Skeletal Muscles Modeling (Hill) – A Tutorial

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This tutorial has been developed to help you understand what Muscles Modeling is, why it is important, and how to use it. While the mathematics are included, practical examples and analogies have been used wherever possible.

Muscles: Why are they important?

Muscles and nerve fibers allow us to move our bodies. They enable our internal organs to function. The human body has over 600 muscles, which make up around 40 percent of our bodyweight. Each muscle consists of thousands, or tens of thousands, of muscle Smaller sections.

According to Figure 1 muscle is a hierarchical structure, composed of a core of force generating sarcomeres arranged in bundles of myofibrils, fibers and fascicles that together form a complete muscle. Fibers, fascicles and muscles are surrounded by a matrix of connective tissues. We might view these connective tissues as just packaging; the scaffold that organizes an array of actuators (muscle fibers) into an effective geometry and attaches muscle to bone. However, it is clear that the elastic properties of tendons influence the force, power, and energetics of contraction, and evidence is growing that the elastic properties of the connective tissue matrix within muscle also provide an important mechanical role. While the sarcomere is the ultimate source of muscle power, the mechanical output of muscle depends very much on the properties of extracellular tissues, their arrangement, and the flow of elastic strain energy through them.

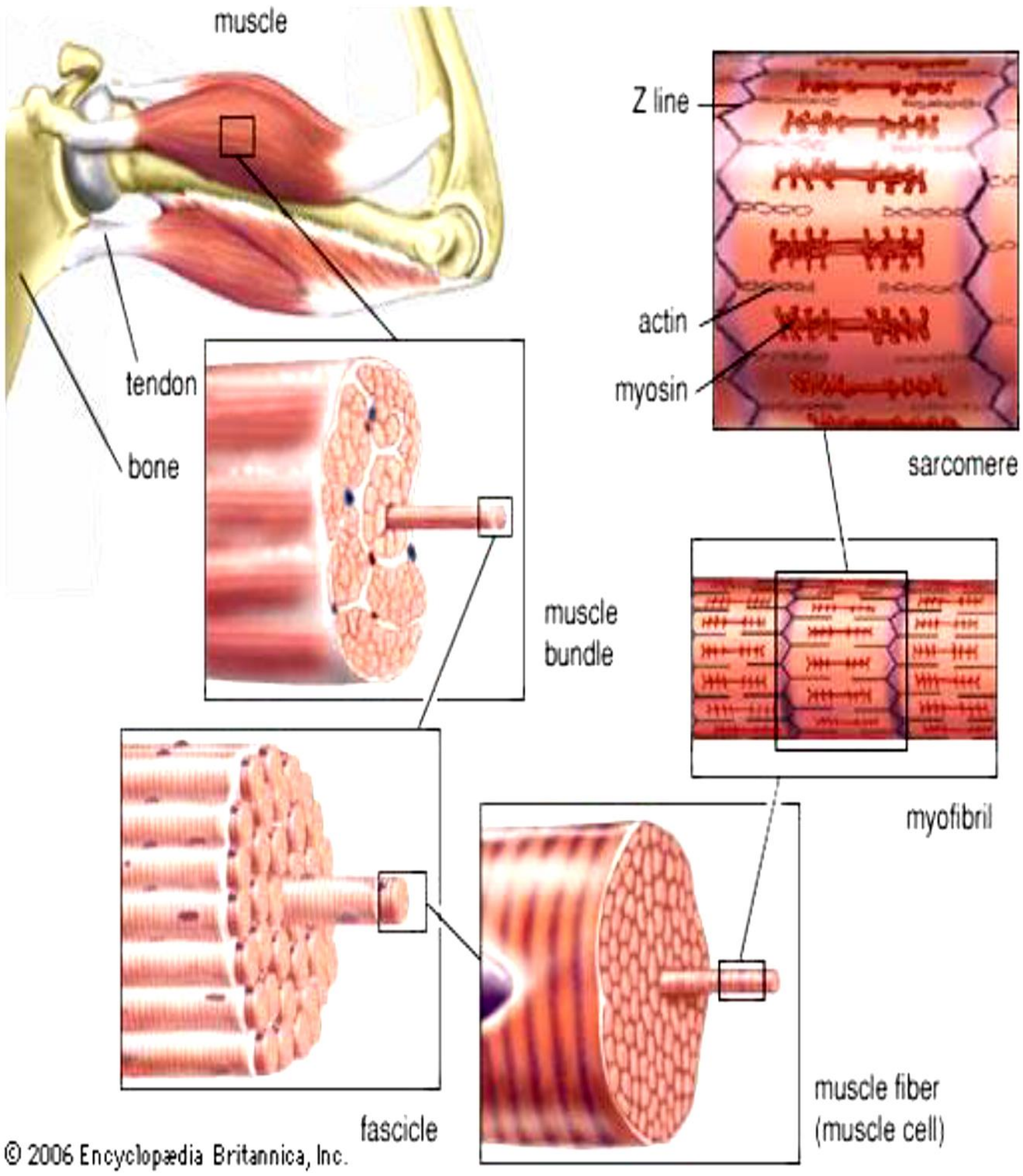


Figure 1: Muscle structure

Types of muscle

There are three types of muscle found in the human body:

- Skeletal (muscles that move voluntarily)
- Smooth (involuntary muscles in organs)
- Cardiac (only found in the heart)

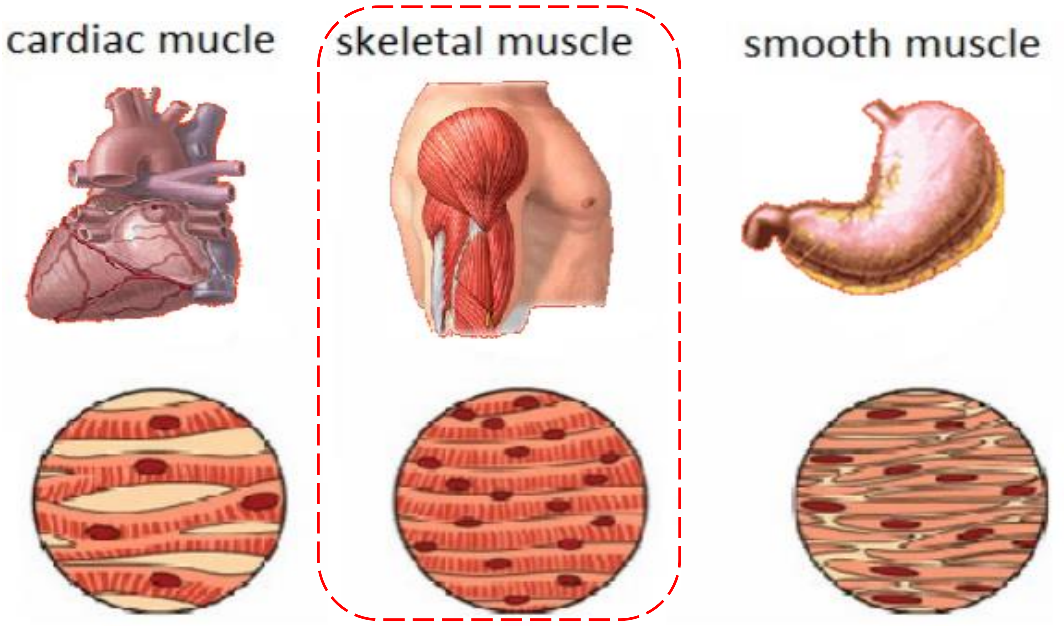


Figure 2: Type of Muscle [From teachpe.com site Anatomy and muscle types]

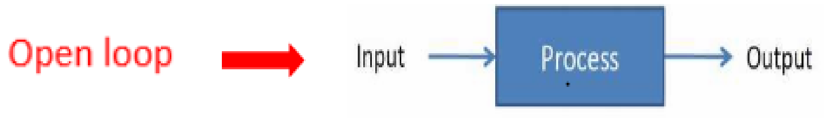
Table 1: Type of Muscle

Characteristics	Types of muscle Skeletal	Smooth	Cardiac
Location	Disposed over the skeletal system	Walls of hollow organs	Heart
Cell-shape	Very long and cylindrical	Fusiform	Cylindrical and branched
Function	Body movement	Regulation of the blood vessels' diameter, the size of the eye pupil…	Pumping blood
Control	Conscious	Inconscious	Inconscious

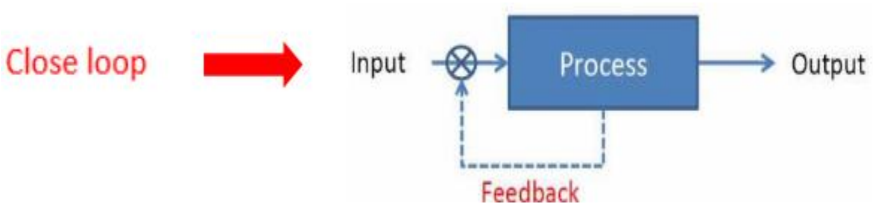
So far, we have been introducing muscle and muscle types. Now Consider skeletal muscle. We want to model skeletal muscle. Before doing anything, explain the muscle system and modeling.

System

Consider a system. A system is a combination of interconnected components that is capable of performing a task. Muscle is a system. By itself, muscle is an open loop system, which means that it generates its out puts from its inputs without using feedback to guide or improve its performance.



In contrast, a closed loop system uses feedback (e.g., position and/or velocity error) to control the states and/or the outputs of the open loop system being controlled. A closed loop description of muscle must include the muscle itself, the neural drive to the muscle, and the sensory feedback from the nervous system. Together, neural drive and sensory feedback constitute the control system that closes the loop.



Why model muscle?

To study the behavior of a modeling system is a suitable method. In other words, one of the best ways of understanding a given physiological system is to model it. The muscle model allows a better understanding of muscle function without the need to know its details. Also, with the aid of the model, we can study the effect of various factors on the system. We will continue to model the muscle.

Muscle model

The force-producing properties of muscle are complex and nonlinear. For simplicity, dimensionless muscle models, capable of representing a range of muscles with different architectures, are most commonly used in the dynamic simulation of movement.

The strategy for building a muscle model is to first introduce the basic mechanical elements of a spring and damper(Figure 3), and explain how series (Figure 4) and parallel (Figure 5) arrangements can be made to accurately model the viscoelastic behaviour of soft tissues.

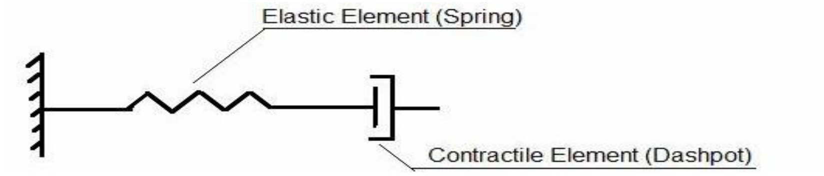


Figure 3: spring and damper

- Maxwell (series)

  – Equal forces; displacements sum

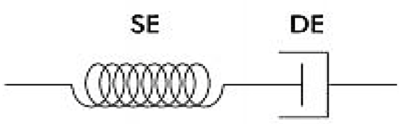


Figure 4: Maxwell (series) model

- Voigt-Kelvin (parallel)

  – Equal displacement; forces sum

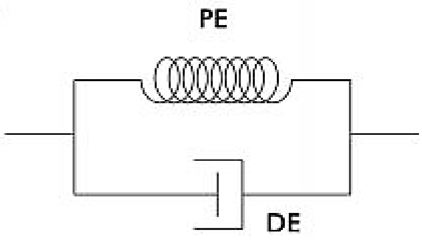


Figure5: Voigt-Kelvin (parallel) model

- Hill's Model

  – Hill-type muscle model is one of the most used models to describe the mechanism of force production. It is composed by different elements that describe the behaviour of the muscle (contractile, series elastic and parallel elastic element) and tendon.

  – The three element Hill-type model (Figure 6) provides the simplest and arguably the most widely implemented model of muscle function that can characterize interaction between contractile and elastic elements. The model includes a contractile element (CE) that represents the fundamental mechanical behavior of the sarcomere, governed by activation kinetics, force-length properties, and force-velocity properties derived from isolated muscle studies. Springs in parallel with the CE and in series will influence the force, length and speed of the entire unit. This model is useful for exploring and describing the significance of the interaction between these different elements, and is commonly implemented in forward-dynamic simulations of movement.

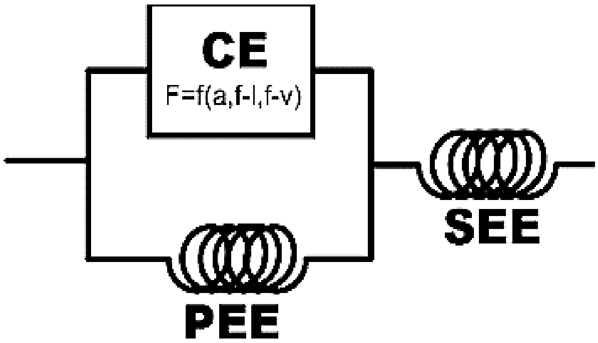


Figure 6: Muscle model of Hill (A Hill-type model of muscle with a contractile element (CE) arranged alongside a parallel elastic element (PEE) and in series with a series elastic element (SEE). Force development within the CE is a function of activation kinetics (a), force-length (f-l) properties, and force-velocity (f-v) properties. Force developed by the PEE depends on the CE length, while force in the SEE is equal to the sum of PEE and CE forces).

Figure 7 illustrates the schematic of the Hill model.

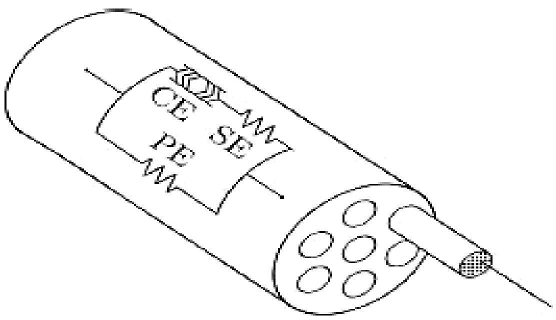


Figure7: Schematic of the Hill-type muscle fiber (contractile element (CE), a parallel element (PE), and a series element (SE)).

- Three element model
  - Contractile Component (CC)
  - Series Elastic Component (SEC)
  - Parallel Elastic Component (PEC)

The chart below shows the Hill's Muscle Model.

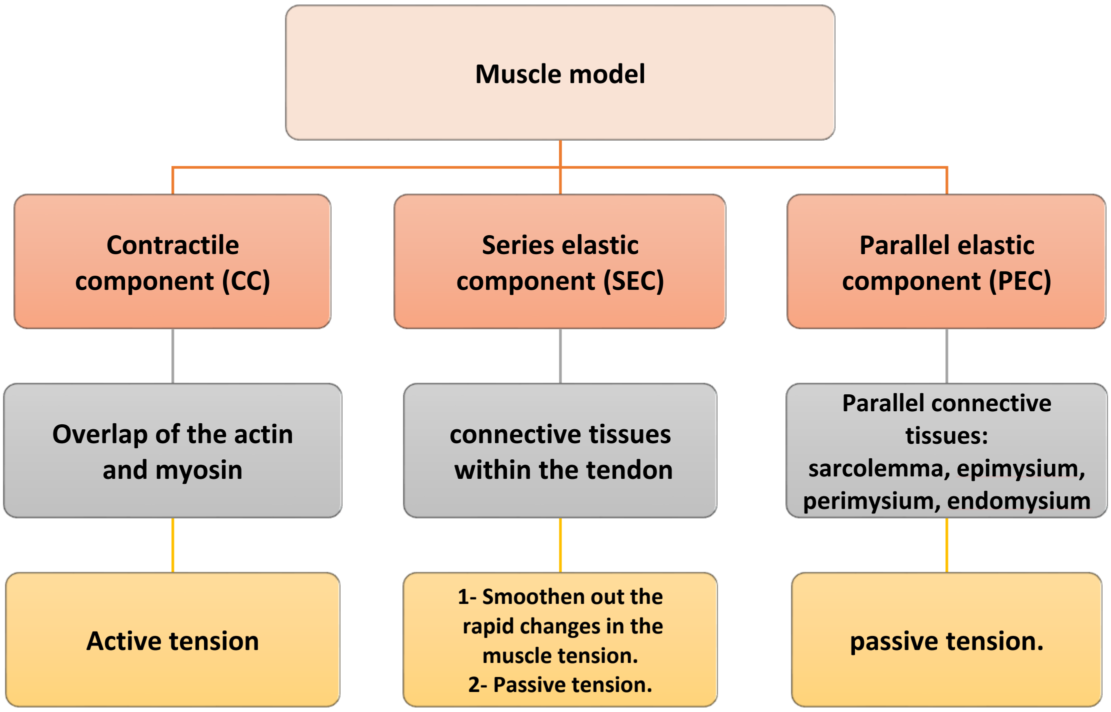


chart 1: Muscle model

If we want to introduce the Hill model as a block diagram, the Figure 8 will show it well.

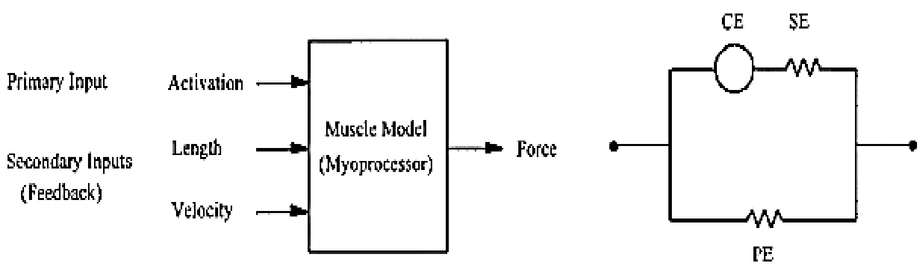


Figure8: Hill- type muscle model – block diagram.

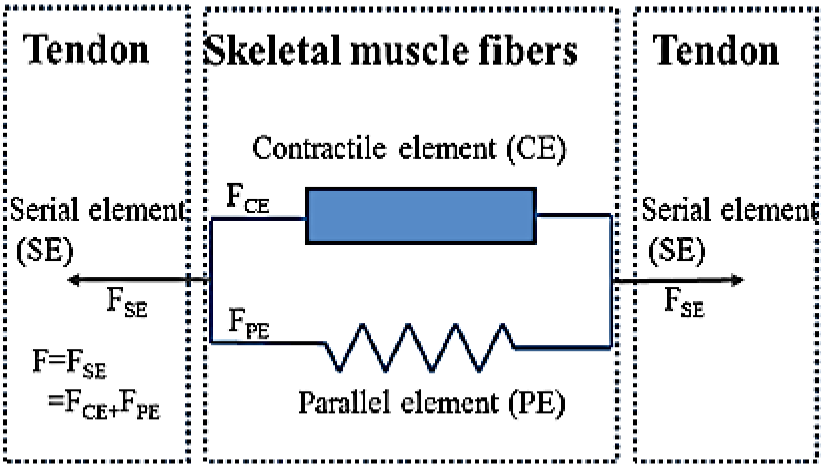


Figure9: 3-elements of a typical skeletal muscle according to Hill

[Know more: Research in muscle biomechanics, a vital and broad field for over 80 years now (A.V. Hill 1922: Nobel prize in physiology and medicine for his discovery relating to the production of heat in the muscle), explains the function and design of real biological muscle].

Hill's Model (Hill equation)

Hill model includes 2 parts:

1. A maximal F versus v relationship for quick release from isometric contraction with isotonic force.
2. Lumped parameter model to phenomenologically represent elastic stiffness component of muscle.

- Hill model was developed from energy balance concepts.

Hill showed:

- Muscle produced heat in isometric contraction.
- When isometrically contracted, muscle was released under an isotonic load that allowed muscle shortening.

$$H \propto x$$

where **H** is shortening heat and **x** is distance shortened

$$H = ax$$

where a is constant of proportionality and is function of level of action.

- **Hill also showed:**

$$\frac{a}{F_0} \approx 0.25$$

where F_0 is max isometric force.

During shortening contacting muscle produces extra heat (greater than isometric) and mechanical work

$$Work = Fx \qquad\qquad Heat = ax$$

Total energy in excess of isometric contraction then is

$$Energy = (F + a)x$$

Therefore, the rate of extra energy liberation is:

$$(F + a)\frac{dx}{dt} = (F + a)v$$

where v is the speed of shortening

Hill showed that rate of extra energy liberation was inversely proportional to load F applied to muscles in shorting experiments.

For isometric experiments

$$F = F_0 \qquad\qquad (F + a)v = 0$$

For contracting muscle experiments

$$(F + a)v = b\left(F_0 - F\right) \qquad \text{(Equation 1)}$$

where b is a constant associated with the rate of energy liberatio.

If v_0 is the maximum velocity of contraction at $F = 0$

Then Hill showed that parameter was related to v_0 by

$$\frac{b}{v_0} \approx 0.25$$

Rewriting equation 1 yields

$$(F+a)(v+b)=(F_0+a)b$$

Rearranging terms produces the Hill equation

$$F=\frac{F_0 b-av}{b+v}$$

Summary

- Why Muscles they important?
- There are three types of muscle found in the human body: Skeletal, Smooth, Cardiac.
- System and why muscle model?
- Muscle model (series, parallel,Hill model).
- Hill model and Hill equation.

For more information, refer to the following reference

- V. Hill/The Abrupt Transition from Rest to Activity in Muscle/ Series B,Biological Sciences, Vol. 136, No.884 (Oct. 19, 1949), pp. 399-420

- A. V. Hill/ the Series Elastic Component of Muscle/ Series B, Biological Sciences, Vol. 137, No.887 (Jul. 24, 1950), pp. 273-280

- Zajac, F. Muscle and tendon: Properties, models, scaling and applications to biomechanics and motor control, Crit. Rev. Biomed. Eng., 17, 359–411, 1989

- Winters, J. M.: Hill-based muscle models: a systems engineering perspective, Springer-Verlag, 69–93, 1990a.

- Winters, J. M.: Hill-based muscle models: a systems engineering perspective, in: Multiple muscle systems, Springer, 69–93,1990b.

- Robertson, D. G. E. (2nd Ed.). (2013). *Research methods in biomechanics*. Human Kinetics.