

# Force, Work, and Power\*

## I. Introduction; review and overview

A. Review: In the past classes, we have learned how muscles produce force and most recently we came up with a mechanical model of the muscle that contained both contractile and elastic components.

1. The contractile components (the sarcomeres), of course, are the main part of the muscle and are responsible for generating force.

2. The elastic elements are a much smaller part of the muscle's mass.

(a) They do not actively generate force but instead:

(b) serve to slightly smooth out the force of contraction (series elastic element)

and more importantly,

(c) serve to reduce the effects of external forces on the muscle (overloads) that might tear the muscle.

(1) The parallel elastic elements (fascia) are especially important in this regard because they will absorb externally inputted energy if the muscle is stretched beyond its normal "resting" length. We have seen that muscle stretches are especially likely in falls or when the muscle is dealing with an overload (for example in catching a massive falling object).

(2) The series elastic elements (tendons) also help, and their effects are independent of the length of the muscle.

B. In this class, we will deepen our understanding of the operation of muscle by seeing the effects of different loads (weights) on all muscles':

1. Speed
2. Power.

## II. Speed and Load.

A. What is **load**? The term has the same meaning to a physiologist that it does to anyone else -- a load something that is to be moved. So a load is a force that a muscle must either support or overcome. We usually divide loads into two general types:

1. External load: Some weight or force, external to the muscle and the immediate part of the body that it operates. A load can be some object in the environment or it could be the mass of one's own body or some part of it. So, note the definition is a bit slippery. It is easiest to understand, when we are talking about some object external to the environment. Consider a bat and ball. These are clearly external to the subject and are things that a person tries to move with one or more muscles. Likewise, when someone is running, the load on the person's muscles consists of the person's mass, friction between their feet

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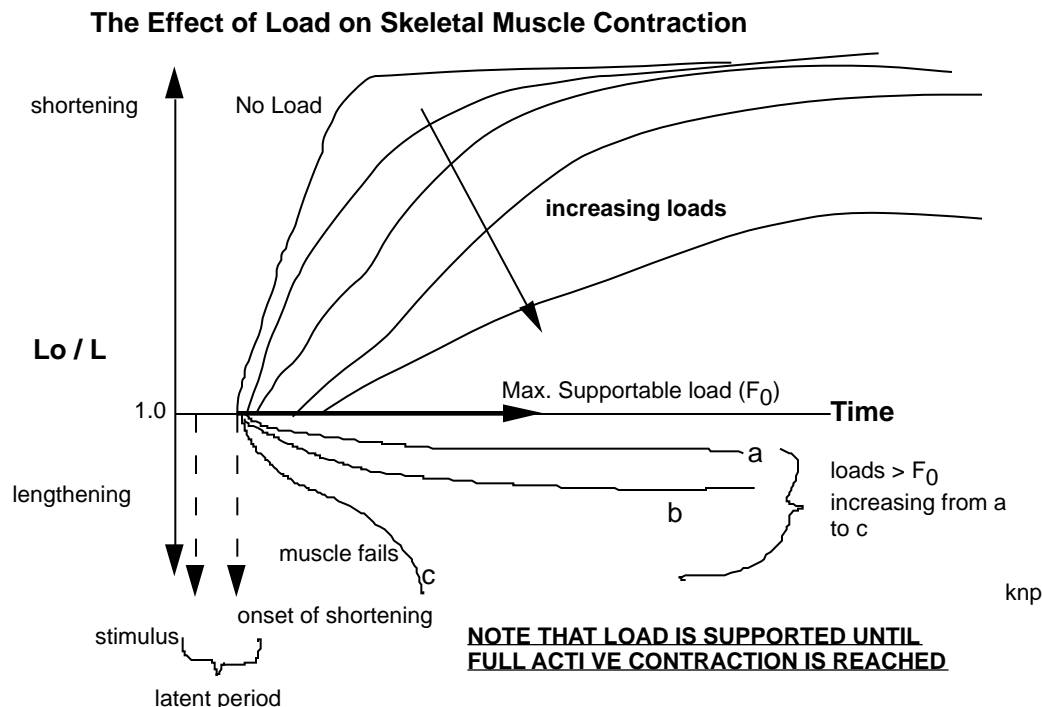
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and the ground, and wind resistance. And in some cases, for instance, in the case of antagonistic muscles operating against each other, the load on each muscle is the other muscle. The common element to all of these examples of loads is that the load is what the person intends to move or support. In some way, this motion is useful to the subject. So, moving external loads involves what is called useful work. **What is useful is somewhat arbitrary**. What is useful is whatever we decide is useful. Let's contrast this with internal work, which is not useful:

2. Internal Load: There are also internal forces that muscles must overcome. Example -- if I am throwing a javelin. The useful work my muscles do is in accelerating the javelin at the correct angle to get a long throw (or in old days -- to hit my enemy or some animal). However, to throw the javelin, I also must accelerate the mass of my arm. That is not particularly useful to me, but it is something that must be done as a part of the exercise.

3. Convention: when we talk about the work that a muscle does, we will generally just consider the useful component only. So, we should take some care to define what is useful in a given movement.

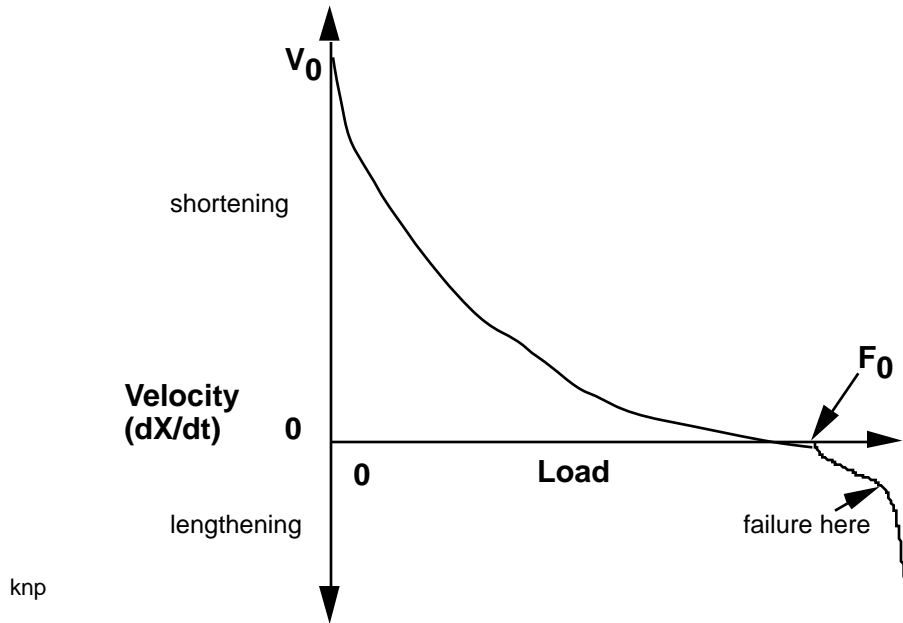
**B. The effect of load on shortening:** What happens if we attach various sized loads, induce a muscle to contract tetanically for 1 s. and measure the movement of the load over time? The following graph shows the result of such an experiment:



*As load increases from unloaded to the maximum load that a muscle can support without lengthening ( $F_0$ ), the distance that a muscle can shorten begins to decrease as does the velocity with which it shortens. The latent period (time between the stimulus and the onset of movement) increases. Beyond  $F_0$ , the muscle lengthens even though contracting maximally; at some load (C) the muscle fails elastically.*

What does this experiment teach us?

1. There is a **latent period** in all muscle contractions. This is the period between the sending of an AP and the start of a noticeable movement of the load. The latent period gets longer as the load increases. The latent period can be explained by:
  - (a) the time required for EC-Coupling
  - (b) the time required to stretch the series elastic elements (tendons) such that the elastic force in them is greater than the external load.
2. The contractions can be divided into two types:
  - (a) **isotonic**: contractions taking place against a constant load where shortening occurs.
  - (b) **isometric**: contractions where the muscle does not, overall, shorten. The lowest load that results in an isometric contraction is called  **$F_0$** . Put another way,  $F_0$  is the first load that the muscle, even when contracting maximally, cannot move.
    1. **At loads greater than  $F_0$  the muscle actually lengthens.** This lengthening is a result of the fact that the work done on the muscle by the load is greater than what the muscle can do. The muscle contracts maximally and supports much of the load (by what is an isometric contraction since it does not manage to shorten). However, the load is greater and so the muscle starts to stretch a bit. As it stretches, the parallel elastic elements lengthen and absorb some of the force applied to the muscle by the load. Once they have stretched enough so that the force stored in them plus the force of the contraction is equal and opposite to the force of the load, the muscle stops lengthening and a true isometric contraction occurs.
    2. Note that all isotonic contractions have an isometric component. When the muscle first starts to contract, the load will not move until the series elastic element stretches enough so that the force stored in it is greater than the force of the load. So, before the muscle shortens noticeably, contractile elements shorten and the tendon lengthens to the same degree. Overall the muscle is at a constant length. When the force of the muscle is finally fully transmitted to the load, the contraction becomes truly isotonic.
  3. There is one additional contraction type that needs to be considered. When a muscle contracts against no load, the graph shows that it attains its greatest velocity. We call this  **$V_0$**  -- note this term is also used as a synonym for "unloaded contraction".
  4. We can summarize the results of the previous graph by calculating either the peak or the average velocity of the load in a given contraction. If we then plot these velocities against the load we get:



An idealized relationship between velocity and load for a skeletal muscle.  $V_0$  is the maximum velocity of contraction and occurs in an unloaded muscle, at  $F_0$ , the maximum force that the muscle can support, the contraction becomes totally isometric (the muscle does not change length).

- (a) To no one's surprise, the fastest contractions are produced with an unloaded muscle and
- (b) as loads get heavier, the velocity of a contraction becomes less and less.
- (c) All values for loads greater than zero and less than  $F_0$  represent cases where **positive work** is done by the muscle.
- (d) On the other hand, for all loads greater than  $F_0$ , **negative work** is done.

**Some Questions:**

How would the graph above change if the muscle becomes stronger?  
 Specifically, which would probably change more  $F_0$  or  $V_0$ ?  
 How about speed at loads in between  $F_0$  and  $V_0$ ?  
 What would the effect of increased strength be on the speed of contraction at most loads?

**C. The Effect of Load on Power**

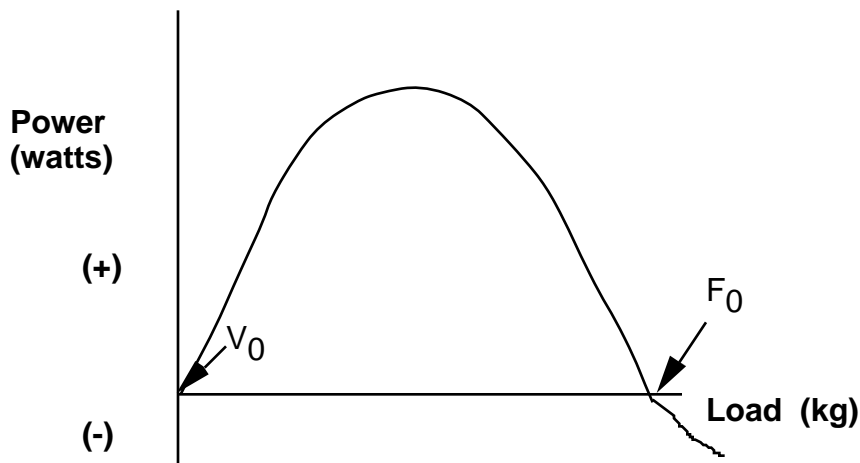
- 1. We can calculate the muscles useful power, also known as its **power output**, from the last graph.
  - a. Recall that in the mks system power is joules per second. If we multiply the average velocity during a contraction times the load we get the average power. Here is the explanation:

- b. Recall that:  
 $V = \text{distance} / \text{time}$   
 $\text{Work} = \text{Force} * \text{distance}$   
 $\text{Power} = \text{Work} / \text{time}$

Thus:  $\text{Force} * \text{Velocity} = \text{Force} * \text{distance} / \text{time}$   
 $= \text{Work} / \text{time}$   
 $= \text{Power}$

- c. So, if we take the velocity at each point on the graph above (where it is positive) and multiply it by the load we can get the power. If we then plot this power vs. the load:

**Muscle Power Output (Useful work)  
as a Function of Load**



*This graph is derived from the velocity plot by simply multiplying the load (mass \* acceleration due to gravity) by the velocity. Note that at both  $V_0$  and  $F_0$  the useful power output is zero; maximum power is transferred from the muscle to the load at some intermediate load value.*

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Notice that **maximum power output comes with loads intermediate between  $V_0$  and  $F_0$ .**

Questions:

1. What is the useful work done at  $V_0$  and  $F_0$ ?
2. What is the useful work done in an isometric contraction? Does this mean that the muscle consumed no energy for the contraction? Explain. What happens to energy liberated from the breakdown of ATP that is not converted to useful work?
3. Given the answer to question 1, does the power graph make sense?