Chapter 4

Work and Energy Influenced by Athletic Equipment

D.J. Stefanyshyn and B.M. Nigg

Athletic equipment is designed to protect athletes, provide comfort, and enhance performance. A recreational athlete may use athletic equipment to improve comfort (e.g., by using a specific backpack), to improve safety aspects (e.g., by using a helmet for rock climbing), or to minimize pain (e.g., by using a shoe insert to prolong the pain-free walking distance). Helmets, shin guards, ankle braces, ice hockey equipment, and many other pieces of athletic equipment are used to protect specific body parts during contact with an opponent, an implement, or the environment.

A competitive athlete attempts to use athletic equipment to enhance performance. Athletic equipment that has been developed to enhance performance is constructed to optimize the energy transfer between athlete and equipment. As mentioned earlier, this is generally achieved by maximizing the (conservative) energy that is returned, minimizing the (nonconservative) energy that is lost, and optimizing the musculoskeletal system.

To optimize the use of athletic equipment it is necessary to understand how athletic equipment influences an athlete's performance. The following section concentrates on this aspect, enhancing performance using athletic equipment. It addresses the first two of the aspects that were previously presented: how athletic equipment can store and re-utilize (conservative) energy and how (nonconservative) energy loss to the environment can be minimized.

**Energy Return**

The relationship between stiffness $k$, deformation $\Delta x$, and stored energy has been discussed earlier. Briefly, energy return increases linearly with increasing material stiffness and quadratically with increasing deformation. The approximate ranges of maximal possible energy storage for different athletic surfaces, assuming that the material behaves like an ideal linear spring, are summarized in table 4.1.

**Storage and Return of Energy in Sports Equipment**

Any elastic material is capable of storing energy. Some examples of materials or equipment that can store and return energy during physical activities include trampolines, diving boards, poles in pole-vaulting, surfaces, and shoes. The next few paragraphs discuss the potential of sport equipment to store and return energy during actual physical activity.

**Trampoline and Diving Board**

A trampoline is capable of storing large amounts of energy due to its rather low stiffness (approximately
Table 4.1 Energy Return From Elastic Sports Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>k (N/m)</th>
<th>Δx (m)</th>
<th>E_p (J)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trampoline</td>
<td>5,000</td>
<td>0.800</td>
<td>1600</td>
<td>2.30</td>
</tr>
<tr>
<td>Tumbling floor</td>
<td>50,000</td>
<td>0.100</td>
<td>250</td>
<td>0.36</td>
</tr>
<tr>
<td>Gymnastic floor</td>
<td>120,000</td>
<td>0.050</td>
<td>150</td>
<td>0.22</td>
</tr>
<tr>
<td>Running track</td>
<td>240,000</td>
<td>0.010</td>
<td>12</td>
<td>0.02</td>
</tr>
<tr>
<td>Gymnasium floor</td>
<td>400,000</td>
<td>0.005</td>
<td>5</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*The calculated height indicates the height a mass of 70 kg could be raised using the maximal possible returned energy. Approximate values for spring constants (k (N/m)), maximal deformations (Δx (m)), and maximal energy storage (E_p (J)) of different athletic equipment assuming a linear elastic spring behavior.

5000 N/m) and the large deformation this allows. A diving board is slightly stiffer than a trampoline (k ~ 6000–7000 N/m) (Kooi and Kuipers 1994). However, it does not store more energy than a trampoline because the deformation that it allows is smaller than the deformation of the trampoline springs and fabric. While in contact with the trampoline or the diving board, the athlete works to further deflect the apparatus. Thus, the deflection of the equipment results from the kinetic energy of the landing athlete and the work of this athlete during the first half of contact. The athlete also performs additional work during the second half of the contact phase in order to accelerate his or her center of mass upward relative to the surface. The combination of the energy return from the trampoline and the work performed by the athlete when in contact with the apparatus allows greater heights to be achieved.

Gymnastics Floors

Gymnastics and tumbling make extensive use of energy return from equipment. The gymnastics floor routine is performed on a springy surface that is specially designed to store and return energy to the athletes. The additional energy allows for spectacular tumbling routines that would not be possible without the additional energy from the surface. A competition surface for the floor exercises in gymnastics has a stiffness of approximately 120 kN/m. A competition surface for tumbling has a stiffness of approximately 50 kN/m. Assuming an ideal elastic spring, these material characteristics correspond to an additional jumping height of about 0.20 m for gymnastics and about 0.30 to 0.40 m for tumbling. This additional height corresponds to an additional time in the air (0.20 s for gymnastics and 0.30 s for tumbling), which allows for more somersaults and twists. In analogy to the trampolining and diving examples, the gymnasts or tumblers work during the short ground contact to increase their performance. Additionally, gymnasts also make use of energy storage and return when they compress the springboard during vaults.

Track and Field Surfaces

Indoor track and field surfaces can be tuned to return energy. McMahon and Greene (1978, 1979) studied track surfaces with different compliances. They used a theoretical model with experimental input. Their theoretical model predicted:

- that runners would increase their step length and ground contact time for increased compliance of a running surface that would result in slower running speeds,
- that the fastest running surface would be infinitely stiff without any deformation if the human body was an ideal elastic system consisting of only mass and stiffness without any damping,
- that the stiffest or hardest surfaces were necessary for the surfaces where the athlete would be the fastest,
- that there is some intermediate value stiffness for a track surface that maximizes running speed when assuming that the musculoskeletal system includes some internal damping that dissipates energy,
- that this optimal stiffness is two to four times the athlete’s lower leg stiffness, and
- that this optimal stiffness leads to an increase in ground contact time and an increase in step length.

Using this surface stiffness, the researchers predicted a 1 to 3% increase in running speed. Experimental results from a running track construct...
with a stiffness of approximately three times man’s lower leg stiffness \( k \approx 80 \text{kN/m} \) showed speed enhancements of approximately 2%. A 2% increase is certainly substantial in any track and field running discipline. It represents approximately 0.2 s in a fast 100 m sprint and about 80 s in a marathon.

**Tennis Racquets**

The type and tension of tennis racquet strings can have an influence on the efficiency of energy return during impacts of tennis racquets with tennis balls. Nylon strings have been found to be slightly inferior to gut strings in their ability to store and return energy to the ball (Ellis, Elliot, and Blanksby 1978). Lower string tensions were also found to have higher rebound coefficients (velocity of the ball before impact compared to after impact) (Baker and Wilson 1978; Ellis, Elliot, and Blanksby 1978; Bosworth 1981; Elliot 1982). It has been shown that the strings can be considered as purely elastic (Brody 1979; Leigh and Lu 1992). Therefore, the increase in energy return is due to less energy being lost in the ball. For example, Leigh and Lu (1992) report that as string tension decreases from 200 N to 98 N, the compression of the tennis ball is decreased by 36% while the impact times are only decreased by 18%. The result is a decrease in the rate of compression of the tennis ball and less energy being lost. One drawback of flexible strings is that control is sacrificed (Brody 1979).

**Vaulting Poles**

The ultimate goal in pole-vaulting is to obtain a maximal height jump. In a rough approximation, this is equivalent to the athlete obtaining maximal potential energy. The kinetic energy of the athlete during the run-up is converted to potential strain energy in the pole as the pole flexes. Then as the pole extends, the strain energy is converted to gravitational potential energy as the athlete’s center of mass is raised. The ultimate performance is substantially influenced by the ability of the pole to store and return strain energy. Theoretical models have been developed to study the influence of pole stiffness on performance (Braff and Dapena 1985; Ekevad and Lundberg 1997). Both studies indicate that there is an optimal stiffness that maximizes performance. A pole that is too stiff straightens before the athlete is in the maximal vertical position, pushing the athlete horizontally back away from the bar. A pole that is not stiff enough straightens too slowly and the athlete is horizontally past the bar before the maximal vertical position is reached. The optimal stiffness is dependent on the mass and strength of the athlete. Similar to the trampoline example, the athlete performs additional work by extending his or her arms just before releasing the pole to maximize performance.

**Sport Shoes**

In the past two decades, several unsuccessful attempts have been made to produce energy return with the help of sport shoes (Alexander and Bennet 1989; McMahon 1987; Turnbull 1989). There are several factors that represent possible reasons for these unsuccessful attempts (see chapter 1). The main reason, however, is that the deformation of the shoe sole is generally small.

The maximal deformation of the shoe sole under the forefoot, where most takeoff movements are initiated, is typically small. Currently, sport shoe manufacturers do not want to produce high performance sport shoes with soft forefoot soles because they would produce instability during stance and takeoff. Three different possibilities of energy return during running are calculated to illustrate the current situation and the theoretically possible solutions, using the following assumptions:

1. The peak takeoff force in all examples is \( F = 2000 \text{N} \).
2. The first example uses a deformation of \( d_1 = 2 \text{mm} = 0.002 \text{m} \).
3. The second example uses a deformation of \( d_2 = 5 \text{mm} = 0.005 \text{m} \).
4. The third example uses a deformation of \( d_3 = 10 \text{mm} = 0.010 \text{m} \).

The results of the calculations, with the corresponding sole stiffness and the maximal possible energy return, are summarized in table 4.2.

These energy return values (see table 4.2) should be compared with the total energy spent during one ground contact. Based on oxygen consumption measurements the total energy spent during a marathon corresponds to about 10% of J. Assuming about 20,000 steps during a marathon, the total energy spent during one ground contact in marathon running can be estimated as about 500 J (Nigg and Segesser 1992). Using this approximation, the maximal returned energy is about 0.4% of the total energy spent during one ground contact for a deformation of about 2 mm, 1% for a deformation of about 5 mm, and 2% for a deformation of about 10 mm. Thus, existing shoes do not deform enough in the forefoot to utilize energy return. A construction that would allow a deformation of 10 mm while still being stable could provide an estimated maximal
Table 4.2  Maximal Energy Return for Three Shoe Conditions

<table>
<thead>
<tr>
<th>Force (F) (N)</th>
<th>Stiffness (k) (N/m)</th>
<th>Deformation (Δx) (mm)</th>
<th>Maximal returned energy (E_{\text{returned}}) (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1,000,000</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2000</td>
<td>400,000</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2000</td>
<td>200,000</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Energy return assumes a linear spring behavior with no energy dissipation.

increase in performance, in running, for example, of about 2%, a substantial increase.

In addition to small deformations, other factors that play a role in limiting the energy return from sport shoes include the following:

- The shoes do not act like ideal linear springs.
- The stored energy is not returned at the right location, with the right frequency, and at the right time.

The importance of these aspects to energy return in athletic footwear has been discussed earlier. However, these limitations are not restricted only to sport shoes. They are important for energy return in all types of sport equipment and are discussed in the following paragraphs.

Consequently, one should work in two directions to improve the performance enhancement in sport shoes. First, one should develop shoe soles that allow a deformation under the forefoot of at least 10 mm. Second, one should use materials and constructions that act like ideal springs.

Nonlinearity and Energy Dissipation

The model of a linear elastic spring is the simplest example of energy storage. However, materials used for sport equipment typically do not behave linearly and often dissipate some of the stored energy. Nonlinearity and dissipation of energy are common material properties of such equipment. A typical force deformation diagram (see figure 4.1) demonstrates this. It can be seen that the curves for increasing and decreasing force are not coincidental. This is known as hysteresis. The area under the increasing force curve represents the energy that is put into or the work that is done on the material. The area under the decreasing force curve represents the energy that is returned by or the work that is done by the material. The difference in force is the area between the two curves, which is also known as the hysteresis loop. This is the energy that is dissipated within the material. Therefore, in returning to its original shape, the work done by the equipment on the athlete is less than the work done by the athlete to deform the equipment. The result is that a piece of athletic equipment will only be able to return a percentage of the energy that is put into the equipment. The fraction of the input energy returned is called the efficiency of the equipment and is determined by

\[
\eta = \frac{E_{\text{output}}}{E_{\text{input}}} \tag{4.1}
\]

where

\( \eta = \) efficiency,

\( E_{\text{output}} = \) energy the equipment returns to the athlete, and

\( E_{\text{input}} = \) energy the athlete puts into the equipment.

The efficiency of a piece of equipment can range from zero to one. A zero efficiency indicates that a material does not return any of the input energy while an efficiency of one indicates that a material returns all of the input energy. An efficiency of one would only be true for a perfectly elastic material. An efficiency of greater than one can never be attained as it would indicate that the material is generating energy.

A trampoline does not behave like an ideal spring. Some of the energy put into the trampoline is dissipated as the trampoline returns to its original position (see figure 4.2). A trampolinist falling from a height \( H_0 \) into the trampoline will bounce back to the height \( H_\text{max} \), which is only about 80% of its original height \( H_0 \) (Vaughan 1980). About 20% of the original energy is dissipated in the trampoline as frictional and heat energy.

Running shoe midsole materials are not 100% efficient. It has been shown that running shoe soles
are only 60 to 70% efficient (Alexander and Bennet 1989; Shorten 1993). The values of potential enhancement of performance discussed previously should, therefore, be reduced by 30 to 40% for those materials, to account for the energy dissipation. However, even those potential enhancements (e.g., 1.4%) are substantial.

Return of Energy at the Right Time

The return of stored energy by athletic equipment must occur at the appropriate time in an athlete’s performance as outlined earlier. Pole-vaulters use their poles to store energy as they flex. When the pole reaches its maximum deformation and begins to return the stored energy, the athlete must be in exactly the right position. The vaulter must have his center of mass close to or behind the line of the pole so that the pole exerts a force on the vaulter that results in an increase in height of the athlete. Furthermore, the vaulter must tuck his knees toward his chest to minimize his moment of inertia, which further facilitates the raising of the athlete (Angulokinzler et al. 1994). The timing is critical. If the athlete’s technique is just slightly off and the pole returns the energy a moment too soon or a moment too late, the ultimate performance will be compromised.

Return of Energy at the Right Location

Energy stored in athletic equipment can be of use to an athlete only if it can be returned at the right location. Diving boards, trampolines, and gymnastics surfaces are good examples where energy is returned at the right location, the location of the athlete at takeoff. In all of these cases, the location of maximal deformation, and therefore maximal possible energy return, is the location where the returned energy can have the most influence on performance. This is due to the fact that the athlete who caused the deformation remains in the same position on the equipment during both the energy storage and return phases. However, if the athlete compresses the equipment at one location during the storage phase and then moves to another location during the return phase, the energy return will not be at the right location to maximize performance.
An example of where this may occur is in sport shoes and surfaces. During a running stride, a heel-toe runner lands on the heel, attains a foot flat position, and then rolls off the forefoot during takeoff. Therefore, the heel is not the location where effective use can be made of returned energy (Nigg and Segesser 1992). For energy return to have an optimal effect on performance, the energy must be returned in the forefoot region during takeoff. However, manufacturers of sport shoes who have attempted to return energy with their shoes have almost exclusively been concerned with the heel. Although the midsole of the forefoot is capable of storing and returning energy (Shorten 1993), the thickness in the forefoot region is quite small (approximately 1 cm), which limits the amount of energy that can be stored in that region.

**Return of Energy With the Right Frequency**

A piece of equipment (e.g., a sport surface or a diving board) stores energy when deformed and releases this energy when the deformation restores. The storage occurs typically in about the first half and the release in about the second half of the total time of contact. The deformation and release correspond roughly to one-half of a sine wave. The total duration of a full sine wave allows the determination of the frequency of this deformation and release process. In the loaded condition, sport equipment should match this frequency. In other words, the loaded natural frequency of sport equipment should correspond to the actual frequency of the deformation and restoration process.

To illustrate this concept with an example, the ground contact time in sprinting is about 100 ms. One-half sine wave takes about 100 ms. One full sine wave lasts about 200 ms. This corresponds to a frequency of 5 Hz. Therefore, an optimal sprinting surface should have a loaded natural frequency of 5 Hz.

A diver on a diving board has a natural frequency in the range of 2 to 5 Hz. When the diver exerts a downward force on the board, the board deforms. Then as the board returns in an upward direction, it exerts a force propelling the diver upward. If the diver wants to perform a second bounce on the board he or she should match the frequency of the vibrating board to maximize the deflection and the energy stored in the board. The diver utilizes the frequency of the system to enhance the amount of energy that can be stored and, therefore, returned. In fact, it appears that skilled divers contact the board when it is near its maximal downward velocity (Jones, Pizzimenti, and Miller 1993), thus matching the frequency of the vibrating board.

The natural frequency of a system or piece of equipment is dependent on the mass and the stiffness of the system:

\[
f_n = \frac{\sqrt{\frac{k}{m}}}{2\pi}
\]

where

- \( f_n \) = the natural frequency of the system,
- \( m \) = the mass of the system, and
- \( k \) = the stiffness of the system.

The natural frequency changes with changes in either the mass or the stiffness of the system. For example, taking the system consisting of a diver and a diving board, the system has a natural frequency that is dictated primarily by the stiffness of the board and the mass of the athlete. When a diver of different mass is on the board, the system has a different natural frequency. If the new diver is heavier, the natural frequency of the new system is lower, and if the new diver is lighter, the natural frequency of the system is higher. Therefore, it is in the best interest of the diver to be able to adjust the board to match the frequency associated with the diver’s mass. The frequency of vibration of the diving board is dependent on the length of the board and is modified by adjusting the position of the fulcrum under the board.

Despite the difficulties of storing and returning energy in sport equipment that have been presented, there are several instances where the concept of energy return in sport equipment is successfully applied. As was mentioned previously, trampolines, diving boards, vaulting poles, tennis racquets, and athletic surfaces are examples where energy storage and return have a large influence on performance.

**Minimizing the Loss of Energy**

An athlete performing a given task spends energy for aspects that are directly related to performance and energy for aspects that are not directly related to performance of the task (see figure 4.3). The concept of minimizing the loss of energy attempts to minimize the use of energy that is not related to performance but would be available to enhance performance if it would not have been spent unnecessarily. Such energy loss includes loss due to
• friction,
• drag,
• mass and inertia,
• energy dissipation in materials,
• stabilization, and
• vibrations.

Many athletic activities can be characterized as physical endeavors to overcome external resistance forces. Swimming and speed skating are prime examples where an athlete works against forces from the environment such as the resistance of the water, air, and ice. Energy is used to overcome these resistive forces. If the magnitudes of these external resistive forces can be reduced, the amount of energy that is lost combating these forces can be decreased. The net result is that an athlete can perform a given task while expending less energy or use the saved energy to enhance performance. The following paragraphs discuss possibilities to reduce the expenditure of unnecessary energy.

**Friction**

Friction forces occur when two contacting surfaces slide with respect to each other. The frictional force is called a *static friction force* if the two objects are not moving with respect to each other. The frictional force that exists between two objects is directly proportional to the normal force between the two objects.

The simplest mathematical description of frictional behavior is Coulomb friction. Coulomb friction assumes that the frictional behavior of the two contacting objects is independent of contact area and relative velocity of the two surfaces. Coulomb friction will be assumed for the following examples. However, one should be aware that this is a simplification of many real athletic situations.

For the dynamic case, the friction force is determined by

\[
\mu_{\text{dyn}} = \frac{F_{\text{tan}}}{N}
\]

where

- \(\mu_{\text{dyn}}\) = dynamic friction coefficient,
- \(F_{\text{tan}}\) = frictional force tangential to the two contacting surfaces, and
- \(N\) = normal force.
For the static case, the friction force is determined by

$$\mu_{stat} \leq \frac{F_{tan}}{N}$$

4.4

where

- $\mu_{stat}$ = static friction coefficient,
- $F_{tan}$ = frictional force tangential to the two contacting surfaces, and
- $N$ = normal force.

For objects where the shape of the two contacting surfaces does not change (e.g., two hard surfaces), the friction coefficient should not depend on the mass of the two objects. A reduction in mass will reduce the absolute friction force but the relative magnitude stays the same.

If the two objects are not moving with respect to each other, the force of friction is equal to or less than the product of the static friction coefficient and the normal force. For example, if a force less than $\mu_{stat} \cdot N$ is applied to the object, the object will not move. In this case, the opposing friction force will be equal to the force applied. Once the applied force exceeds the product of the static friction coefficient and the normal force, the objects will begin to move with respect to one another. At the instant the object begins to move, the friction force will decrease slightly. Thus, the dynamic friction coefficient is smaller than the static friction coefficient. Therefore, the force that is required to overcome friction and initiate movement is greater than the force that is required to sustain movement.

The absolute magnitude of the frictional force is directly proportional to both the normal force and the coefficient of friction. Thus, the frictional resistance can be reduced by reducing either the normal force or the coefficient of friction. For most athletic activities, the normal forces are dictated, as they depend on the movement being performed. Therefore, attempts to reduce the frictional resistance during athletics have concentrated on reducing the friction coefficient associated with different equipment. Typical friction coefficients for different athletic equipment are shown in table 4.3.

Friction coefficients between ice and skate blades have been reported to lie between 0.003 and 0.007 (de Koning, de Groot, and van Ingen Schenau 1992; Jobse et al. 1990; Kobayashi 1973). These values are dependent on the ice conditions, especially ice temperature, as well as the material and structure of the skate blades. If a normal force during speed skating of 700 N is assumed (approximately the weight of a skater with a mass of 70 kg), the force due to friction is between 2.1 and 4.9 N. Therefore, the energy lost due to friction during a 500 m sprint is approximately 1050 to 2450 J. It has been estimated that the energy expended by a skater during a 500 m sprint is approximately 16,500 J (van Ingen Schenau, de Boer, and de Groot 1989). Therefore, energy lost to ice friction accounts for approximately 6 to 15% of the total energy generated by the athlete. Consequently, skates with a friction coefficient of 0.003 rather than 0.007 will provide a major advantage to an athlete. In fact, reducing the coefficient of friction by just 0.001 will reduce the amount of energy the athlete requires by 2%.

Ice friction is also extremely important in bobsledging. Differences in the sled runners such as shape and material and differences in the track such as slope, temperature, and ice composition have a dramatic effect on the friction forces. Through advances in these variables, the ice friction force for a

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Surface</th>
<th>Friction coefficient</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skates</td>
<td>Ice</td>
<td>0.003-0.007</td>
<td>Jobse et al. 1990</td>
</tr>
<tr>
<td>Bobsled runners</td>
<td>Ice</td>
<td>0.01-0.05</td>
<td>van Valkenburg 1988</td>
</tr>
<tr>
<td>Skis</td>
<td>Snow</td>
<td>0.05-0.20</td>
<td>Frederick and Street 1988</td>
</tr>
<tr>
<td>Tennis balls</td>
<td>Wood, Artificial surfaces</td>
<td>0.25, 0.50-0.60</td>
<td>Brody 1984, 1984</td>
</tr>
<tr>
<td>Tennis shoes</td>
<td>Artificial grass</td>
<td>1.3-1.8</td>
<td>Nigg 1986</td>
</tr>
<tr>
<td>Basketball shoes</td>
<td>Wooden floor, Wooden floor (dusty)</td>
<td>1.0-1.2, 0.3-0.6</td>
<td>Valiant 1994, 1994</td>
</tr>
<tr>
<td>Cleated shoes</td>
<td>Astroturf</td>
<td>1.2-1.7</td>
<td>Valiant et al. 1985</td>
</tr>
</tbody>
</table>
standard bobsled run averages about 1.5 to 5% of the normal force (Van Valkenburgh 1988). Similar to speed skating, small changes in the friction forces can have a dramatic influence on reducing the energy lost to the environment and ultimately on performance.

The friction between snow and a gliding ski is the most important mechanical factor limiting performance in cross-country skiing (Frederick and Street 1988). Snow friction depends on the characteristics of the snow, the characteristics of the ski, and the preparation (waxing) of the skis. The coefficient of friction between ski and snow varies between 0.05 and 0.2. Frederick and Street (1988) found that the characteristics of the skis had a larger influence than the ski preparation on friction between the ski and the snow. Stiff skis glided better on hard snow because more pressure was distributed to the tips and tails. Conversely, more flexible skis glided better on softer snow due to a more even pressure profile. They estimated that ski design and waxing could influence performance by about 8 to 10%, which corresponds to about eight minutes in a 30 km cross-country race. Friction between ski and snow also plays an important role in alpine skiing. A reduction in the snow-ski friction will result in higher speeds and shorter times for races.

Friction is also intrinsic in various other sport equipment. Friction in the bearings of in-line skates is a limiting factor in achieving top speeds during in-line skating. The higher the friction in the bearings, the greater the resistance to rolling, the harder the athlete has to work to achieve the same speed. Similarly, friction exists in bicycle chains and gears. The friction force in bicycle chains and gears can account for up to 5% of the force required to propel the bicycle and rider (Faria and Cavanagh 1978). However, of greater importance in cycling is the energy that can be conserved if drag forces are reduced.

**Drag**

Any object passing through a viscous medium experiences a resistive force opposite to the direction of motion. This resistive force is known as a *drag force* or simply as *drag*. Air and water are the two most common viscous mediums that athletes encounter. Swimmers spend energy to travel through the water due to the drag of the water. Similarly, runners, speed skaters, skiers, and cyclists must work against air resistance.

There are two main aspects when considering drag forces associated with athletic equipment and athletic activities: viscous or friction drag and pressure drag.

*Viscous or friction drag* results from surface friction between the medium, such as air or water, and the athlete or athletic equipment. Viscous drag depends on the surface properties of the material over which the medium moves.

*Pressure drag* results from the pressure in front of a moving object being greater than the pressure behind the object. Pressure drag depends on the projected surface area of the object.

Mathematically, friction drag and pressure drag are combined to determine the overall drag force, which is described by

\[
F_d = \frac{1}{2} \rho v^2 A C_d
\]

where

- \( F_d \) = drag force,
- \( \rho \) = density of the medium,
- \( v \) = speed of the object,
- \( A \) = frontal area of the object, and
- \( C_d \) = drag coefficient.

Pressure drag is represented by the first part of the equation, \( \frac{1}{2} \rho v^2 A \). The drag coefficient, \( C_d \), is included in the equation to account for friction drag.

Air density can change depending on the height above sea level. Through theoretical modeling, Ward-Smith (1985) estimated that a 100 m sprint run at Mexico City would be 0.2 s faster than an identical sprint at sea level due to the lower air density at altitude. Water density can change depending on the mineral content of the water. For example, salt water is denser than fresh water. However, the density of air or water is predetermined for any athletic competition. Thus, an athlete can reduce the drag during a competition by decreasing the velocity, the frontal area, or the drag coefficient.

The largest influence in reducing the drag coefficient is achieved by decreasing the velocity (see figure 4.4). It is obvious from equation 4.5 that if the velocity is zero, the drag force is zero and that the drag force increases with the square of the velocity. Most athletic competitions, however, require the velocity to be maximized. Therefore, reducing the velocity is generally not a useful method of reducing drag. However, it has been shown that the work required to overcome drag can be reduced by reducing fluctuations in velocity (Nigg 1983, 1984). The theoretical models used in these studies on swimming and rowing showed that the least amount of...
Drag force

![Drag force chart](image)

Figure 4.4 Drag forces associated with three sports as a function of the speeds obtained in the different sports.

energy was required when the velocity was constant. For rowing, changes in velocity of the boat occur due to the forward and backward movement of the rower on the sliding seat. The model predicted that changes in velocity of 15 to 25% would lead to an increase of 3 to 10% in the work required by the rower.

Numerous athletic activities involve high speeds where the friction coefficient of apparel can have a large influence on the drag forces. Downhill and cross-country skiing, ski jumping, speed skating, swimming, cycling, bobsled, and luge events are all activities where apparel design can have a substantial influence on performance. High performance athletes in these sports wear tight fitting neoprene or spandex suits to minimize the drag coefficient. Wind tunnel tests on current cross-country suits have shown reductions in drag forces of 6 to 10% in comparison to traditional wool suits and caps (Frederick and Street 1988). Similar tests have shown speed-skating suits to be 2 to 3% faster than traditional woolen suits at high velocities (van Ingen Schenau 1982). However, the woolen suit was faster than the tight suit at velocities below 6 or 7 m/s. The fact that the wool suit was faster at lower velocities than the neoprene or spandex suit is related to the drag resistance for laminar and turbulent flow.

Laminar flow is classified as regular flow where individual fluid particles follow paths that do not cross those of neighboring particles (Massey 1968). Turbulent flow is irregular flow characterized by intermingling fluid particles. For nonstreamlined bodies, laminar flow is associated with larger aerodynamic drag forces than turbulent flow. Thus, the wool suit worn while speed skating reinforces the turbulent flow at lower velocities, resulting in lower drag forces at these low speeds. Introducing turbulent flow by means of small anomalies on athletic suits has been proposed as a possible means of further reducing the drag coefficient (van Ingen Schenau, de Boer, and de Groot 1989; van Valkenburgh 1988).

Apparel for downhill skiing has been closely regulated for safety reasons. As a result, current suits actually have about 5% higher drag than the first stretch suits introduced about 30 years ago (Holden 1988). The original neoprene suits were hazardous due to the extremely low friction coefficient on snow. If a skier fell, he or she would actually accelerate rather than decelerate in the fallen position. Current suits have placed the neoprene on the inside of the suit and are required to have a minimum porosity to allow the body to breathe. The required porosity has led to the increase in drag forces.

Overcoming drag has been estimated to account for 4 to 8% of the total energy cost of running, depending on the running speed (Davies 1980; Pugh 1970). Due to the higher speeds, drag has been estimated to account for 8 to 13% of the total energy cost of sprinting (Davies 1980; Frohlich 1985; Pugh 1971). Although the specific influence of athletic apparel on drag forces during running has not been addressed, apparel design will have an influence on the drag coefficient. Again due to the larger velocities, apparel will have a larger influence on drag during the sprinting events. Recently sprinters have moved toward a one-piece tracksuit, which minimizes friction drag.

In addition to apparel, other athletic equipment has been modified to decrease drag coefficients. The dimples in a golf ball are essential in reducing drag of the ball, allowing the ball to be hit for distances that cannot be obtained with smooth balls. The layer of air that is in contact with the ball is known as the boundary layer. The boundary layer can be classified as either laminar or turbulent flow. If the air in the boundary layer travels in streams parallel to one another, the flow is laminar. If the air in the boundary layer is not in parallel streams (e.g., random, swirling, and crossing paths), the flow is turbulent. As the air flows around the ball, it eventually separates from the boundary layer causing a turbulent region behind the ball (see figure 4.5a). The drag coefficient depends on the location where this separation occurs. The earlier the separation occurs, the larger the drag coefficient. The dimples in golf balls are designed to produce a turbulent boundary layer, which results in separation of the layers occurring farther back on the ball (see figure 4.5a). The final effect is that the drag coefficient is reduced substantially by using a dimpled golf ball.
Reductions in the drag coefficient of bicycles by nearly 50% can be obtained with solid wheels and aerodynamic frames (Pons and Vaughan 1988). Smooth hulls are essential in reducing drag coefficients during rowing, sailing, and windsurfing. Recent bobsled research using wind tunnels has led to a reduction in the drag forces by about 40% (van Valkenburg 1988). Changes in driver and rider positions, helmet configurations, overall shape modifications, and external fairings have led to these substantial reductions of drag forces and improvements of performance. Similar to the dimples in golf balls, fairings delay the separation point of the boundary layer from the air flow, thus reducing the drag (see figure 4.5b). Fairings have also been proposed to reduce drag on luge sleds. Regulations in downhill skiing and ski jumping prevent the use of fairings at the back of ski helmets.

Frontal area and pressure drag are typically influenced more by body position than by athletic equipment. A downhill skier can decrease the drag force by a factor of approximately four by assuming a low tuck versus a standing position (Holden 1988). A speed skater who keeps the upper body horizontal can have a 20% lower drag force than a skater who has an inclined trunk (van Ingen Schenau, de Boer, and de Groot 1989). Cyclists in a fully crouched position reduce their drag forces by about 30% from an upright posture (Faria and Cavanagh 1978).

There are some instances where reductions in area of athletic equipment have been applied in an attempt to reduce overall drag. Streamlined ski poles and a decrease in the frontal area of ski tips have been used in cross-country and alpine skiing. Streamlining and reducing the projected frontal area of the bobsled and luge have also been attempted.

Mass and Inertia

Mass is defined as the amount of matter in a body that causes it to have weight in a gravitational field and can be thought of as a measure of a body’s resistance to translational acceleration. The moment of inertia is a quantity that describes the distribution of mass within a body and can be thought of as a measure of a body’s resistance to rotational acceleration. The greater the mass or inertia of a piece of equipment, the more energy is required to accelerate the equipment. Conversely, the smaller the mass or inertia, the less energy lost in accelerating the piece of equipment. Any sport requiring equipment to be accelerated or decelerated tends to benefit...
from a reduction in mass and moment of inertia of the equipment.

**Question**

Given the same exerted force, compare the kinetic energy of two pieces of equipment with different mass. Assume the following:

- General: \( F = 100 \text{ N} \); \( t = 2 \text{ s} \).
- Equipment A: \( m_A = 10 \text{ kg} \).
- Equipment B: \( m_B = 20 \text{ kg} \).

**Solution**

For equipment A (lighter),

\[
\begin{align*}
F &= m_A \cdot a. \text{ Thus,} \\
a &= 10 \text{ m/s}^2. \\
v &= a \cdot t = 10 \text{ m/s} \cdot 2 \text{ s} = 20 \text{ m/s}. \\
E_i &= \frac{1}{2} m v^2. \\
\text{Substituting,} \\
E_i &= \frac{1}{2} \cdot 10 \text{ kg} \cdot (20 \text{ m/s})^2, \text{ and} \\
E_i &= 2,000 \text{ J}. \\
\end{align*}
\]

For equipment B (heavier),

\[
\begin{align*}
F &= m_B \cdot a. \text{ Thus,} \\
a &= 5 \text{ m/s}^2. \\
v &= a \cdot t = 5 \text{ m/s}^2 \cdot 2 \text{ s} = 10 \text{ m/s}. \\
E_i &= \frac{1}{2} m v^2. \\
\text{Substituting,} \\
E_i &= \frac{1}{2} \cdot 20 \text{ kg} \cdot (10 \text{ m/s})^2, \text{ and} \\
E_i &= 1,000 \text{ J}. \\
\end{align*}
\]

**Comments**

Under the influence of the same force, the heavier piece of equipment will have half the velocity of the lighter piece of equipment. As a result, the lighter piece of equipment will have twice the kinetic energy of the heavier piece of equipment. Thus, the lighter the equipment the easier it can be accelerated, which leads to higher velocities obtained.

During batting, baseball players who are not strong enough to sufficiently accelerate the bat will "choke up" on the bat. They will move their hands away from the extreme end of the bat and hold the bat farther up the handle. By doing this, they have effectively reduced the moment of inertia of the bat with respect to the axis of rotation, thus making it easier to accelerate. As a result they are able to obtain a higher bat velocity, allowing the possibility of transferring a larger amount of energy to the ball.

Materials such as fiberglass, aluminum, graphite, Kevlar, titanium, and ceramics have had a large influence on decreasing the mass of athletic equipment. Nordic skis, ski poles, bicycles, racquets, golf clubs, bats, boats, paddles, and skates have benefited from the reduced mass of the new materials. The reduction in mass of protective equipment used in contact sports like football and hockey also has a large influence on reducing the energy expenditure of an athlete.

**Energy Dissipation**

**in Materials at Impact**

When two objects impact one another energy is typically lost to heat. The two objects will have a relative velocity after the impact that is less than their relative velocity before the impact. The change in velocity is dependent on the amount of energy lost and is represented by the coefficient of restitution:

\[
e = \frac{v'_A - v'_B}{v_A - v_B}
\]

where
- \( e \) = coefficient of restitution,
- \( v_A \) = velocity of object A before impact,
- \( v_B \) = velocity of object B before impact,
- \( v'_A \) = velocity of object A after impact, and
- \( v'_B \) = velocity of object B after impact.

The contact of a tennis racquet with a tennis ball, a bat with a baseball, a shoe with a soccer ball, or a hand with a volleyball are examples where the coefficient of restitution plays an important role in reducing the energy lost at impact. The coefficient of restitution depends on the structure and materials of both the striking implement and the object being struck. The coefficient of restitution also depends on the impact velocity and temperature of the impacting ball. It has been shown that the coefficient of restitution decreases with increasing impact velocity (Chapman and Zuyderhoff 1986; Snowden and Dowell 1991) and increases with increasing ball temperature (Chapman and Zuyderhoff 1986; Hay 1978).

In the example of a bat and a baseball, the harder the bat, the higher the coefficient of restitution and the higher the amount of energy transferred to the
ball (House 1996). The result of the larger amount of energy transferred to the ball is a higher ball velocity. If an athlete uses a softer bat, the athlete would have to swing harder to achieve the same ball velocity. Thus, due to the energy lost between the ball and the bat, the athlete would have to expend more energy to achieve the same results. Bats constructed of metal, graphite, or ceramic materials are generally harder and have a higher coefficient of restitution than their wooden counterparts.

Studies into the rebound heights of tennis balls have determined that the coefficient of restitution increases from the initial value after about 800 impacts and tends to decrease after about 3200 impacts (Rand, Hyer, and Williams 1979). The most likely explanation for this increase is the wearing of the nap on the ball. Additionally, the coefficient of restitution of the tennis balls decreases with age even if the balls are not used.

The coefficient of restitution differs for balls used in different sports (see table 4.4) and is particularly important for sports involving inflatable balls. Energy requirements during volleyball, basketball, soccer, and rugby can be increased substantially if the balls are underinflated and the coefficient of restitution is too low.

**Stability**

Depending on the activity, athletes may expend large amounts of energy to stabilize their movements. For example, cross-country skiers expend energy to control and stabilize ankle joint movements to appropriately position their skis on the snow. Volleyball and basketball athletes use muscular contraction to stabilize the ankle joint during landing after a jump.

Whenever an athlete uses muscle activation to stabilize a movement, energy is lost. Therefore, if stability can be achieved by other methods, by use of athletic equipment, for example, the energy the athlete would normally expend to stabilize the movement could be conserved and maybe used to enhance performance. Cross-country ski boots use high-cut constructions to increase stability of the ankle joint. It is speculated that stiff high-cut cross-country boots reduce the amount of energy required by the athlete to stabilize the ankle joint. Similarly, basketball shoes are traditionally high-top shoes in order to provide support and stability at the ankle joint, especially during landing movements. Volleyball players commonly use ankle braces to protect their ankle joints during competition. The braces provide external support, which helps reduce the incidence of ankle injuries, but also reduces the stabilizing influence required by the muscles crossing the ankle joint.

**Vibrations**

The human body is a composition of rigid and nonrigid structures. The rigid structures include primarily bones. The nonrigid structures include muscles, fat, heart, kidney, and others. The nonrigid structures are attached to the rigid structures through connective tissue. Impact forces excite the soft tissues, producing vibrations of the soft tissue relative to the underlying rigid structures. Exposure to long-term or high-energy vibrations often results in subjective discomfort, reduction of performance in the work place, and pathological changes to the nervous and vascular systems (Sakakibara 1994).

External body locations and internal organs have a resonance effect around 4 Hz. The upper extremities show resonance effects at about 10 to 20 Hz (Dupius and Jansen 1981). However, these frequencies (4 to 20 Hz) are right in the frequency range of

<table>
<thead>
<tr>
<th>Type of ball</th>
<th>Type of surface</th>
<th>Coefficient of restitution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf</td>
<td>Floor</td>
<td>0.83–0.89</td>
<td>Snowden and Dowell 1991</td>
</tr>
<tr>
<td>Tennis</td>
<td>Racquet</td>
<td>0.76–0.88</td>
<td>Hatze 1993</td>
</tr>
<tr>
<td>Racquet</td>
<td>Floor</td>
<td>0.74–0.88</td>
<td>Snowden and Dowell 1991</td>
</tr>
<tr>
<td>Hand</td>
<td>Floor</td>
<td>0.72–0.85</td>
<td>Snowden and Dowell 1991</td>
</tr>
<tr>
<td>Rugby</td>
<td>Floor</td>
<td>0.77–0.81</td>
<td>Gallagher and Cooke 1998</td>
</tr>
<tr>
<td>Soccer</td>
<td>Floor</td>
<td>0.69–0.80</td>
<td>Snowden and Dowell 1991</td>
</tr>
<tr>
<td>Squash</td>
<td>Plywood</td>
<td>0.48–0.60</td>
<td>Chapman and Zuyderhoff 1986</td>
</tr>
</tbody>
</table>
impact forces during landing in sport activities. The musculoskeletal system must activate the muscles accordingly to minimize excessive vibrations at these frequencies. The additional muscle activation, however, costs work. The additional work depends on both the magnitude and frequency of the induced vibrations.

Athletic footwear is one area of equipment that can have an influence on the vibrations transferred to the human body. A recent theoretical model (Nigg and Anton 1995) predicted that viscous materials implemented in a shoe should reduce the work requirements during locomotion. It was speculated that the reduction of work was a result of the damping of the lower extremity vibrations by the viscous material. Results of a recent experimental investigation where oxygen consumption was measured on subjects running in shoes with and without a viscous midsole tend to support the theoretical predictions (Stefanyshyn and Nigg 1998).

Striking implements such as baseball bats, golf clubs, and tennis racquets are prone to vibrations after impact with the ball. The frequency and amplitude of the vibrations depend on two factors. The first is the manner in which the equipment is held; for example, the amplitude of the vibrations depends on the grip pressure (Hatze 1976). The second is the construction of the implement. For example, one way to reduce the vibrations of a tennis racquet (or any striking implement) is to ensure that the ball contacts the center of percussion of the racquet (Elliot, Blanksby, and Ellis 1980). The center of percussion is the point at which a striking implement impacts an object without causing an unbalanced reaction force at the pivot point, which, for most striking implements, is the point where the implement is being grasped by the hands. Athletes will often refer to the center of percussion as the sweet spot. If the ball contacts the implement at a point other than the sweet spot an athlete will feel the vibrations, which may sting the athlete’s hands. Additionally, the ultimate performance is compromised because part of the kinetic energy of the implement is lost.

Manufacturers of striking implements have tried to optimize the location of the center of percussion. Conventional tennis racquets did not have the center of percussion in the geometric center of the strings (Brody 1979). By modifying the shape of the racquet head and distributing the weight appropriately to the perimeter of the racquet, manufacturers have been successful in repositioning the center of percussion in the geometric center of the racquet head. Perimeter weighting has also been used successfully in golf clubs to enlarge the sweet spot. It has been indicated that the sweet spot of an aluminum bat is larger than that of a wooden bat (Bryant et al. 1977).

**Additional Situations With an Unnecessary Loss of Energy**

During sprinting, an athlete lands on the ball of the foot. Immediately after impact, the rear of the foot rotates backward toward the track. One may argue that this rotation is counterproductive for the sprinting movement as the athlete loses energy when the leg moves down and has to perform work to lift the heel and the leg up again. Several years ago a spiked shoe was introduced where a wedge was placed under the midfoot to prevent the heel from rotating backward (see figure 4.6). It was speculated that the energy is not lost with this construction and that no additional work needs to be performed. These shoes were used for some exceptional sprinting times. However, it has never been shown experimentally that this wedge was responsible for the excellent sprinting results.

The metatarsophalangeal joint absorbs large amounts of energy as athletes roll onto the ball of the foot during running and jumping movements (Stefanyshyn and Nigg 1997). However, very little energy is produced during takeoff since this joint is only minimally extended. Therefore, energy is dissipated and lost during the bending of the joint in the shoe and foot structures. Improvements in shoe design that reduce the initial bending of the metatarsophalangeal joint may have an influence in reducing the amount of energy the athlete loses at this joint.

![Figure 4.6](image_url)

Figure 4.6 Schematic illustration of a theoretical concept to prevent energy loss during sprinting. The wedge placed under the midfoot is to prevent the loss of energy due to the foot rotating backward during ground contact.
Situations Where a Loss of Energy is Advantageous

In some athletic activities, energy loss is a required component of the activity. For example, braking or stopping is essential for control in some sports (e.g., cycling, skating, and skiing). Braking is nothing more than the dissipation of kinetic energy to thermal energy or heat. For most of this chapter, this transfer to thermal energy has been equated to a loss of energy because the energy did not serve a beneficial purpose to the athlete. Thus, although a major goal of athletic equipment is to minimize the loss of energy, there are certain circumstances where athletic equipment is specifically designed to lose energy.

Summary

Over the past 20 to 30 years, sport scientists and sport equipment manufacturers have investigated ways of improving athletic equipment to make sport safer and to enhance performance. The result is equipment that is stronger, lighter, more durable, and more pleasant to use. Consequently, sport performances are faster, higher, longer, and more accurate than they used to be. In fact, every world record in sport that was set before 1980 has been broken (Begley and Rogers 1996), an indication of the recent developments in athletic ability and improvements in athletic equipment.

Two of the main principles that have led to the improvements in equipment are

- the increase in the return of conservative energy and
- the reduction of the loss of nonconservative energy.

Energy return refers to the storage and re-use of elastic strain energy. The amount of energy that can be stored by a piece of athletic equipment depends on the stiffness and the deformation of the equipment. Deformation is the more important variable since energy storage increases linearly with increasing stiffness and quadratically with increasing deformation. In general, a system must fulfill several conditions to return energy. It must be able to return the energy at the right time with the right frequency at the right location. Return of energy to improve athletic performance has been studied for different equipment such as trampolines, diving boards, vaulting poles, sport surfaces, and sport shoes.

By reducing the amount of energy lost, an athlete can perform a given task while doing less work. The end result is that the athlete has an additional work capacity to apply toward improving performance. Energy applications in equipment for aspects that are related to an improvement of performance include energy loss due to friction, drag, mass and inertia, and dissipation in materials, stabilization, and vibrations. Reduction of the loss of energy has been studied for equipment such as athletic apparel, skis, balls, skates, and bicycles.

References


Stefanyshyn, D.J., and Nigg, B.M. 1998. The influence of viscoelastic midsole components on the biomechanics
of running. *Abstracts of the Third World Congress of Biomechanics*, 379.