By now, you should have completed the introductory unit of this course. It is now time to get started on the actual course content. Unit 1 is presented as an introductory unit to exercise physiology. In this unit, you will complete two lessons and one lab. The lab is associated with the second lesson of this unit. The information in this first unit is very basic to the study and understanding of exercise physiology.

Lesson 1 attempts to define exercise physiology and put it into perspective in relation to other branches of science. You should read Chapter 1 of the text to gain an understanding of the history and concepts of exercise physiology. This chapter will give you a perspective on exercise physiology as a defined discipline, especially the historical perspective, and introduce you to terms that will be used throughout the course.

Lesson 2 starts the "meatier" material, addressing work, power, energy and related concepts. The material covered in Lesson 2 is absolutely fundamental, and basic to almost everything studied in exercise physiology. Chapter 6 in the textbook deals with the topics in Lesson 2. Lab 1 is designed to expand on and give practice with concepts addressed in Lesson 2.

Specific learning objectives are listed at the beginning of each lesson and the lab. These objectives should guide your understanding of the material. If you have difficulties with a concept or idea, you should refer to one of your sources of information for clarification.
studying as you strive to master the material. An outline of each lesson’s content is also presented at the beginning of each lesson. These outlines are also presented below, to help you see the Unit as a whole.

### Outline of Content

**Lesson 1 – Introduction to Exercise Physiology**

I. Definition and description of *exercise physiology*

A. What is *physiology*?
B. What is *exercise*?

II. Types of exercise

A. Modes or devices
B. Primary demand or stress
   1. Strength
   2. Power
   3. Endurance

III. Principles of training

A. Principle of Overload
B. Principle of Specificity
C. Principle of Reversibility
D. Principle of Optimization

**Lesson 2 – Work, Power and Energy; Efficiency and Economy**

I. Exercise as work

II. Energy

III. Power

IV. Mechanical efficiency

V. Economy of movement

Lab 1 - Work, Power, Efficiency and Economy
Please proceed to Unit 1 – Lesson 1.

This lesson defines *exercise physiology* and puts it into perspective in relation to other branches of science -- to begin to describe the boundaries of what is included and what is not included in this exercise science. Also, some fundamental concepts are addressed in this lesson, such as the major types of exercise stresses, and the primary training principles. Most of the concepts introduced in this lesson will be covered in more detail in later lessons. Nothing in Lesson 1 is very "deep," so wade in and start to get used to the waters of exercise physiology.

**Assignments**

1. Read Chapter 1 of the text.

2. Study and master the content presented online.

3. Check the course Announcement Page for other possible assignments.

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- Learning Objectives

After completion of this lesson, you should be able to:

1. Describe what is meant by and included in the discipline of exercise physiology. Include in this description reference to anatomy, normal vs. abnormal function, and pathology.

2. State 10 specific examples of exercise, including five examples from competitive athletics and five examples that are not directly related to competitive athletics. For each of these examples, as well as other examples that may be presented, discuss what makes it "exercise" and the relative demands of strength, power and endurance. Include the concepts of absolute intensity and relative intensity.

3. Write definitions of acute exercise and chronic exercise, and illustrate each of these concepts with at least three examples.

4. Write a definition of physiological mechanism.

5. State four principles of training; for each, list two exercise examples that involve application of the principle and briefly discuss each example to clarify the application of the principle.

6. Write a definition of overtraining and briefly discuss a real or hypothetical example of overtraining.

- Outline of Content

I. Definition and description of exercise physiology
   
   A. What is physiology?
   
   B. What is exercise?

II. Types of exercise
   
   A. Modes or devices
   
   B. Primary demand or stress
      
      1. Strength
      
      2. Power
      
      3. Endurance
III. Principles of training

A. Principle of Overload

B. Principle of Specificity

C. Principle of Reversibility

D. Principle of Optimization

Definition and Description of Exercise Physiology

What is exercise physiology, or the physiology of exercise?

Let's start with the physiology part. Physiology and anatomy are two closely related branches of biology. Biology is the study of living organisms. Anatomy is the study of the structure of living organisms.

Physiology is the study of the function of living organisms.

It is impossible to study either anatomy or physiology completely separately from the other. For example, we will study the function of the heart in this course. It simply is not possible to study cardiac function, dealing with variables such as left ventricular stroke volume, without at least a basic knowledge of the heart's structure. Nevertheless, physiology emphasizes function – function of tissues, organs, and organ systems, as well as function of the entire organism, the body.

Definition and Description of Exercise Physiology: Normal and Abnormal Responses

Another aspect of physiology is that it deals with normal function, unaffected by disease. Pathology is the branch of biology that deals with study of structure and function related to diseases. Sometimes the term pathophysiology is used to specifically refer to the study of function related to disease. Just as one cannot study physiology without at least some reference to anatomy, one cannot study physiology without some reference to pathophysiology.
An important distinction must be made between the concepts of *abnormal* and *diseased*. Abnormal simply means "different from the average or typical." It does not necessarily mean there is underlying disease. To use a very simple example, if we know that heart rate increases from the resting value when we start to exercise, we then also know that if heart rate does not increase when a person exercises, this is an abnormal response. For a better example:

Suppose we have measured the heart rate of 1,000 people engaged in an aerobics class and found their heart rate values ranged between 120 and 170 beats per minute. Then, suppose we test a new individual engaged in the same exercise and found that his/her heart rate is 115 (or 180) beats per minute. We would correctly conclude that this person's response is abnormal compared to the group previously measured. In other words, the individual's heart rate response is different from the normal or usual responses measured in the group of 1,000 people. The response could be due to underlying disease (i.e., pathology), but NOT necessarily. It could just be an extremely unusual response.

To complicate matters a little more, just because a person has a certain disease doesn't mean he/she will have an abnormal response to exercise, or at least an abnormal response that is obvious. A common example of this is the person with narrowing of the coronary arteries (i.e., the blood vessels that supply the heart muscle with blood) who has an apparently normal response of heart rate, blood pressure, and other variables when exercising.

- **Definition and Description of Exercise Physiology: Intensity Issues**

In this course we will emphasize physiology (normal function apart from disease) rather than pathology. Nevertheless, we will also discuss abnormal function from time to time, including pathology. It is certainly important, and sometimes critical, that the physical education teacher and coach can distinguish between normal and abnormal responses of the body to exercise.

Now let's deal with the *exercise* part of *exercise physiology*.

Many times, P.E. teachers and coaches relate sports activities to exercise. Sure, running a 100-m sprint or a marathon is considered exercise. Playing in a football, basketball, or volleyball game is exercise. Working out with weights at the gym or at home is exercise. These are obvious examples, and important ones. Much of exercise physiology applies to such
However, exercise physiology is not merely a sports related science. Exercise physiology is also concerned with those activities that physical education teachers and coaches may not think about, but that are very important to the general population. Examples of other activities include: job-related physical activity (lifting loads, moving objects, walking and standing for eight hours, etc.), activities of daily living (doing laundry, mowing the lawn, cleaning house, cooking dinner, etc.), and rehabilitation of patients, such as following a stroke or heart attack. In all of these non-sport-related activities, exercise is involved. When we discuss exercise, we generally discuss it in terms of intensity and duration. You know, how hard was the work-out (intensity) and how long did it last (duration).

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**Definition and Description of Exercise Physiology (cont.)**

The intensity of the exercise may be very high such as lifting heavy loads for an eight-hour shift on the job, or it could be considered extremely low for an athlete such as, learning to walk again after a stroke or accident.

A word of caution here: The relative intensity of exercise depends on the person’s fitness related to the activity. **Relative intensity** is the intensity of exercise as a percentage of the person’s maximum capacity. In contrast, **absolute intensity** refers to the specific intensity regardless of the person’s maximum capacity. For example, If I were to ask each of you to curl a 50-pound barbell, the absolute intensity for everyone who lifts the weight is 50 pounds. But it may be a major challenge for some of you, especially if your maximum capacity to curl is 50 pounds. So, when we discuss relative intensities, we will discuss them in terms of percentage of maximum capacity.

An example of relative intensity:

Suppose we have two individuals lifting in a bench press competition. We know that individual 1 has a 1 RM of 100 pounds for the bench press and individual 2 has a 1 RM of 200 pounds for the bench press. ("RM" stands for "repetition maximum"; 1-RM refers to the load that can be lifted only one time.) We now ask each to bench press 75 pounds. The absolute intensity of the exercise is 75 pounds, but the relative intensity for individual 1 is 75% of his maximum capacity (75/100) and 38% (75/200) of individual 2’s maximum capacity. Therefore, in relative terms, individual 1 is exercising at a higher percentage of his maximum capacity than individual 2.
at a higher percentage of the maximum capacity compared to individual 2.

- **Definition and Description of Exercise Physiology (cont.)**

The duration of the exercise may be very long (e.g., working a double shift in a job involving manual labor) or very short (e.g., lifting bags of groceries out of the trunk and carrying them into the house; walking down the hall and back for the first time after coronary bypass surgery).

The exercise may be repeated day after day or even several times a day (e.g., letting the dog out of the house and taking it for a walk), or it may occur infrequently (e.g., changing a flat tire). In all cases the body must adjust to the demands placed on it by the exercise. If the body does not adjust appropriately, the person may be unable to do the exercise, may be unable to perform the task as needed, may be injured, or may even die!

In summary, the exercise physiologist must have a very broad view of what exercise is.

From the physiological perspective, it is useful to think about what the essential factor is that makes something exercise. I think it is contractions of skeletal muscles. Skeletal muscles exert force to (a) cause movement of the body or a body segment (e.g., lifting a weight, running, swinging a bat), (b) resist movement (e.g., lowering a weight, absorbing a hit in football, catching an object), or (c) prevent movement (e.g., holding the iron cross position on the rings in gymnastics, holding a football lineman's stance until the ball is snapped). It is the muscle contractions that do the activity we call exercise; without muscle contractions we don't do any exercise. Muscle contractions are fundamental. Then, a lot of other things have to happen in the body to support the muscular activity: adjustments of the heart's function, circulation of the blood, lung function, etc.
Definition and Description of Exercise Physiology (cont.)

Exercise may be acute or chronic.

**Acute exercise** is a single bout of exercise: jogging for 20 minutes, lifting weights for an hour, playing a tennis match, changing a tire, mowing the lawn, etc.

**Chronic exercise** is exercise that is repeated over days, weeks, months and sometimes years. What we commonly refer to as training or conditioning programs are examples of chronic exercise.

To summarize, exercise physiology in the broadest sense is the study of how the body functions in response to any activity that involves skeletal muscle contractions.

Because the body is so complex, the responses of the body to acute and chronic exercise are also extremely complex. This is especially true if we would like to know the mechanisms that underlie the body’s responses.

**Mechanism** refers to the detailed explanation of a bodily response. For example, we will study the response of the body’s oxygen transport system to both acute and chronic exercise. We will see that with chronic endurance training the capacity of the oxygen transport system increases, that is, the body is able to use oxygen in energy metabolism at a higher maximal rate (often referred to as **aerobic capacity**, **maximal aerobic power**, or **VO2max**). Knowing that this response occurs is important, but the exercise physiologist would like to know what changes occur in the body to bring about this increase in oxygen transport capacity (i.e., the mechanism of this training effect). Scientists like to discover mechanisms simply to understand things better. But understanding mechanisms also often leads to better understanding of how things can be improved.

In this course we will study mechanisms to a certain extent. For example, we will study specific changes that occur in the heart’s function with months and years of endurance training that contribute to the increase in oxygen transport capacity. We will not be able to go into the really basic aspects of mechanisms, however, which are usually at the molecular level. In other words, ultimately changes in the organism (e.g., increased total-body **VO2max**) are caused by changes in...
Increased total-body VO\(_\text{2}\text{max}\)) are caused by changes in organs, which in turn are caused by changes in tissues, which in turn are caused by changes in cells, which in turn are caused by changes in molecules! Really thorough understanding of exercise physiology requires study and understanding of cell and molecular biology. This degree of detail is beyond the scope of this class, however. We will deal almost exclusively with physiology of the entire organism (i.e., the body) and systems within the organism. To try to organize the many responses of the body to exercise, I think it is helpful to picture the body as a factory. The product this factory produces is exercise, and the skeletal muscles are the machines that make the product. Lots of things must happen in a coordinated way if the factory is to be effective.

- Definition and Description of Exercise Physiology (cont.)

For one thing, the machines themselves must be the right machines for the job, able to produce the desired product. That is, skeletal muscles must be able to generate appropriate force and have the necessary endurance.

The machines must be provided with power or energy. Metabolic adaptations must take place to transform energy from ingested food or stored depots, and changes take place in the heart, circulation and blood to transport the things needed by the muscle machines to keep going (e.g., glucose, fatty acids, oxygen).

A factory also has to be concerned with removal of waste products, so the environment stays appropriate for the machines to be effective. During exercise, for example, the body has to make a number of adjustments to handle the increased levels of waste products (e.g., carbon dioxide, lactic acid, and heat).

Finally, quality control is essential. If the machines are not closely monitored and adjusted as needed, the factory’s product will be inferior. It is the responsibility primarily of the nervous and endocrine systems to control the skeletal muscle "machines" to be sure their output is precisely what is needed in the given exercise situation.

A big challenge in this course will be to see the big picture of the factory producing exercise of various types, intensities, durations, and frequencies, while at the same time seeing and understanding the individual components of the factory and how they work together.
- Types of Exercise

I want to overview several other very basic concepts and terms.

One of these has to do with categorizing the different types of exercise. There are at least two different ways the term "type of exercise" is used. One way is sometimes also referred to as the *mode of exercise*, and this means the specific exercise device (modality) used or task done. For example, I could design a training program to develop cardiorespiratory endurance fitness, and this program could be done on a treadmill, a bicycle ergometer, a rowing machine, or a stair-climber machine, or could use walking or jogging on a track. Each of these could be referred to as the type or mode of exercise. This is, of course, a very important part of prescribing exercise. Selecting the right mode for a given person in a given situation may be critical in terms of obtaining optimal benefits of training, in terms of safety and injury prevention, and in terms of what the person enjoys doing and what the person will actually do.

Very important in the study of exercise physiology is recognizing the type or category of exercise in terms of the primary demand or stress placed on the body. In this sense, there are three types of exercise: strength, power, and endurance.

**Strength** activities require high muscular force; they are necessarily of short duration, and power is not especially high.

We will study the specific meaning of *power* in exercise physiology in Lesson 2, but the important point related to analyzing the type of exercise is that *power* involves a combination of muscular force and speed. Activities involving the highest power involve rapid movements, but muscular forces are much less than maximal. High power activities are necessarily of short duration.

**Endurance** exercise requires continuation of the muscular activity for prolonged periods of time. Endurance is inversely related to muscular force and power. That is, the longer exercise must be continued, the lower the required muscular forces and especially power have to be.
- Types of Exercise (cont.)

Let me give a common example of each type of exercise.

Doing a **1-RM bench press** is a **strength exercise**. Obviously, high (maximal) muscular force is required. Even though force is high, the power is relatively low because the movement is relatively slow. And endurance is not a factor.

**Running 100 meters** in 9.79 sec (the world record as of May, 2000) is a **high power activity**. Muscular contractions are fast, but the muscular forces are not close to maximal. Again endurance is not a factor.

**Running a marathon** is clearly an **endurance activity**. The muscles involved in running do not generate high forces and they do not contract at particularly high speeds. But they must contract some 80 to 90 times per minute for at least 125 minutes (the world record in the marathon is 2:05:42), that is, at least 10,000 to 11,250 contractions during the race.

Note that this categorization of exercise activities emphasizes the **predominant** physiological demand or stress. In reality, most activities involve two or even all three of these demands, but in different proportions. Nevertheless, it is important to recognize the three basic types of physiological stress involved. These three types of exercise require very different adaptations by the body. Furthermore, the responses to training programs involving these three types of exercise are quite different. Therefore, it is very important to evaluate the involvement of strength, power, and endurance in an activity to be able to assess the requirement of each of these by the exerciser. (This is especially true in competitive athletics, in which optimal performance is the goal.) This in turn forms the basis for prescribing specific training to develop the performer. In this course, we will study physiological considerations related to these three categories of exercise.

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- Principles of Training

Other concepts that I want to introduce early in the course relate to so-called "principles of training." Various exercise physiologists list different principles. I want to emphasize four, and the first two are the most fundamental: (a) **Principle of Overload**, (b) **Principle of Specificity**, (c) **Principle of Reversibility**, (d) **Principle of Optimization**.

The **Principle of Overload** is that the body or a body system does not improve its ability to function unless it is overloaded,
that is, subjected to stress that is greater than it is regularly subjected to.

The concept is pretty straightforward: the weight-lifter must lift heavier and heavier weights to continue to gain in strength; the distance runner must run more miles per week (within limits; see Principle of Optimization) to improve distance running performance. In practice, however, it is not always easy to quantify overload appropriately.

- Principles of Training (cont.)

The Principle of Specificity is that training adaptations are very specific. And they are specific in two ways.

First, the adaptations occur only in the specific tissues of the body that are stressed (overloaded) during training. An obvious example: Training by lifting weights doing arm curls will increase strength of the elbow flexor muscles, but will have no effect on strength of the calf muscles. A less obvious example: If a person trains with the same submaximal arm curls in every workout, certain muscle fibers in the elbow flexor muscles may be active while some remain inactive, because not all fibers are needed to lift the submaximal loads. In this case, the active fibers will gain some training benefit but the inactive ones will gain little or none.

The second aspect of the Principle of Specificity is that the training adaptation is specific to the demand of the training exercise. If high muscular force is demanded during the training, the trained muscles will adapt specifically by becoming stronger. If training involves repeated muscle contractions over a prolonged period of time, the trained muscles will adapt specifically to have improved endurance.

Proper application of the Principle of Specificity is essential for the optimal physiological development of an athlete.

- Principles of Training (cont.)

The Principle of Reversibility is actually a corollary or the opposite of the Principle of Overload, but it deserves some emphasis. The Principle of Reversibility is that gains in function with training reverse and are lost when the training stimulus is too low ("underload").
All functional gains from training are reversible—they can be lost. The term "detraining" is sometimes used to refer to a period or program during which function deteriorates. One example involves the athlete who must be relatively inactive due to injury. Another all-too-common example is the typical resident of the United States who has a very sedentary job and does not exercise during leisure time. This person is chronically detraining (a couch potato is detraining)!

The Principle of Optimization is that there is a single training program that produces optimal gains in function and performance. To a certain extent, this principle is theoretical, since no one can know for sure what the absolutely best training program is for a given athlete in a given set of circumstances. Nevertheless, athletes, coaches and exercise physiologists constantly search for this program.

Perhaps one of the most important practical aspects of this principle is that there can be too much training, so-called overtraining. In other words, the total training load can be so great that performance actually deteriorates. This is a topic of great interest to elite athletes and their coaches, and there is quite a bit of research being done to try to identify indicators of overtraining.

- Review of Lesson

You have come to the end of the online content of Unit 1 - Lesson 1. When you want to review the concepts in this lesson, go back to the Learning Objectives listed on Page 2 of this lesson. These should be a good study guide. If you can correctly do what the Objectives ask, you will have mastered the most important concepts in Lesson 1. Please realize, however, that those Objectives do not exhaustively cover all the information in Lesson 1.

If you are uncertain about any Objective, or if you want clarification or expansion of any point in Lesson 1, I urge you to start a threaded conference discussion in the "BARN" on WebBoard. Other students may have the same concerns, will probably benefit from the discussion, and may have the information you seek. And, of course, feel free to contact me (Dr. Eldridge) for assistance.

Be sure to check the Announcements Page to see whether there is a specific WebBoard or other assignment.
- Introduction to Unit 1 - Lesson 2

This lesson gives the "first serving of the meat" of exercise physiology. The very basic concepts of work, power and energy, as well as related concepts, are presented. Mastering these concepts early will stand you in good stead for the rest of the course.

Assignments

1. Read, study and master the content presented online.

2. The textbook reading assignment is Chapter 6, "Measurement of Work, Power, and Energy Expenditure." You may also want to check key terms in the textbook index; sometimes topics are addressed in more than a single chapter.

3. Check the course Announcements Page for other possible assignments.

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- Learning Objectives

After completion of this lesson, the student should be able to:

1. Explain the relationship and draw a graph that depicts the relationship between rate of work and rate of energy required.

2. Write definitions of work and power, and illustrate each of these variables with examples of exercise activities.

3. Calculate work and power.
4. Write definitions of power input, power output, and mechanical efficiency, and explain the relationships among these variables.

5. Do calculations involving power input, power output and mechanical efficiency.

6. State limitations of the concept of physical work (as strictly defined) in exercise physiology.

7. Define energy; state examples of different types of energy and how each type can be converted to work.

8. Define economy of locomotion. Explain why economy is a more useful concept and measurement in many exercise situations, and explain the advantages a runner has who is more economical at a certain running speed.

9. Explain and give examples of a physiological steady state. Briefly explain why some argue that the body is never in a steady state.

10. List and briefly discuss factors that are associated with running economy.

11. Discuss the following: Can running economy be improved with training?

- Outline of Content of Lesson 2

   I. Exercise as Work
   II. Energy
   III. Power
   IV. Mechanical Efficiency
   V. Economy of Movement
## I. Exercise as Work

An important consideration in studying the physiology of exercise is the concept of exercise as work. In Chapter 6 of your text, work is calculated as:

\[
\text{Work} = \text{force} \times \text{distance}
\]

There are many examples in exercise and athletics when this definition is easily applied and useful. One example is the lifting of a weight. Imagine that while doing an arm curl, a person lifts a 25-pound dumbbell 2 feet (measured as a straight line from the starting position of the dumbbell to the ending position). The physical or external work done on the dumbbell is:

25 pounds (the force) \times 2 \text{ feet (the distance)} = 50 \text{ foot-pounds.}

In another example, imagine that an 80-kilogram person steps up on a step that is 0.5 meter in height. The purely external, physical work done in lifting the body vertically is: 80 kg (force) \times 0.5 \text{ m (distance)} = 40 \text{ kilogram-meters.}

**Note**: In Chapter 6, the authors discuss the use of SI units and Common Units. Strictly using SI units, the kilogram is a unit of mass and not weight or force; therefore, technically the kilogram-meter is not a unit of work. To be technically correct, the unit **kilopond** is often used instead of kilogram as a force unit, and **kilopond-meter** as a unit of work. Numerically the kilopond and the kilogram are equal. In this course, I will use the kilogram as a Common Unit, and equate it to a unit of force, since in practice we use kilograms as weight units, just as we do pounds, and weight is a force. It is not uncommon in exercise physiology to see kilogram-meters (kgm) and kilopond-meters (kpm) used interchangeably, even if this is technically incorrect.

Other examples of physical work will be dealt with in the Laboratory assignment.
- Exercise as Work (cont.)

Although any unit of force may be multiplied by any unit of distance to give work, the most common units in exercise physiology are: kilogram-meters (kgm) which are numerically the same as kilopond-meters (kpm), and Newton-meters (Nm) or joules (j). (See table 6.2 in your text for the appropriate use of these terms). Following are important mathematical conversions involved in changing from one unit of work to another.

1 kilogram (kg) = 2.205 pounds (lb); divide pounds by 2.205 to change to kilograms

1 inch (in) = 2.54 centimeters (cm); multiply inches by 0.0254 to change to meters

1 kilogram (kg) = 9.81 newtons (N); multiply kilograms by 9.81 to change to newtons

1 kilogram-meter (kgm) = 9.81 joules (j); multiply kilogram-meters by 9.81 to change to joules

Remember that any time during the course, you can go to Glossary and search for the word UNIT to find conversion factors.

Unfortunately, the calculation of external physical work as the force X distance product has significant shortcomings that limit its application in exercise physiology.

One limitation is that we often can't measure all forces and distances involved in external work, and therefore we can't measure work. In the simple example of lifting a dumbbell in an arm curl, the lifting of the forearm would have to be included to calculate the total work done. In a relatively simple movement of a running stride, the total body mass is lifted, but also individual body segments (i.e., arms, legs) are lifted with each stride. All of these movements would have to be accounted for to calculate total external work done. This is practically impossible.
- **Exercise as Work (cont.)**

  A *second limitation* of the physical definition of work (i.e., $F \times d$) has to do with negative work. Calculation of negative work is straightforward, but it does not translate easily in terms of physiological stress.

  Using the earlier example, if the person lifts the 25-LB dumbbell 2 feet, 50 ft-LB of positive work is done. When the person then lowers the dumbbell to the starting point (i.e., the weight moves in the direction opposite to the direction of the muscular force):

  $$\text{Work} = 25 \text{ LB} \times -2 \text{ ft} = -50 \text{ ft-LB}$$

  Considering the entire arm curl, +50 ft-LB of work was done in the lifting phase and -50 ft-LB in the lowering phase; when these are added to give total work: $(+50) + (-50) = 0 \text{ ft-LB}$; no net work was done!

  The same calculation applies with running around a track. The runner starts and stops at exactly the same place, so the amounts of positive and negative external work are the same and mathematically cancel out; no net work is done (even though the runner may be exhausted!). In reality, of course, a lot of work is done.

- **Exercise as Work (cont.)**

  A *third limitation* of the physical definition of work (i.e., $F \times d$) is its application to static or isometric exercise, in which there is no movement. In such a case the distance value in the equation is zero. So even if a lot of force is exerted, the force multiplied times zero equals zero work. Similar to the track runner above, a person could exert isometric tension until exhaustion but no external work would be done!

  Let me remind you that there are times when the strict definition and calculation of physical work as "$F \times d$" are useful
in exercise physiology. But because of the noted limitations, a more useful concept in exercise physiology is that of "physiological work." Simply, physiological work during exercise is any muscular activity that requires energy. Using this concept, the work calculated by the force-times-distance equation is referred to as external work or work output and the work that must be done by the body (principally by skeletal muscles) to do the external work is referred to as internal work. As already noted, external work may or may not be measurable. The same is true for internal work; sometimes it can be measured or estimated, and sometimes it cannot. We will study this more later.

II. Energy

A critical factor in exercise is energy. Every single muscle contraction requires energy that ultimately must come from the foods that we eat. A major difference between the sub-10-second 100-meter sprinter and the "slow" 10-second 100-meter sprinter is the rate at which each runner makes energy available in the key muscles. As with work, energy has a strict definition in physics: "the ability or capacity to do work." This definition may seem a little strange, but it implies two important things about energy:

(a) no work is done without energy; energy is involved in all work;

(b) energy and work are equivalent; in fact, they are absolutely the same if one has a perfect machine that doesn't waste any energy.

To expand on the latter point, you should note that units of work can be used as units of energy, and vice versa. Thus, we could talk about 100 kgm of energy, although we usually don't. It is more common in exercise physiology to use the kilocalorie as the unit of energy. But if we know work in kgm, we can convert to kilocalories by multiplying kilogram-meters by 0.0023 to get kilocalories (kcal).
Energy (cont.)

There are different forms of energy, including chemical, electrical, heat, kinetic, nuclear, potential, and radiant energy. Energy cannot be created or destroyed, but it can be changed (transformed) from one form to another (The First Law of Thermodynamics). A critical aspect of exercise physiology is the transformation of energy stored in chemical substances (i.e., chemical energy) to another form of energy, such as potential energy or kinetic energy. For example, energy from the substance ATP is used to "cock" the head of the muscle protein myosin (putting it in a high-energy state, like a stretched spring or the hammer on a revolver). When this myosin head springs back, it pulls on another muscle protein, actin, developing muscular force. We will study this in more detail later in the course. The important point here is that if there is no energy transformation, there is no muscle contraction and no work done.

Not only do muscle and other tissues transform energy from one form to another, but also they transfer energy from one chemical substance to another chemical substance. For simplicity, in this course I will use the term energy turnover to include both transfer and transformation of energy within the body. When comparing this energy turnover to work or power output, I will also refer to energy input or power input.

Thus, energy turnover = energy input = (energy transformation) + (energy transfer).

III. Power

In analyzing adaptations of the body in response to exercise, consideration of power is usually more important than consideration of work. Power is defined as the rate of doing work (i.e., work per unit of time).

\[ \text{Power} = \frac{\text{force} \times \text{distance}}{\text{time}} \]

In the example of the 80-kg person stepping up on a 0.5-m step used previously, imagine that he/she takes exactly 2.0 seconds to step up. This person's rate of doing work (power) = (80 kg x 0.5 m) / 2.0 sec = 20 kilogram-meters per second.
per second (kgm/sec). Now imagine that this person continues to step up and down for one minute, stepping up 15 times in the minute. The power over the entire minute (considering only the positive external work) = (15 steps x 80 kg x [0.5 m/step]) / 1 min = 600 kgm/min.

**- Power (cont.)**

Let me give another example to illustrate the important difference between work and power. You might look at Dr. Schwane (above) and bet me a lot of money that he can't bench press 225 kg (about 500 pounds). But if you don't put any qualifiers on the rate of work, I'd take your bet and win. Here's how. Dr. Schwane probably can't bench press 225 kg in a single lift. To do that, he'd have to lift the 225 kg about 1 meter in no more than a few seconds:

Power = (225 kg x 1 m) / 3 sec = 75 kgm/sec = 4,500 kgm/min. I don't think he can generate that much power; as a matter of fact, I can't generate that much power. But, I know he can bench press 25 kg! And if he were to do that 9 times (let's say in 30 sec), He would have lifted the 225 kg involved in the bet. Notice the difference between work and power in doing the nine repetitions.

Work = 9 lifts x 25 kg x 1 m/lift = 225 kgm.

Power = 225 kgm / 30 sec = 7.5 kgm/sec = 450 kgm/min.

So, the total work is the same whether he lifts 225 kg once or 25 kg nine times, but the rates of work (power) are very different. This difference is obvious to anyone who has ever had to divide up a job to get it done. In most athletic competition, however, dividing up the work is not an option, and the athlete who can generate the greatest power has a tremendous advantage.
### Power (cont.)

The units of power most commonly used in exercise physiology are **kilogram** (or **kilopond**) -meters per minute (kgm/min or kpm/min) and **watts** (W). Divide kgm/min by 6.12 to convert to watts; multiply watts by 6.12 to convert to kgm/min.

One other very important point about units of power: Since work and energy have the same units and can be interconverted, the same applies to power and rate of energy transformation. Most importantly, multiply kgm/min by 0.0023 to convert to kilocalories of energy per minute (kcal/min), or multiply watts by 0.014 to convert to kcal/min.

### Power (cont.)

There are two aspects of power that must be distinguished: power output and power input.

**Power output** is the rate at which external work is done (i.e., force x distance / time) or the rate at which equivalent energy is used. As noted previously for external work, power output very often cannot be measured.

**Power input** is the rate at which chemical energy is turned over in the body. As also noted previously for internal work, sometimes power input can be measured and sometimes it can't.

With both power output and power input, when these can't be measured they often can be estimated fairly accurately.

I hope you have noted that the terms **work** and **power** are defined in very strict ways in exercise physiology and science in general. These words are used in many other ways outside scientific circles. For example, the sport of **power lifting** simply involves certain lifts; the winner is the athlete who lifts the greatest weight, not necessarily the one who exerts the greatest power. So make sure you know what meanings of these terms are being used. When dealing with exercise physiology, as much as possible you should use **work** and **power** in the strict sense discussed in this lesson.
- IV. Mechanical Efficiency

**Efficiency** is another term that is used in various ways in different settings, and sometimes it is used rather loosely. It is not uncommon, for example, for a runner with a certain stride that looks good compared to another runner's stride to be described as a "more efficient runner," or to hear that "training makes a runner more efficient." In each of these cases, it is unlikely that anything is really known about mechanical efficiency and the statement could actually be false. Also, in these cases, what is really of interest is probably **effectiveness** or **fitness** rather than efficiency per se. Was the stride the one that was most effective in getting the runner to the finish line in the fastest time? Did the training help the runner improve his/her time for a given distance? (There have been some great runners who set world records and won Olympic races but had running forms or styles that looked "inefficient.")

In exercise physiology, **mechanical efficiency** has a very specific definition: **The percent of energy put into a system that is converted to external work**. Mathematically, efficiency is calculated as:

\[
\text{% Mechanical Efficiency} = \left( \frac{\text{Power output}}{\text{Power input}} \right) \times 100
\]

Be sure to note the concept of efficiency, in addition to the way it is calculated. The concept of efficiency has to do with how much external work (or power) is derived from a given amount of internal work or energy turned over in the body, compared with the amount of the energy that is wasted. It is highly desirable to have high efficiency, that is, to convert more of the energy to external work and therefore to waste less.

Let's consider an example. Assume that a person was turning over energy in the body at the rate of 15 kcal/min (this is power input), and he/she was doing external work at the equivalent rate of energy expenditure of 3 kcal/min. This person's efficiency of doing this task is: \( \frac{3 \text{ kcal/min}}{15 \text{ kcal/min}} \times 100 = 20.0\% \). This also means that 12 kcal/min or 80% of the energy input was wasted in terms of useful external work, probably converted to heat.
As alluded to earlier, a very critical determinant of successful exercise performance is often the ability to turn over energy in the body at a high rate (i.e., power input). We can rearrange the mechanical efficiency equation as follows:

\[ \text{Power input} = \frac{\text{Power output}}{\left(\%\text{ M.E.} / 100\right)} \]

This form of the equation emphasizes a very important point about power and energy: Power input must *always* meet the amount required by the power output and mechanical efficiency values — the body is on a "pay-as-you-go system" in terms of energy. There is no borrowing and paying back later. To put it another way, if a given power output is being done, a given, required power input is absolutely being provided.

The graph illustrates the relationship between power output and power input during 12 minutes of testing on a bicycle ergometer. During the first 3 minutes of measurement, the subject is seated on the ergometer at rest. There is no power output; no external work is being done on the ergometer. Resting power input is 1 kcal/min. (You should remember that for people of average body size, resting metabolic rate is *about* 1 kcal/min. This is one of those "rules of thumb" that are useful to remember.) At 3 minutes, the subject begins to work at a power output of 2 kcal/min. This can be done almost instantaneously on a bicycle ergometer; there is little or no
Instantaneously on a bicycle ergometer, there is little or no time needed to make the transition from rest to this power output. An important point here is that the power input must adjust over precisely the same time course to provide what is needed. In this illustration the power input is 10 kcal/min from 3:00 to 6:00.

\[
\begin{align*}
\text{Mechanical Efficiency (cont.)} \\
\text{At Minute 6 of this test, the power output was raised instantaneously to the equivalent of 3 kcal/min. Since the person's mechanical efficiency stayed at 20%, power input had to increase instantaneously to 15 kcal/min for the person to do this exercise. Similar increases in power occurred at 9:00.}
\end{align*}
\]

**Point of Emphasis:** If ever during a given stage of this exercise, power input would have fallen from the value shown in the graph, power output would have fallen too, to 20% of the power input. For example, imagine that at 9:00, when the resistance on the ergometer was increased, the person could have increased power input from 15 kcal/min to only 18 kcal/min (instead of the 20 kcal/min required). The equivalent power output would be 3.6 kcal/min instead of 4.0. There is no way it could have been 4.0 kcal/min.

\[
\begin{align*}
\text{Mechanical Efficiency (cont.)} \\
\text{EXAMPLE: Consider a female runner competing in a 1500-meter race. She starts "kicking" 200 m from the finish line, increasing running speed from 4.8 m/sec to 5.2 m/sec. For simplicity, let's assume that this runner's efficiency is 22% and that efficiency does not change throughout the race (which may be the case in "real life"). It would be practically impossible to measure the work this runner is doing, but let's assume that she was working at the rate of 307 W during the first 10-20 m of her kick. This is equivalent to a power output of 4.39 kcal/min (307 watts x 0.0143 kcal/watt), or 0.073 kcal/sec. We can now calculate the runner's}
\end{align*}
\]
We can now calculate the runner's power input at this moment:

\[
\text{Power input} = \frac{\text{Power output}}{\%\text{ME} / 100} = \frac{4.39 \text{ kcal/min}}{\frac{22\%}{100}} = 19.95 \text{ kcal/min} (0.33 \text{ kcal/sec}).
\]

In other words, this runner has to be turning over energy in her body at the rate of 0.33 kcal/sec to run at 5.2 m/sec. Now let's assume that 50 m from the finish, our runner (who is in the lead) is challenged by another runner, and she wants to increase her speed to 5.4 m/sec, which is equivalent to a power output of 0.075 kcal/sec. Can our runner do it? It depends on whether she can increase power input to the new requirement: power input = \(0.075 / \frac{22\%}{100} = 0.34 \text{ kcal/sec}\). Let's assume that she cannot turn over energy at this required rate, due to factors we generally refer to as "fatigue." The result is that she absolutely cannot run at the desired pace of 5.4 m/sec, not even for one or two meters. All she can do is keep going at the pace that requires a power input she can provide and hope that's good enough to beat her challenger.

**Mechanical Efficiency (cont.)**

To summarize, power input is determined by power output and mechanical efficiency. For the most part, we can't do anything about efficiency, especially not as a short-term adaptation during exercise. We certainly can regulate power output, however, by adjusting what is often referred to as the intensity of exercise (e.g., the speed of running, cycling or swimming; the steepness of the incline on which one is running or cycling; the resistance on a bicycle ergometer). As exercise intensity is varied, the body adjusts the power input to meet the requirement (power output / [ME / 100]). If the body is ever unable to meet the requirement of a desired exercise intensity, the person absolutely cannot exercise at that intensity. The intensity will be lowered to what can be done with the power input.
### V. Economy of Movement

As noted previously, consideration of efficiency has limited usefulness in exercise physiology, especially because it cannot be easily measured. This is especially true during locomotion, such as walking and running. Since walking or running is involved in most athletic activities, efficiency is not a useful consideration in evaluating most activities. Furthermore, in walking and especially in running, the total rate of energy turnover (i.e., power input) is more important than either efficiency or the precise amount of physical work done. Of course, the efficiency value and the external work done are determinants of power input, but the bottom line is that it is advantageous for the competitive runner to have as low a power input as possible at a given running speed. There are important physiological reasons why this is so:

(a) A lower power input is less stressful on the cardiorespiratory system. The work that the heart has to do, for example, is directly related to the body's power input (metabolic rate).

(b) A lower power input uses the body's fuel stores at a slower rate, so they will last longer.

(c) Metabolic waste products accumulate at a slower rate at a lower power input.

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### Economy of Movement (cont.)

Economy of movement is a very useful concept and often an important measurement in evaluating performance. Economy has been applied most to running.

**Running economy** is "the steady-state rate of oxygen consumption (VO2) at a given running pace." Being in a steady state is an important requirement in the measurement of economy.

**Steady state** refers to the state or condition of the body (or some system in the body) when no changes are occurring. For example, if heart rate remains at the same value for several minutes, one might refer to that as a "steady-state heart rate." Some physiologists argue that there is no such thing as a steady state, because the various systems of the body are constantly adjusting. Technically this is true, but there are times when changes are relatively small compared to other times so that at least a relative steady state exists.
During a marathon race, in the first couple of minutes after the start, the body is clearly not in a steady state. Heart rate, stroke volume and cardiac output increase, as do rate of ventilation of the lungs, rate of energy turnover in the leg muscles and many other variables (which we will study later in this course). Other things decrease during this period, such as total resistance to blood flow and pressure of oxygen in the active muscle fibers (which we will also study later). After these initial adjustments early in the marathon, there are long periods during which the runner maintains a fairly constant pace, and most variables change very little from one moment to the next. During these times, the runner is in a steady state, at least relative to the start of the race and to other periods when he/she is changing paces.

- Economy of Movement (cont.)

The steady-state condition required by the definition of running economy dictates two important considerations in the measurement of economy.

First, the runner must run at a constant speed, and time must be allowed for the body's systems to adjust.

Second, the runner's VO2 must be below his/her maximal rate of consuming oxygen. (This maximal rate is usually abbreviated "VO2max," and it represents the person's highest rate of transporting and using oxygen. VO2max is a very important determinant of performance in many activities, and we will study it in more detail later in the course.)

In brief, to measure economy, the runner runs for 6-10 minutes on a treadmill at a constant speed (following appropriate warm-up), and VO2 is measured during the last 2-3 minutes. (We will study how VO2 is measured in a lab later in the course.) VO2 is expressed in milliliters of oxygen per kilogram of body weight per minute (mL/kg/min). This is then divided by the speed of running, in meters per minute, to give an economy value expressed as amount of oxygen needed per kilogram of body weight to run a given distance.

**EXAMPLE:** A runner was tested running at 214 m/min (8.0 mph). His steady-state VO2= 46.0 ml/kg/min. This information is enough to compare this runner's economy to that of others. The one with the lowest VO2 when running at 214 m/min is the most economical. Economy could also be expressed as: VO2 (46 ml/kg/min) / speed (214 m/min) = 0.21 ml/kg/m. This value can now be used not only to compare with other runners, but also to compare with economy of running at other speeds.
- Economy of Movement (cont.)

Note that when economy is expressed in VO2 units (i.e., either ml/kg/min or ml/kg/m), the measured value is inversely related to the concept of economy. Conceptually, it is desirable to have a high level of economy, which means having a low rate of oxygen consumption for a given speed or given distance covered.

Sometimes you will see economy expressed as meters run per milliliter of oxygen consumed per kilogram of body weight. To express economy in these units one simply divides the running speed by the VO2. Referring to the example above: (214 m/min) / (46 ml/kg/min) = 4.6 m/ml/kg. In these units, it is desirable to have a high value, indicating ability to run a greater distance for a given amount of oxygen consumed (i.e., more economical).

- Economy of Movement (cont.)

There is often a considerable difference in economy of running between one person and another. As a general rule, highly trained distance runners are more economical than others. But even within a group of trained runners there can be large differences in economy.

In one study of 12 highly trained male distance runners (Conley and Krahenbuhl, Med. Sci. Sports Exerc. 5:357-360, 1980), VO2 of the most economical runner at 10 mph (268 m/min) was 45 ml/kg/min (0.17 ml/kg/m; 6.0 m/ml/kg) and VO2 of the least economical runner was 54 ml/kg/min (0.20 ml/kg/m; 5.0 m/ml/kg). The most economical runner could run 20% farther for a given amount of oxygen consumed! This provides a big advantage for the more economical runner. He can either run at the same pace as the other runner with a lower VO2 and therefore less stress on his oxygen transport system, or he can run at a faster pace than the other runner at the same VO2.
Better economy means better performance. Within their group of highly trained runners, Conley and Krahenbuhl (Med. SCI Sports Ex., 1980) found a very strong correlation between measured economy and 10-kilometer run time. In general, the better the economy the faster the 10-k time. 10-k performance in this group was unrelated to VO2max values, but we must be careful in interpreting this finding. All of these runners had high VO2max values (67.3 - 77.7 ml/kg/min). Without these high VO2max values these runners could not have had the 10-k run times that they had: 30.52 - 33.55 minutes. But once runners get "into the club" of good distance runners with high VO2max values, economy becomes a critical discriminator.

What are the factors that determine running economy? And most importantly, can an athlete do something to improve economy? The answers to these questions aren’t completely known, despite many research studies. These studies have identified a number of factors that are associated with running economy, although not all are clearly related to economy in a causal way:

(a) **Mechanical efficiency** - Greater efficiency translates into better economy. Unfortunately, it is not at all clear that efficiency of muscles can be changed or, if so, how it can be changed. (Note that in the study of Conley and Krahenbuhl referred to above, nothing was known about the efficiency of the runners. This simply could not be measured.)

(b) **Mechanics of running** - (i.e., movements in running that affect the total external work) - Unnecessary movements, especially involving the lifting and lowering of body segments, should be avoided. Unnecessary movements may seem obvious in some runners, but there may be unnecessary movements that are not obvious. One has to be very careful when recommending changes in form, however. Economy might be improved, but other physiological, mechanical or psychological variables could be negatively affected.

(c) **Muscle fiber type distribution in the leg muscles** - There are two major types of skeletal muscle fibers, "fast-twitch" and "slow-twitch." Slow-twitch fibers are more economical than fast-twitch fibers. In most muscles in most people, there are approximately equal numbers of these fiber
types. Some individuals, however, have certain muscles with a predominance of one type. In fact, as a general rule, elite distance runners have relatively high proportions of slow-twitch fibers in their leg muscles. Such differences among individuals in the relative distributions of fiber types in the leg muscles could contribute to differences in running economy. Muscle fiber type distribution is largely (some would say completely) determined by genetic factors. Therefore, this factor cannot be easily changed (or perhaps not changed at all) to improve running economy. (We will study muscle fiber types in more detail later in the course.)

(d) **Ability to use muscular elasticity** - One of the properties of skeletal muscles is that they are elastic, that is, a muscle returns to its original length after it has been stretched (similar to a rubber band or spring). Since running involves a series of bounding or jumping movements, in which muscles are stretched at certain times in each stride (especially in landings), muscular elasticity contributes to the active forces the muscles generate. The more elastic force the muscle develops, the less active force is required, and this saves energy. So, a person who has muscles with greater elasticity would likely be more economical. It is possible that plyometric training enhances ability of muscles to store and reuse elastic energy, but there is still a lot that is not known in this area.

(e) **Other factors** - Although more research is needed, studies have found associations between running economy and (i) sex (perhaps lower economy in women; not all studies agree), (ii) age (lower economy in the elderly), (iii) fatigue, and (iv) nutritional state.
would, of course, still be other benefits of years of training).

### Economy of Movement (cont.)

It is likely that running economy can be improved with training, although many questions related to this remain to be answered. What type of training is most likely to improve economy? High intensity interval running. Dr. Jack Daniels, a well-known exercise physiologist and collegiate track coach, recommends what he calls "reps training." This is a form of interval training consisting of 30-second to 90-second runs at a fast pace (above VO2max; about 5 seconds per 400 m faster than 5-km race pace), with a 1:5 work:rest ratio (Daniels, J. Training Distance Runners – A Primer, *Sports Science Exchange*, Vol. 11, No. 11, 1989). The mechanism whereby training improves running economy is not known for sure. In other words, we don't know exactly what changes occur with training to result in improved economy.

### Review of Lesson

You have come to the end of the online content of Unit 1 - Lesson 2.

Lab 1 deals with the same topics addressed in Lesson 2. It presents examples of lab measurements and gives more practice with actual data. I suggest you go to Lab 1 as soon as you can, because Lesson 2 and Lab 1 are "part of the same package."

When you want to review the concepts in this lesson, go back to the Learning Objectives listed on Page 2 of this lesson and to the Learning Objectives of Lab 1. These should be a good study guide. If you can correctly do what the Objectives ask, you will have mastered the most important concepts in Lesson 1. Please realize, however, that the Objectives do not exhaustively cover all the information in Lesson 2.
Included in the Objectives is ability to do basic calculations related to mechanical work, power and efficiency. If you need more practice with these, you may want to go back through the examples and practice problems presented in Lesson 2.

If you are uncertain about any Objective, or if you want clarification or expansion of any point in Lesson 2 or Lab 1, I urge you to start a threaded conference discussion in the "Barn" on WebBoard. Other students may have the same concerns, will probably benefit from the discussion, and may have the information you seek. And, of course, feel free to contact me (Dr. Eldridge) for assistance.

Be sure to check the Announcements Page to see whether there is a specific WebBoard or other assignment.

**- Unit 1 - Exam**

Unit 1 - Exam will be available:

*Monday through Tuesday, June 11 - 12, 2001*

The exam will be e-mailed to students on those days.