1.54 ± 0.10</td>
</tr>
<tr>
<td>Below-knee amputees using p.t.b. prostheses</td>
<td>29.90 ± 11.00</td>
<td>1.6310</td>
<td>46.10 ± 9.29</td>
<td>1.47 ± 0.16</td>
</tr>
<tr>
<td>Crutch-using leg amputees</td>
<td>27.30 ± 7.10</td>
<td>1.5930</td>
<td>47.23 ± 9.23</td>
<td>1.45 ± 0.17</td>
</tr>
</tbody>
</table>

Environmental conditions

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature, deg C</td>
<td>27.9</td>
<td>21.0 – 32.0</td>
</tr>
<tr>
<td>Relative humidity, %</td>
<td>62.3</td>
<td>31.0 – 87.0</td>
</tr>
<tr>
<td>Effective temperature, deg F</td>
<td>77.2</td>
<td>66.0 – 84.0</td>
</tr>
</tbody>
</table>

*Body weight without the prosthesis
†Body weight without the crutches

The gross mechanical efficiencies of the subjects, for the above two exercises, were computed as follows:

For step test, gross mechanical efficiency (\%) is

\[
\text{Efficiency} = \frac{100 \times n \times h \times w \times 0.002342}{\text{Energy expenditure, k cal/min } \times \text{total period of exercise, min}}
\]

where \( n \) = number of ascents in time \( t \)
\( h \) = height of the stool, m
\( w \) = body weight, kg, the work output having been calculated according to the standard method given by Lange Andersen et al. (1971). The values of \( n \) and \( h \), in this case, were 150 (15 ascents per minute for 10 mins) and 0.2 m, respectively.

For stair climbing, gross mechanical efficiency (\%) is

\[
\text{Efficiency} = \frac{100 \times \text{external work performed, k cal}}{\text{Gross energy expenditure during exercise, k cal}}
\]

\[
= \frac{100 \times \text{body weight, kg } \times \text{vertical height of ascent, m } \times 0.002342}{\text{Energy expenditure, k cal/min } \times \text{time of ascent, min}}
\]

\[
= \frac{100 \times \text{body weight, kg } \times 18 \text{ m } \times 0.002342}{\text{Energy expenditure, k cal/min } \times \text{time of ascent, min}}
\]

Before administering the tests, the testing procedure and the purpose of the study were carefully explained to the subjects. They reported to the laboratory at 10 a.m. in a post-absorptive state, and all the tests were conducted between 10 a.m. and 12 noon.

Results and discussion

The values obtained for energy expenditure (cal/min) and peak heart rate (beats/min) are presented in Fig. 1. The values of gross mechanical efficiencies computed by the formulas already discussed are presented in Table 2 and have also been included in this Figure.

t tests were employed for all the parameters recorded to identify the differences, if any, between those for the different groups of subjects, and the results are presented in Table 3.

Physically, following common practice, mechanical efficiency is expressed here as a percentage ratio of