Summarizing muscle energetics: activities lasting 30 seconds or more require oxygen consumption. There is enough energy stored in the muscle to last for about 2 minutes.

Hydrolysis of ATP results in muscular work. All other energy sources must be converted to ATP before muscular work can begin. Each mole of ATP in the muscle represents 46,024 N·m of energy, but there is not enough ATP stored in the muscle to supply more than 0.5 seconds of energy use.

More cellular energy is stored in the form of creatine phosphate than as ATP. Phosphorylation of ADP from creatine phosphate provides additional ATP as needed (Equation 1.3.2). There is enough creatine phosphate, and the action of creatine kinase (the enzyme that mediates the reaction in equation 1.3.2) is so rapid that it is difficult to determine an overall decrease in ATP (Brooks et al., 1996).

The third immediate energy source in muscle is the formation of ATP from ADP (equation 1.3.5) involving the enzyme adenylate kinase, and the fourth nonoxidative muscular energy source is the anaerobic oxidation of glucose (glycolysis) to form ATP plus lactate (equation 1.3.3). Because the free glucose concentration in the muscles is low, most nonoxidative energy using this source uses glycogen in the process called glycogenesis.

A 70 kg man has about 30 kg of muscle tissue. In this 30 kg of muscle, stored ATP represents about 230 N·m of energy, creatine phosphate represents 1170 N·m of energy, and stored glycogen (and glucose) represents about 62,800 N·m of energy (Brooks et al., 1996). All this energy is available for anaerobic work should it be necessary to use it. If this energy is considered to be used uniformly over the 2 minute anaerobic time interval, then the rate of energy used would be 535 N·m/sec. If the muscles were 20% efficient in converting energy into mechanical work, then 107 N·m/sec of power ought to be produced. Many individuals can sustain 400-500 N·m/sec mechanical work for 2 minutes. Thus, there must be additional oxidative energy sources to power muscles during this time.

Oxidation represents the means to generate large amounts of energy. Oxidative catabolism (equation 1.3.4) generates 18 times as much ATP per mole of glucose as does nonoxidative glycolysis. Oxidation of palmitate, a commonly occurring fatty acid, generates 64.5 as much ATP as nonoxidative glycolysis (Brooks et al., 1996). Body total oxidative energy stores are:

- glycogen in muscle: \(2.01 \times 10^6\) N·m
- glycogen in liver: \(1.17 \times 10^6\) N·m
fat (triglycerides in adipose tissue) \( 590 \times 10^6 \text{ N} \cdot \text{m} \)

body proteins \( 100 \times 10^6 \text{ N} \cdot \text{m} \)

Reference:


Biomechanics and Exercise Physiology

Section 1.3.4, p. 15 (supplement)

From the appearances of Figures 1.3.5 and 1.3.6, one might conclude that oxygen uptake is linearly related to work rate, and that once a particular level of power has been reached, oxygen uptake remains constant. Researchers have found neither of these to be strictly true. Oxygen uptake associated with work appears to have a fast and a slow component. The fast component yields the linear work rate-oxygen consumption relationship and constant oxygen uptake at any given rate of work. The slow component is different: there is a somewhat greater than linear increase in oxygen consumption with work rate increase above the anaerobic threshold (see Section 1.3.5), and if work is sustained at any given level (as long as the work rate is sufficient to produce significant lactate), oxygen consumption continues rising over time.

The cause of the slow component has been the subject of much study, and possible causative agents have been catecholamines, lactate, hydrogen ions (acidification), potassium ions, and temperature. It appears that, as a muscle becomes more acidic throughout sustained fatiguing work, force production declines and more muscle fibers must be recruited to continue work at the same level. The greater muscle mass working then requires extra oxygen consumption and is a major cause of the slow component. Muscle temperature is likely to be another major cause.

The ratio of oxygen consumption to muscular power development is directly related to the mix of fast and slow twitch muscle fibers (see Section 1.3.1). Slow twitch fibers are more efficient for sustained exercise and exhibit less slow component of oxygen consumption. The relative proportions of fast and slow twitch fibers can be changed during exercise training, and that means the slow component can be influenced by training as well.

Note: Units on axes of graphs in this text have been easily misunderstood. Units are given in parentheses, and multipliers are outside the parentheses. Thus, it is intended that the numbers on the horizontal axis of Figure 1.3.4 represent seconds multiplied by 0.01 rather than representing the number of hundredths of a second. The scale range is thus 0 to 3600 seconds and not 0 to 0.36 seconds.
Section 1.3.4, p. 15 (Supplement 2)

The Kamon formula, equation 1.3.6, can be used to calculate expected endurance times for exercising individuals. If used with measured oxygen consumptions for a particular task, the formula works well. If the beginning information is the type of task, as, for example, entries in Table 5.2.22, then measured oxygen consumption values from the table can be used with maximum oxygen uptake values in Table 1.3.2 to form the ratio \( \frac{\dot{V}_{O_2\max}}{\dot{V}_{O_2}} \). Endurance time can then be calculated.

If, however, rate of physical work is given as the input information (for example, the vertical axis variable in Figure 1.2.1), then several steps must be taken to use equation 1.3.6. First, physical (or external) work rate must be converted into physiological work rate. This conversion is accomplished by dividing physical work rate by muscular efficiency (usually considered to be 20% for the larger muscles, and much lower for smaller muscles and finer movements).

The next step is to convert physiological work rate into oxygen consumption rate. There are about 20.18 x 10^6 N·m of energy for each cubic meter of oxygen utilized, so the physiological work rate is divided by this number in order to obtain the rate of oxygen consumption.

For very intense work, the value just calculated will be too large because some of the energy to perform this work will be obtained from anaerobic sources. Actual oxygen consumption may not be nearly as high as calculated. To account for this, obtain aerobic fraction from a curve such as in Figure 1.3.4, and multiply by the oxygen consumption rate calculated previously. This resulting value can then be used in the Kamon formula to determine endurance time.

Section 2.4.3, p. 64 (supplement)

Johnson and Benjamin (1999) investigated the oxygen consumption, heat production, and muscular efficiency of uphill versus downhill walking on a treadmill at a constant speed of 1.11 m/sec. They found that for uphill walking (zero grade not included):

\[
\dot{V}_{O_2} = 1.5 \times 10^{-5} + 5 \times 10^{-5} G
\]

(1)

where \( G \) = fractional (not percent) grade, dimensionless

Downhill walking was found to require half as much oxygen consumption as uphill walking at the same numerical grade (with different sign).

Other measured oxygen costs of activities can be found in Table 5.2.22.

Reference:

Biomechanics and Exercise Physiology

Supplement 2.5.2

The legs are about twice as strong as the arms for both men and women. In Tables 2.2.3 and 2.2.4 are shown maximum forces relative to body weight able to be developed by arm and leg muscles (ACSM, 1999). Strength decreases with age, and women’s relative strength is again about 70% of that of men (remember that women’s body weights are also lower, so absolute strength is about 50% of that of men).

Reference:

### Table 2.2.3. Upper Body Strength Compared to Body Weight (ASCM, 2001)

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Age 20-29</th>
<th>Age 30-39</th>
<th>Age 40-49</th>
<th>Age 50-59</th>
<th>Age 60+</th>
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*One repetition maximum bench press, with bench press weight ratio = weight pushed/body weight.*

†Data provided by the Institute for Aerobics Research, Dallas, TX (1994). Adapted from ACSM’s Guidelines for Exercise Testing and Prescription. 5th ed. Study population for the data set was predominately white and college educated. A Universal dynamic variable resistance (DVR) machine was used to measure the 1-RM. The following may be used as descriptors for the percentile rankings: well above average (90), above average (70), average (50), below average (30), and well below average (10).
Table 2.2.4 Leg Strength Compared to Body Weight (ACSM, 2001)

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*One repetition maximum bench press, with bench press weight ratio = weight pushed/body weight.
†Data provided by the Institute for Aerobics Research, Dallas, TX (1994). Adapted from ACSM’s Guidelines for Exercise Testing and Prescription, 5th ed. Study population for the data set was predominately white and college educated. A Universal dynamic variable resistance (DVR) machine was used to measure the 1-RM. The following may be used as descriptors for the percentile rankings: well above average (90), above average (70), average (50), below average (30), and well below average (10).

Section 3.2.3, p. 94 (supplement)

Exercise is often expressed as percentage of maximal oxygen consumption or as percentage of maximum heart rate. Although work rate is often considered to be linearly related to both of these measures, percent \( \dot{V}_{O_2,\text{max}} \) and percent \( HR_{\text{max}} \) are not the same value. With a few assumptions about equivalence between oxygen uptake and heart rate, the following useful result can be obtained:

\[
\% HR_{\text{max}} = 30 + 0.7 \left( \% \dot{V}_{O_2,\text{max}} \right) \tag{1}
\]

Section 4.2.2, p. 185 (supplement)

Gagge and Nishi (1983) gave the relationship between oxygen uptake and metabolic rate in an adult human as:

\[
M = 21.14 \times 10^6 \dot{V}_{O_2} \left[ (0.23 \dot{V}_{CO_2}/\dot{V}_{O_2}) + 0.77 \right]
\]
where \( M = \) metabolic rate, \( N \cdot m/sec \)

\[ \dot{V}_{O_2} = \text{oxygen uptake, } m^3/sec \]

\[ \dot{V}_{CO_2} = \text{carbon dioxide production rate, } m^3/sec \]

The ratio \( \dot{V}_{CO_2} / \dot{V}_{O_2} \) depends on the nutrient substrate being metabolized, but resting \( \dot{V}_{CO_2} / \dot{V}_{O_2} \) is normally about 0.8.

Reference:

Section 4.2.3, p. 214 (Supplement)

In a series of experiments where they used a sinusoidal pressure applied at the mouth, while measuring esophageal pressure (assumed similar to pleural pressure) with an esophageal balloon, and volume with a volume-displacement plethysmograph, Barnas et al. (1990) were able to determine the magnitude and phase angle of chest wall impedance over a range of frequencies from 0.5 to 10 Hz. From these data, chest wall resistance and reactance have been plotted (Figure 4.2.23.1) for relaxed subjects breathing from FRC with a tidal volume of 2.5% of vital capacity.

Resistance can be seen to decrease with frequency from 0.5 to 3 Hz and to remain constant (or increase slightly) over the range of 2-3 Hz to 10 Hz. Other authors (Lutchen et al., 1990) have shown that chest wall resistance increases again after about 15-20 Hz.

To determine exactly which part of the body contributed to this resistance change, Barnas et al., (1989B) measured resistances of the rib cage, abdomen-diaphragm, and belly wall and found that each of these areas contributed in parallel fashion to the frequency dependence of resistance. They attributed these effects to viscoelastic properties of the chest wall tissue that have been modeled by Hildebrandt (1970) and appear in diagrammatic form in Figure 3.4.1 (left side). Others (Suki and Bates, 1991) include lung tissue mechanics in their treatment.

Tissue resistance of the chest wall was found also to exhibit nonlinear, volume-dependent properties (Barnas et al., 1989B). The results were true for all subjects (Figure 4.2.23.2), but one subject who was tested extensively gave the following linear regression line relating chest wall resistance to tidal volume at a constant breathing rate of 0.4 Hz.

\[ R_{cw} = 2.9 - 0.75 \log (V_T) \] (4.2.90.1)

where \( R_{cw} = \text{chest wall resistance, } cm \ H_2O \cdot sec/L \)

\( V_T = \text{tidal volume, mL} \)

Respiratory resistance has also been found to decrease as lung volume increases (Barnas, et al., 1993).
When the respiratory muscles contracted to produce esophageal pressures different from those during relaxation (Barnas et al., 1989A) resistance was found to increase greatly from that at relaxation (Figure 4.2.23.3). Other nonrespiratory maneuvers that involve respiratory muscles, such as weight holding or isometric tension, also increased chest wall impedance (Barnas et al., 1991).

References


Figure 4.2.23.1. Resistance and reactance of the entire chest wall with sinusoidal forcing at the mouth. Volume of the sinusoid was 2.5% of vital capacity and lung volumes began and ended at FRC (used with permission from Barnas et al., 1999).

Figure 4.2.23.2. Chest wall resistance depends on tidal volume as well as frequency (used with permission from Barnas et al., 1989B)
Figure 4.2.23.3. Chest wall resistance depends on contraction of respiratory muscles. Positive intrathoracic pressures indicate expiratory muscle contraction and negative intrathoracic pressures denote inspiratory muscle contraction (used with permission from Barnas et al., 1989A).
The “reactance” that is based on compliance is given by equation 4.2.105 as \( X_c = \frac{1}{j\omega T} \). Chest wall reactance has been found by Barnas et al., (1990) to vary with frequency of forced oscillations just as resistance varies (Figure 4.2.23.1). The negative sign in the diagram indicates that compliance is involved; a positive reactance value would designate inductance. Compliance can be obtained from the magnitude of \( X_c \) by taking the inverse of radial frequency multiplied by \( X_c \). Because \( \omega \) increases as the magnitude of \( X_c \) is seen to decrease (Figure 4.2.23.1), the value for compliance does not change as rapidly as the value for \( X_c \).

In a manner similar to the effect of the tidal volume amplitude on resistance, chest wall compliance is also dependent upon amplitude. This can be seen in Figure 4.2.25.1, except that elastance, and not compliance, is plotted (Barnas et al., 1989B). Elastance is the inverse of compliance.

Barnas et al., (1989B) found a regression line for the data for one subject gave:

\[
E = 22 - 5.3 \log V_T \tag{4.2.103.1}
\]

where \( E = \text{elastance, cmH}_2\text{O/L} \)

\( V_T = \text{tidal volume, mL} \)

Unlike resistance, there appeared to be no obvious dependence of elastance on frequency in the range of 0.2 to 0.6 Hz.

Sustained respiratory muscle contractions increased elastance at different frequencies, as seen in Figure 4.2.25.2 (Barnas et al., 1989A). Effects of inspiratory and expiratory muscle contractions were similar.
Figure 4.2.25.1. Chest wall elastance changes with tidal volume amplitude (used with permission from Barnas et al., 1989B)

Figure 4.2.25.2. Chest wall elastance with frequency as respiratory muscles are contracted to produce different intrathoracic pressures. Positive pressures denote expiration and negative pressures denote inspiration (used with permission from Barnas et al., 1989A)
Section 4.2.3, p. 220 (Supplement)

We now know that lung tissue and chest wall resistances and compliances are frequency dependent in the frequency range of breathing. Yet, lung time constants, and time constants of various lung segments, must remain constant and nearly identical to each other in order that some portions of the lung do not fill faster than others. Indeed, there are some lung pathological situations where the time constant of one lung is not the same as the time constant of the other lung, and disproportionate filling of one lung occurs at the expense of the other. Flow is even possible between the lungs, as the more rapidly filling lung empties into the slower filling lung. This condition is known as pendelluft (see Section 4.4.2).

In order for tissue time constants to be equal, tissue determinants of resistance and compliance must be related, and resistance and elastance (the inverse of compliance) must be proportional.

Fredberg and Stamenovic (1989) expressed this idea mathematically:

\[ \omega R = \eta E \]

where \( \omega \) = frequency, rad/sec

\( R \) = resistance, cmH\(_2\)O · sec/L

\( E \) = elastance, cm H\(_2\)O/L

\( \eta \) = hysteresivity, dimensionless

They calculated hysteresivity values for lung tissues from cats, dogs, monkeys, and humans, and obtained values of about 0.15 – 0.20 for all species. Vagal or chemical stimulation caused these values to increase to about 0.3, but the proportionality between resistance and elastance was preserved.

Barnas et al. (1991) made the same calculations for chest wall tissues and obtained hysteresivity values of 0.27 to 0.37 with very small differences with frequency or amplitude. Static nonrespiratory muscular maneuvers increased hysteresivity values to the 0.3 to 0.5 range.

References:


Osmotic pressure in leaves can be used to explain water movement in plants. As water evaporates from stomata, it leaves behind a solution of salts and sugars more concentrated than before the water was lost. Water is thus drawn from the roots towards the concentrated solution. The osmotic pressure is of a high enough negative value that it can draw water to the top of the highest plant. That will happen insofar as there is enough free water in the soil so that the concentration of salts in the soil does not hinder the water from moving into the plant.

Physicians often advocate a high initial drug concentration followed by a lower sustained drug level. The DUROS system could be modified to produce such a decreasing level of drug delivery by closely metering the amount of salt in the chamber. Once the salt solution reached the point where it was no longer saturated, additional fluid diffusing through the membrane would continue to dilute the solution, thus slowing fluid flow and leading to a decreasing rate of drug delivered.
Section 5.2.2 Supplement

### 3.2.2 Thermal Conductance

Tabulated values of thermal conductance are sometimes encountered for materials of standard thicknesses. Examples of these are building materials, such as bricks, window glass, and plywood, or film materials such as plastic sheets. Thermal conductance is just thermal conductivity divided by thickness \((C = k/L)\); so that thermal resistance is just the inverse of the product of conductance and area \((R = 1/CA)\).

#### 3.2.2.1 Clothing

Clothing represents a special case of conductive heat transfer. There are social, legal and moral aspects attributable to clothing, aspects of which the biological engineer should be at least aware, but the most important clothing characteristic to be considered here it its modifying effect on heat loss from the body.

The obvious effect of clothing is its insulative property. Not so obvious is the dead air space formed between the skin and clothes, the reduction in permeability to water vapor transmission, and the increase of surface area when wearing clothes (Johnson, 1991a).

The insulation value for clothes is normally found in units of \(\text{clo}\). A clo was suggested in 1941 as the insulation value of a normal business suit worn comfortably by sedentary workers in an indoor climate of 21°C. Since then, the clo has been standardized as the amount of insulation that would allow 6.45 N m/sec of heat from a 1 m\(^2\) area of skin of the wearer to transfer to the environment by radiation and convection when a 1°C difference in temperature exists between the skin and the environment (Goldman, 1967). The higher the clo value of clothing, the less heat will be transferred from the skin.

Thermal conductivity values for clothing would not be very useful because of the variable and unknown thicknesses. Hence the use of thermal conductance is more useful.

Heat conduction through clothing is given by

\[
\dot{q} = \frac{6.45 A}{\text{clo}} (\theta_{sk} - \theta_{\infty}) = C_{cl} A (\theta_{sk} - \theta_{\infty}) \quad (3.2.8)
\]

where \(\dot{q}\) is the heat transferred through clothing (N m/sec); clo, the clothing insulation (clo units); \(C_{cl}\), the clothing conductance [N m/(m\(^2\) sec °C)]; \(A\), the surface area (m\(^2\)); \(\theta_{sk}\), the skin temperature (°C); and \(\theta_{\infty}\), the environmental temperature (°C).
This equation shows the normal means to calculate conductive heat transfer using conduction, and shows the equivalence of clo to the normal units in this text.

In Table 3.2.3 are values of conductance for selected items of clothing. Overall thermal resistance for a clothing ensemble should be related to the parallel and serial combination of resistances of all pieces worn (Figure 1.8.3). Because of potential complexities in this process, the following empirical relationships have been developed (ASHRAE, 1985)

\[
R_{cl} = (0.494 \sum C_{cl}^{-1} + 0.0119) / A, \text{ men (3.2.9a)}
\]
\[
R_{cl} = (0.524 \sum C_{cl}^{-1} + 0.0053) / A, \ \text{women (3.2.9b)}
\]

Where \( R_{cl} \) is the conduction thermal resistance of a clothing ensemble \([\circ C \text{ sec/N m}]\); and \( A \), the surface area \((m^2)\).

The sum of the inverted conductance values \( \sum C_{cl}^{-1} \) is calculated by inverting tabulated conductance values for each item of clothing in the ensemble and summing them. Conduction heat loss through the clothing is then calculated as the temperature difference \( \theta_{sk} - \theta_{\infty} \) divided by thermal resistance

\[
\dot{q} = (\theta_{sk} - \theta_{\infty}) / R_{cl} \quad \text{(3.2.10)}
\]

In order to complete this discussion, a few things need to be explained about surface area and about skin temperature. The following relationships were empirically produced.

Clothing surface area is based upon the DuBois formula for calculation of surface area of nude humans

\[
A = 0.7673W^{0.425}H_t^{0.725} = 0.2025m^{0.425}H_t^{0.725} \quad \text{(3.2.11)}
\]

Where \( A \) is the nude skin surface area \((m^2)\); \( W \), the body weight \((N)\); \( H_t \), the height \((m)\); and \( m \), the body mass \((kg)\).

The increase of surface area due to clothing has been found to be between 15 and 25% (ASHRAE, 1977). An average increase of 20% is used in the following equation.

Mean skin temperature is also affected by clothing. Temperature calculated by means of the following is essentially independent of metabolic rate up to four or five times the rate expended at rest. For a clothed human

\[
\theta_{sk} = 25.8 + 0.267\theta_{\infty} \quad \text{(3.2.12)}
\]

where \( \theta_{sk} \) is an estimate of mean skin temperature \(\circ C\); and \( \theta_{\infty} \), the mean environmental temperature \(\circ C\).
<table>
<thead>
<tr>
<th>Clothing</th>
<th>Men</th>
<th>[N m/ (m(^2) sec °C)]</th>
<th>Women</th>
<th>[N m/ (m(^2) sec °C)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeveless T shirt</td>
<td>110</td>
<td></td>
<td>Bra and panties</td>
<td>130</td>
</tr>
<tr>
<td>T shirt</td>
<td>72</td>
<td></td>
<td>Half slip</td>
<td>50</td>
</tr>
<tr>
<td>Briefs</td>
<td>129</td>
<td></td>
<td>Full slip</td>
<td>34</td>
</tr>
<tr>
<td>Long underwear upper</td>
<td>18</td>
<td></td>
<td>Long underwear upper</td>
<td>18</td>
</tr>
<tr>
<td>Long underwear lower</td>
<td>18</td>
<td></td>
<td>Long underwear lower</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Torso</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shirt(^a)</td>
<td></td>
<td></td>
<td>Blouse</td>
<td></td>
</tr>
<tr>
<td>Light, short sleeve</td>
<td>46</td>
<td></td>
<td>Light</td>
<td>32</td>
</tr>
<tr>
<td>Light, long sleeve</td>
<td>29</td>
<td></td>
<td>Heavy</td>
<td>22</td>
</tr>
<tr>
<td>Heavy, short sleeve</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy, long sleeve</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>43</td>
<td></td>
<td>Light</td>
<td>65</td>
</tr>
<tr>
<td>65 Heavy</td>
<td>22</td>
<td></td>
<td>Heavy</td>
<td>29</td>
</tr>
<tr>
<td>Trousers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>25</td>
<td></td>
<td>Light</td>
<td>25</td>
</tr>
<tr>
<td>Heavy</td>
<td>20</td>
<td></td>
<td>Heavy</td>
<td>15</td>
</tr>
<tr>
<td>Sweater</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>32</td>
<td></td>
<td>Light</td>
<td>38</td>
</tr>
<tr>
<td>Heavy</td>
<td>17</td>
<td></td>
<td>Heavy</td>
<td>17</td>
</tr>
<tr>
<td>Jacket</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light</td>
<td>29</td>
<td></td>
<td>Light</td>
<td>38</td>
</tr>
<tr>
<td>Heavy</td>
<td>13</td>
<td></td>
<td>Heavy</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Footwear</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socks</td>
<td></td>
<td></td>
<td>Stockings</td>
<td></td>
</tr>
<tr>
<td>Ankle length</td>
<td>161</td>
<td></td>
<td>Any length</td>
<td>640</td>
</tr>
<tr>
<td>Knee length</td>
<td>65</td>
<td></td>
<td>Panty hose</td>
<td>640</td>
</tr>
<tr>
<td>Shoes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandals</td>
<td>320</td>
<td></td>
<td>Sandals</td>
<td>320</td>
</tr>
<tr>
<td>Oxfords</td>
<td>160</td>
<td></td>
<td>Pumps</td>
<td>160</td>
</tr>
<tr>
<td>Boots</td>
<td>81</td>
<td></td>
<td>Boots</td>
<td>81</td>
</tr>
</tbody>
</table>

\(^a\)5% lower conductance or 5% higher clo for tie or turtleneck.

Convection and radiation also contribute to heat loss from clothing. Convection and radiation are parallel heat loss processes, and, likewise, the thermal resistances corresponding to convection and radiation are in parallel with one another. The combination of these parallel resistances is in series with the conduction thermal resistance of the clothing. Thus the overall thermal resistance limiting heat loss through clothing is

\[
R_{\text{tot}} = R_{\text{cl}} + R_{\text{c}}|| R_{\text{r}} = R_{\text{cl}} + \frac{(1.24 A h_c)^{-1} (1.2 h_r A)^{-1}}{(1.2 h_c A)^{-1} + (1.2 h_r A)^{-1}} = R_{\text{cl}} + [1.2 A (h_r + h_c)]^{-1}
\]

where \( R_{\text{tot}} \) is the total thermal resistance \( [\degree C \text{ sec/(N m)}] \); \( R_{\text{cl}} \), the conduction thermal resistance of clothing \( [\degree C \text{ sec/(N m)}] \); \( R_{\text{c}} \), the convection thermal resistance \( [\degree C \text{ sec/(N m)}] \); \( R_{\text{r}} \), the radiation thermal resistance \( [\degree C \text{ sec/(N m)}] \); \( h_c \), the convection coefficient \( [\text{N m/sec m}^2 \degree C] \); and \( A \), the nude body surface area \( (\text{m}^2) \).

Convection coefficients are discussed in Section 3.3, and values may be obtained from Tables 3.3.3, 3.3.4, and 3.3.5. The velocity of “still” air is usually taken to be 0.15 m/sec. Radiations coefficients are discussed in Section 3.4.6, and a value of 4.7 N m/(sec m² °C) is often used for people inside a room.

Clothed people subjected to radiant heat gain or loss at radiant temperatures different from mean ambient temperature must be treated somewhat differently than those with ambient and radiant temperatures essentially the same (Johnson, 1991a).

Moisture can also be transmitted through clothing and produce heat loss (McCullough, 1993). Some discussion of this is given in Sections 3.8.1.2 and 4.8.2.3. For more details see ASHRAE (1977) or Johnson (1991a).

**EXAMPLE 3.2.2.1-1. Heat Loss through Clothing**

In a 1972 study, Van Cott and Kinkade found the average body mass of 19-year-old college students in the eastern United States to be 72.1 kg. If one of these students is 185 cm tall and sits quietly in a classroom at 22°C, what will be his heat loss if he wears briefs, a T shirt, blue jeans (assumed to be light trousers), no socks, and sandals?

Solution

The body weight of the student is (72.1 kg) (9.8 N/kg) = 707 N.
The nude skin area of the student is, from Eq. 3.2.11.

\[ A_{\text{nude}} = 0.07673 W^{0.425} H_t^{0.725} = 0.070673(707)^{0.425}(1.85)^{0.725} \]

\[ = 1.79 \text{ m}^2 \]

The clothing conductance values are, from Table 3.2.3,

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Conductance (N/(m sec °C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Briefs</td>
<td>129</td>
</tr>
<tr>
<td>T shirt</td>
<td>72</td>
</tr>
<tr>
<td>Trousers</td>
<td>25</td>
</tr>
<tr>
<td>Sandals</td>
<td>320</td>
</tr>
</tbody>
</table>

Clothing thermal resistance is found from Eq. 3.29a as

\[ R_{ct} = \frac{(0.494[0.00775 + 0.01389 + 0.04000 + 0.00312] + 0.0119)/1.79}{0.428°C \text{ sec/(N m)}} \]

Using values of \( h_c = 3.1 \text{ N m/sec m}^2 \text{ °C} \) and \( h_t = 4.7 \text{ N m/sec m}^2 \text{ °C} \), total thermal resistance is, from Eq. 3.2.13

\[ R_{tot} = 0.428 + [(1.2)(1.79 \text{ m}^2)(3.1 + 4.7 \text{ N m/(sec m}^2 \text{ °C)})]^{-1} \]

\[ = 0.103°C \text{ sec/(N m)} \]

Skin temperature can be calculated from Eq. 3.2.15 to be

\[ \theta_{sk} = 25.8 + 0.257(22°C) = 31.7°C \]

Heat loss is just

\[ \dot{q} = \frac{(\theta_{sk} - \theta_{\infty})/R_{th}}{(31.7°C - 22°C)/0.103 \text{ sec °C/(N m)}} \]

\[ = 94 \text{ N m/sec} \]

Remark

This amount of heat loss is slightly more than the 86 N m/sec indicated in Table 3.5.3 for basal heat production in a 20-year-old male, and would probably be acceptable to maintain comfort.
3.4.7 Solar Flux

The sun is the primary source for much of the energy used by biological systems occurring naturally on the Earth. The sun sends about 1395W m/(sec m$^2$) to the Earth (called the solar flux). Because carbon dioxide, water vapor, and other gases absorb solar energy, and atmospheric dust reflects it, only about one-half of this flux reaches the Earth’s surface, and the actual amount varies with latitude, cloud cover, air pollution, time of the year, and other variables. Solar intensities for “hazy” clear sky at 1400 hours on representative summer days are given as maximum solar flux values in Table 3.4.3 (Johnson, 1991a). Much work has been expended to calculate accurately solar flux at any given location at various months of the year and times of day (Moon et al., 1981). These calculations are often formidable. Nonetheless, approximate methods can be used to correct values in Table 3.4.3 for time of year and time of day.

The time of year adjustment can be made by

$$q_{\text{sol, m}} = 0.5(q_{\text{sol, max}} - q_{\text{sol, min}})\left\{\sin\left[\frac{\pi(d - d_{\text{ve}})}{183}\right] + 1\right\} + q_{\text{sol, min}}$$
The value of solar flux at any time of day can be obtained similarly

\[ q''_{sol} = q''_{sol,m} \sin[\pi(t - t_{sr})/(t_{ss} - t_{sr})] \]  (3.4.22)

where \( q''_{sol} \) is the solar flux during the day \([\text{N m/(sec m}^2]\); \( q''_{sol,m} \), the midday solar flux \([\text{N m/(sec m}^2]\); \( t \), the time of day (h); \( t_{sr} \), the time of sunrise(h); and \( t_{ss} \), the time of sunset (h).

These adjustments are approximate, but can be used to estimate clear sky solar radiation. The presence of clouds and atmospheric pollution will modify the actual solar flux.

In addition to the direct solar flux, there is diffuse radiation and reflected radiation to consider. These are beyond the scope of this text. See Johnson (1991a) for details.

Solar flux can be considered to be a heat source impinging on a flat surface. The actual rate of heat absorbed will be

\[ \dot{q} = \alpha A q''_{sol} \]  (3.4.23)

where \( \dot{q} \) is the absorbed heat \([\text{N m/sec}]\); \( \alpha \), the absorptivity (dimensionless); \( A \), the surface area facing the sun \((\text{m}^2)\); and \( q''_{sol} \), the solar flux \([\text{N m/(sec m}^2]\)
Section 5.2.5, p. 401 (supplement):

Johnson and Benjamin (1999) investigated the oxygen consumption, heat production, and muscular efficiencies of uphill versus downhill treadmill walking at a constant speed of 1.11 m/sec. They found for uphill walking (zero grade not included):

\[
\hat{V}_{O_2}^{\text{up}} = 1.5 \times 10^{-5} + 5 \times 10^{-5} G \tag{1}
\]
\[
\hat{q}^{\text{up}} = 128 + 500 G \tag{2}
\]
\[
\eta^{\text{up}} = 6 + 100 G \tag{3}
\]

where \( \hat{V}_{O_2}^{\text{up}} \) = oxygen consumption of uphill walking, m\(^3\)/sec
\( \hat{q}^{\text{up}} \) = heat production for uphill walking, N\( \cdot \)m/sec
\( \eta^{\text{up}} \) = muscular efficiency for uphill walking, dimensionless
\( G \) = fractional (not percent) grade, dimensionless

For downhill walking compared to uphill

\[
\hat{V}_{O_2}^{\text{down}} = 0.5 \hat{V}_{O_2}^{\text{up}} \tag{4}
\]
\[
\hat{q}^{\text{down}} = 0.67 \hat{q}^{\text{up}} \tag{5}
\]
\[
\eta^{\text{down}} = -2 \eta^{\text{up}} \tag{6}
\]

where down refers to downhill walking.

Grade (G) in these equations is to be used as a positive number for both uphill and downhill walking.

Reference: