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Instructions: Update this file (or recreate a similar one, e.g. in Word) to prepare your answers to the questions. Feel free to add text, equations and figures as needed. Hand-written notes, e.g. for the development of equations, can also be included e.g. as pictures (from your cell phone or from a scanner). ***This lab is graded.*** *and must be submitted before the* ***Deadline : 11-04-2018 Midnight****.*
Please submit both the source file (.doc/*.tex) and a pdf of your document, as well as all the used and updated Python functions in a single zipped file called lab5_name1_name2_name3.zip where name# are the team member's last names. Please submit only one report per team!*

The file `lab#.py` is provided to run all exercises in Python. When a file is run, message logs will be printed to indicate information such as what is currently being run and and what is left to be implemented. All warning messages are only present to guide you in the implementation, and can be deleted whenever the corresponding code has been implemented correctly.

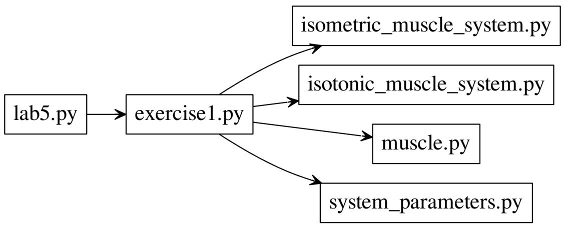


Figure 1: Exercise files dependencies. In this lab, you will be modifying `exercise1.py`.

Files to complete the exercises

- `lab5.py` : Main file
- `exercise1.py` : Main file to complete exercise 1
- `system_parameters.py` : Parameter class for Pendulum, Muscles and Neural Network (Create an instance and change properties using the instance. You do not have to modify the file)
- `isometric_muscle_system.py` : Class to setup your isometric muscle test experiments
- `isotonic_muscle_system.py` : Class to setup your isotonic muscle test experiments
- `muscle.py` : Muscle class (You do not have to modify the file)

NOTE : '*You do not have to modify*' does not mean you should not, it means it is not necessary to complete the exercises. But, you are expected to look into each of these files and understand how everything works. You are free to explore and change any file if you feel so.

Exercise 1 : Hill muscle model

Previous week you explored the role of different passive components and the effects of its parameters on the system. In this exercise, we try to understand the contractile or the active element of the hill muscle model. The components of the hill muscle are described in figure 2. The equations used to model the hill muscle can be found in the pdf `HillMuscleEquations.pdf`

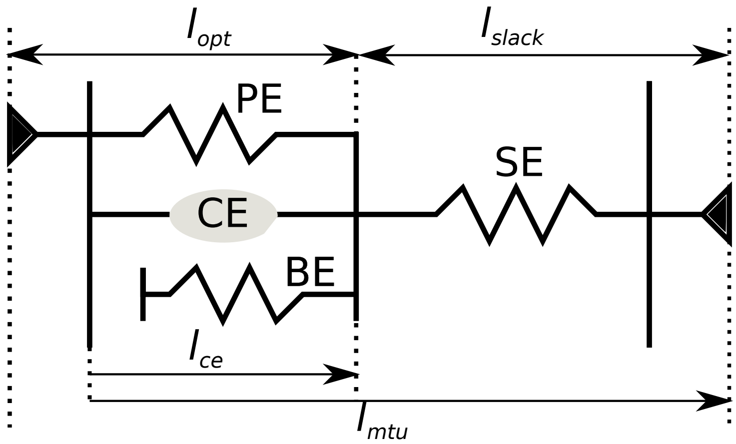
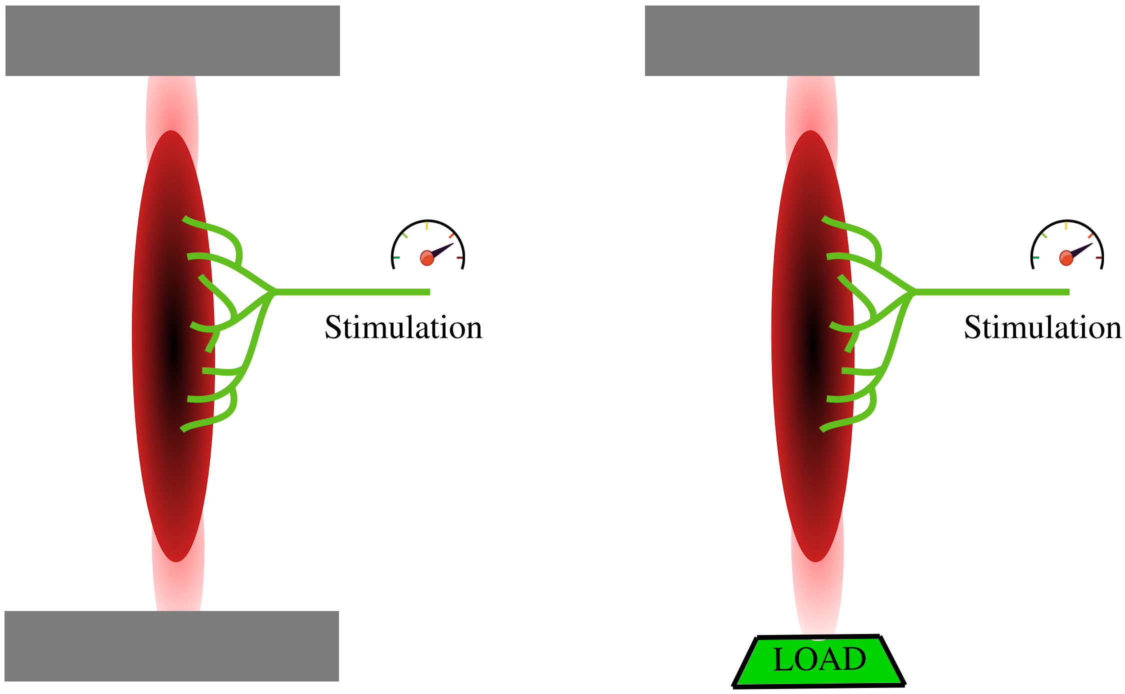


Figure 2: Hill muscle model

Where,

- PE : Parallel element (Prevents muscle from over stretching)
- BE : Muscle Belly (Prevents muscle from collapsing on itself)
- SE : Series element or the muscle tendon element
- CE : Contractile Element or the active element
- l_{opt} : Muscle optimal fiber length
- l_{slack} : Muscle tendon slack length
- l_{CE} : Contractile element length
- l_{MTC} : Muscle Tendon Complex length



(a) Isometric muscle setup :
To study the relationship between Force-Length.

(b) Isotonic muscle setup :
To study the relationship between Force-Velocity.

Figure 3: Muscle Length-Velocity-Force Setup

Muscle Force-Length Relationship

In this exercise you will explore the relation between the length and velocity of the muscle. In order to do this we replicate the set-up show in figure 3.Here the length of the muscle is held constant by attaching it's tendon to two fixed points. While applying a constant stimulation, observing the force produced will give the relationship between muscle contractile element length and force.

1.a For a given stimulation, explore the relationship between active and passive muscle forces and the length of the contractile element. Plot the force-length relationship curve. Discuss the different regions in the plot. Use the `isometric_muscle_system.py::IsometricMuscleSystem` instance to setup your experiment in `exercise1.py`

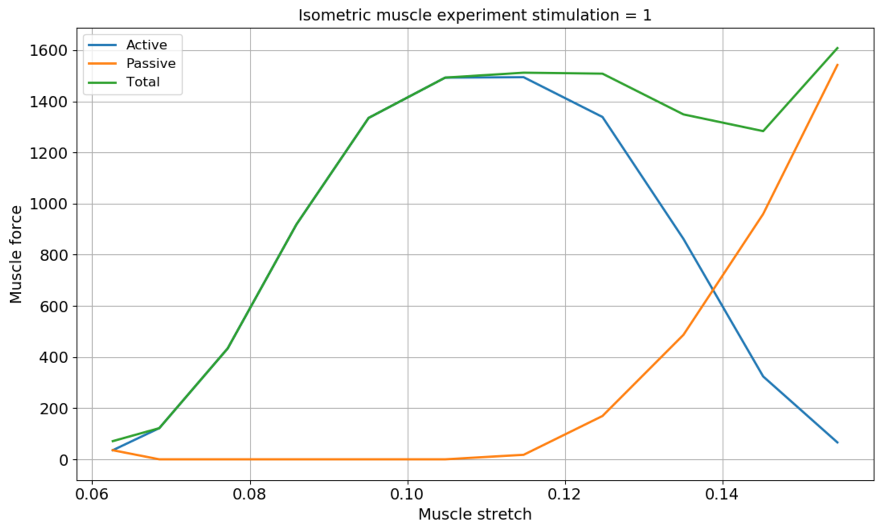


Figure 4: Relationship between active and passive muscle forces and the length of the contractile element in an isometric setup

Tension in skeletal muscles depends on the arrangement of myosin and actin filaments inside sarcomeres, elements arranged in series inside the myofibrils of the muscle fibers.
The passive force occurs when a muscle has been stretched from its resting length and as a result exhibits resistance to this stretching. This force increases exponentially with the muscle elongation until it reaches a plateau. The origin of the passive force is most likely a combination of the extracellular matrix with proteins acting inside myofibrils. It is an intrinsic characteristic of a muscle, you cannot change it as it is based on the internal structure of a muscle.
The active force is strictly dependent on the interaction of overlapping myosin and actin filaments via cross-bridging inside muscle units. It is based on a nervous input signal that recruits these muscle units. When the muscle stretch is too weak, the arrangement of the myosin and actin molecules is not ideal and they cannot create cross-bridges which produce the force. The more the muscle length increases the more the cross-bridges cycling takes place and thus more force is generated. At an optimal length, a maximum tension is reached. By increasing the muscle length beyond the optimal length the myosin and actin filaments are pulled away from each other and can thus no longer build cross-bridges, meaning no tension can be produced.
The total force is the combination of both active and passive forces. Figure 4 shows the curves for both active and passive forces, as well as the resultant total force, upon muscle elongation.

1.b In (1.a), you explored the muscle force-length relationship for a given stimulation. What happens to the relationship when the stimulation is varied between [0 - 1]? Support your response with one plot showing the different force-length relationship curves.

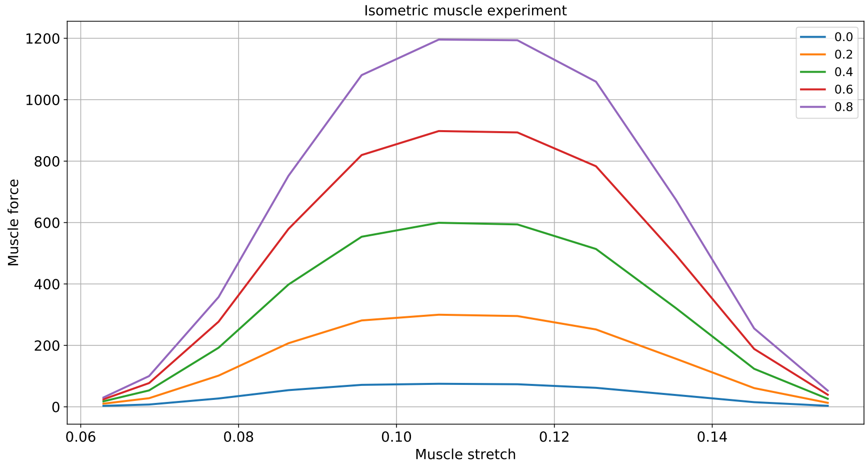


Figure 5: Relationship between active force and the length of the contractile element in an isometric setup with different levels of stimulation between [0-1]

With increased stimulation, the passive force does not change whereas the active force does increase, as can be seen in Figure 5.
Electrical stimulation of the muscle does not change the intrinsic properties of the muscle, which is why the passive force does not change. What does change is the input signal due to the increasing stimulation. The larger this stimulation is, the more muscle units are recruited and thus a larger force can be generated. However, one can observe that the minimum and maximum muscle stretch lengths remain the same no matter the stimulation.

1.c Describe how the fiber length (l_{opt}) influences the force-length curve. (Compare a muscle comprised of short muscle fibers to a muscle comprised on long muscle fibers.). To change the parameter you can use `system_parameters.py::MuscleParameters` before instantiating the muscle. No more than two plots are required.

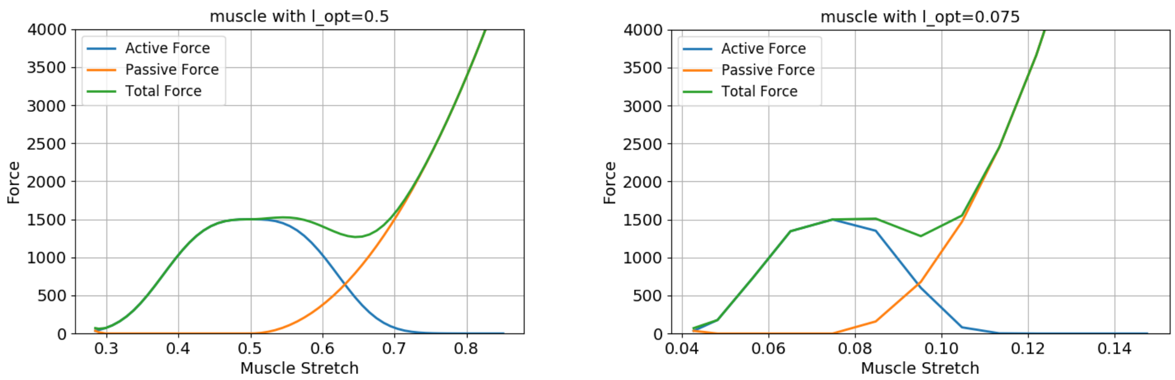


Figure 6: Relationship between active and passive forces and the length of the contractile element with varying optimal length

Changing the optimal length of the muscle fibers does not change the form and magnitude of the

tension produced, as we can observe in Figure 6 (maximal active force of about 1500N, for both graphs, at the optimal length).
However, since the optimal resting lengths are different, the stretch at which we have a local maximum in the total force produced is different. Having a longer optimal length will result in a higher muscle stretch to reach this local maximum, while the opposite can be observed for a short optimal length. Furthermore, the range of elongation of a muscle is bigger when having longer fibers, and smaller for shorter fibers.

Muscle Velocity-Tension Relationship

In this exercise you will explore the relation between the force and velocity of the muscle. In order to do this we replicate the set-up show in figure 3. Here the length of the muscle is allowed to vary by attaching one of its end to a fixed point and the other to a variable external load. While applying a constant load initially and holding the muscle at constant length, a quick release is performed to let the muscle contract and pull the weight. The maximum velocity during this quick release will give us the relationship between muscle contractile velocity and the force.

Note : Since the velocity changes sign and you need to compute the maximum velocity accordingly by checking if the muscle was stretched or compressed at the end of the experiment.

$$V_{ce} = \begin{cases} max(v_{ce}(t)) & l_{mtc} < (l_{opt} + l_{slack}) \\ min(v_{ce}(t)) & else \end{cases} \tag{1}$$

1.d For a stimulation of 1.0 and starting at optimal muscle length, explore the relationship between contractile element velocity and external load. Plot the Velocity-Tension relationship curve. Include shortening and lengthening regions. Use the `isotonic_muscle_system.py::IsotonicMuscleSystem` instance to setup your experiment in `exercise1.py`

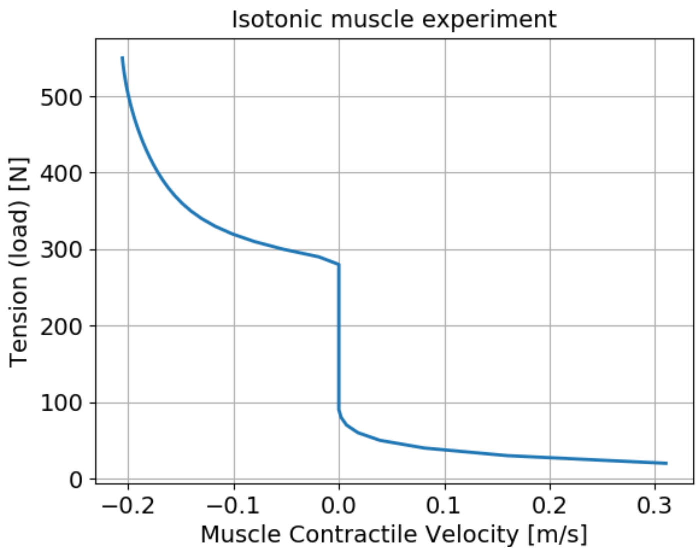


Figure 7: Relationship between the contractile element velocity and the external load, or tension, in an isotonic experiment

By increasing the load, and consequently increasing the force potential, the length of the muscle increases with increasing velocity.

Conversely, by decreasing the load, the force potential decreases and also the length of the muscle decreases with increasing velocity (muscle shortening). For intermediate values of load (between 75N and 275N, in our case) the length stays constant and so the velocity is zero.
As we can observe in Figure 7, the higher the load the larger the change in velocity: this can be explained by the fact that the muscle can only support a certain load until its fibers get damaged.

1.e For the muscle force-velocity relationship, why is the lengthening force greater than the force output during shortening? No plots necessary

As stated during the isometric experiments, the force generated by a muscle depends on the interaction between thick and thin filaments using cross-bridges.
It takes a certain amount of time for the myosin heads to attach to the actin filaments, so when the velocity increases (shortening) the filaments slide one over the other too fast and thus the tension decreases because of the lack of filaments' interactions.
On the other hand, when the velocity decreases (lengthening) there is enough time for the interactions to form and the generated force is greater.

1.f What happens to the force-velocity relationship when the stimulation is varied between [0 - 1]? Support your response with one plot showing the different force-velocity relationship curves.

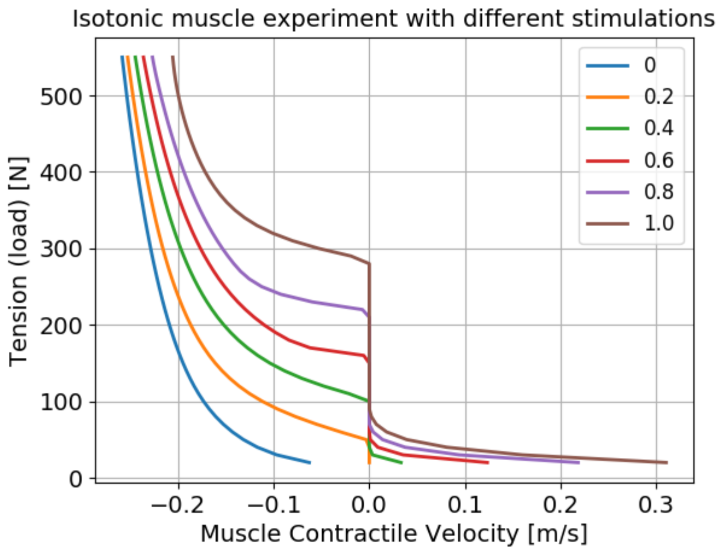


Figure 8: Force-velocity relationship curves for different stimulations between [0 - 1]

When the stimulation is decreased, the shortening range becomes smaller and smaller until disappearing without stimulation, and the contractile velocity decreases.
If the stimulation is too low, there are not enough muscle units recruited and the muscle contraction cannot counter-balance the load and shorten. In this case the muscle would simply stretch and the velocity measured is the one of the elongation.
It is by applying a certain amount of stimulation that enough units are activated and recruited and thus the muscle can contract enough to pull up the load, resulting in an increase of velocity.