Student names: ... (please update)

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 not graded. However, the lab exercises are meant as a way to familiarise with muscle models and to study them using Python to prepare you for the final project.*** *This file does not need to be submitted and is provided for your own benefit. The graded exercises will have a similar format.*

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.

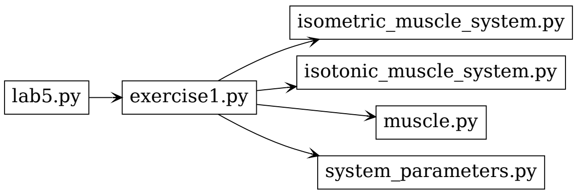


Figure 1: Exercise files dependencies. In this lab, you will be modifying `exercise1.py`.

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 (You do not have to modify the file)
- `isotonic_muscle_system.py` : Class to setup your isotonic muscle test experiments (You do not have to modify the file)
- `muscle.py` : Muscle class (You do not have to modify the file)
- `mass.py` : Mass model 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`

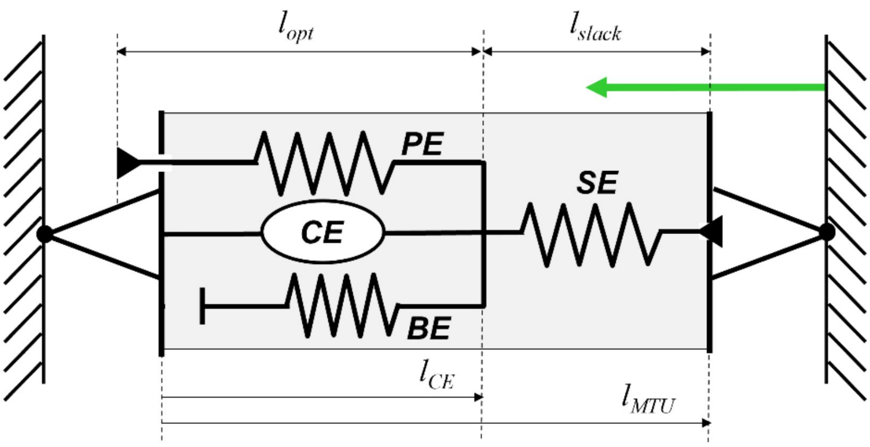
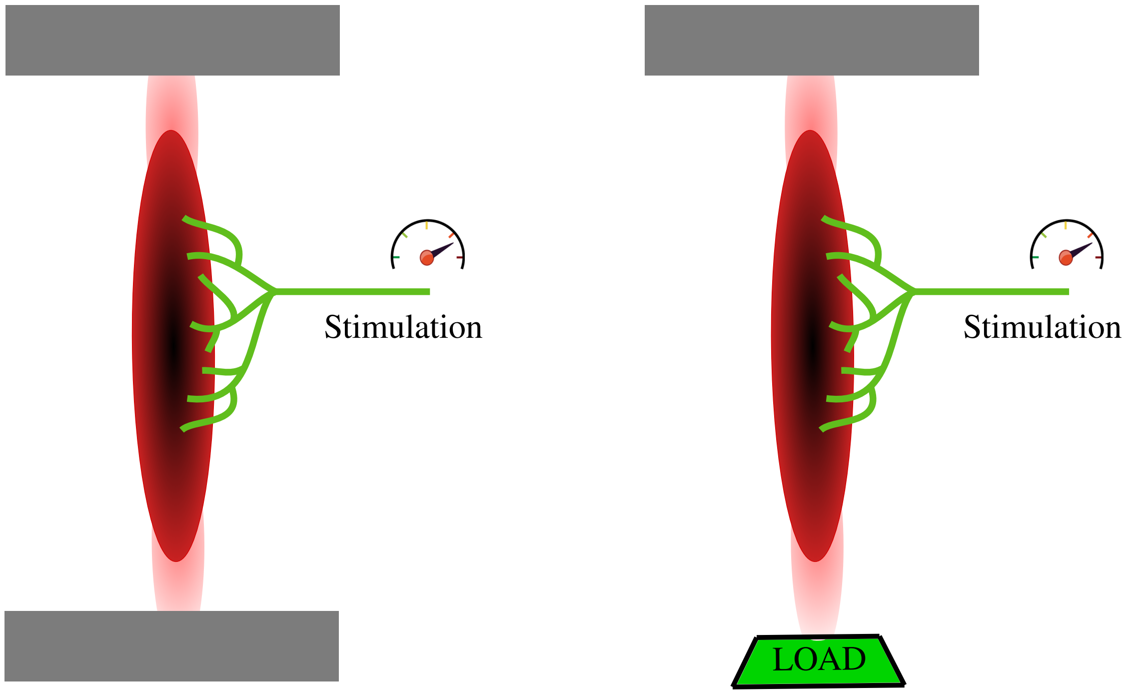


Figure 2: Hill muscle model

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_{mtu} : Muscle Tendon Unit 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`

The students should perform a series of isometric muscle contractions to produce the necessary plot to study the relationship between muscle forces and contractile element length. At a stimulation of 1.0, figure 4 shows the different components of the muscle that contribute to the total force for a given length. The relationship can be divided into two regions, one below optimal length and second above optimal length. The passive force only engages when the normalized muscle contractile element is greater than 1.0. And there after the active force drops as the muscle stretches more and the passive forces increase exponentially. The active muscle force also drops when the normalized contractile length is less than 1.0.

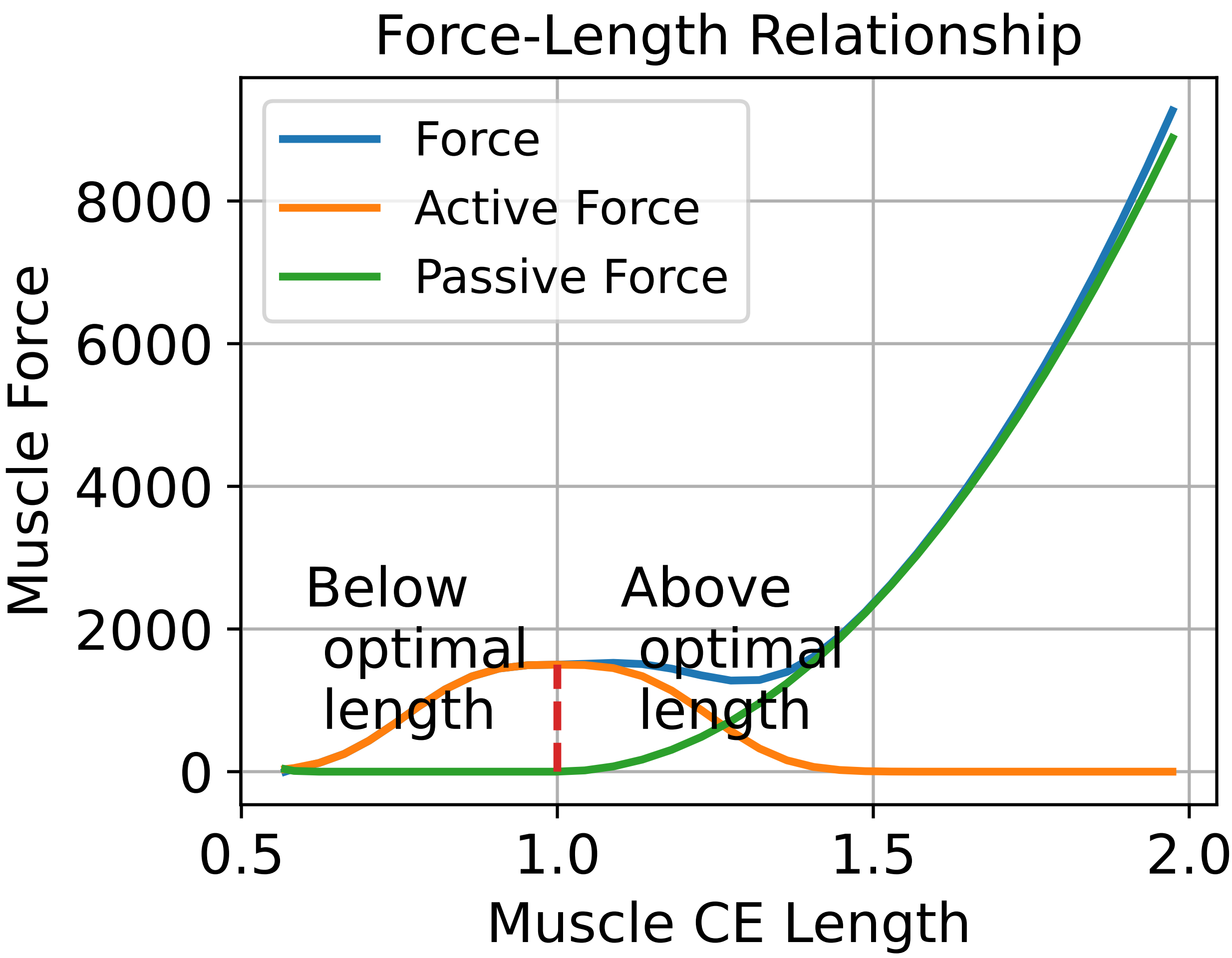


Figure 4: Muscle Length Tension Relationship under isometric condition for a muscle stimulation of 1.0

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 shows the relationship of the muscle force and muscle length under different stimulation conditions. Only active tension is plotted since the muscle activation only influences active force and not the passive components.

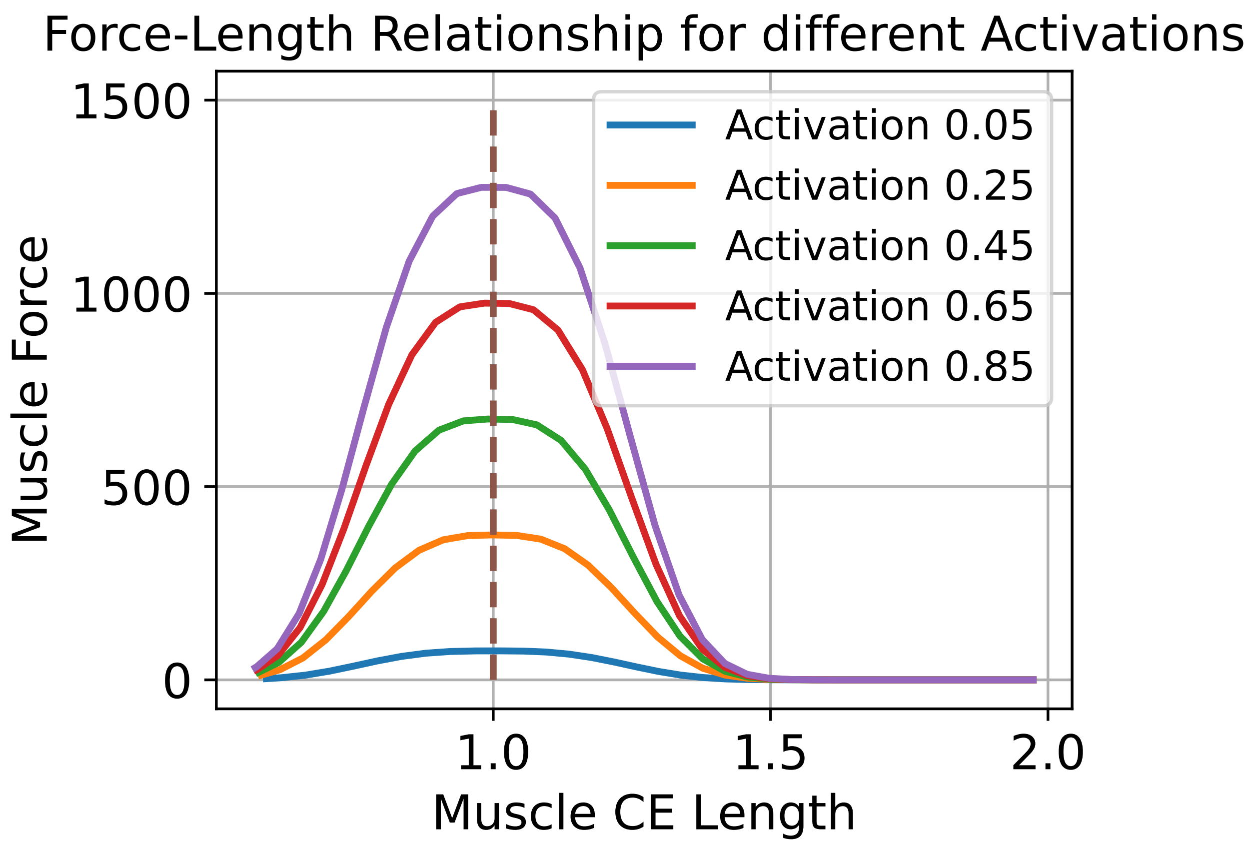
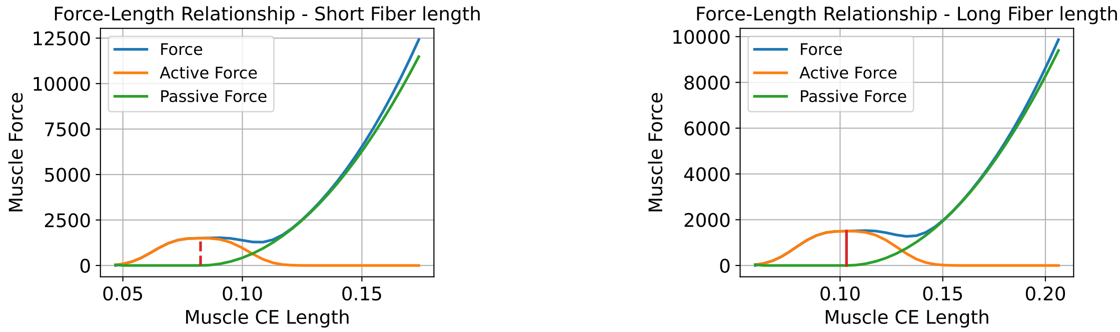


Figure 5: Muscle Length Tension Relationship under isometric condition for a muscle stimulation of 1.0

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.

In order to evaluate the effect of fiber length, we set the $l_{opt} = l_{opt} \pm 0.25 * l_{opt}$ to simulate short and long fibers respectively(Note : The students can choose different l_{opt} values to evaluate). Figure 6a and 6b shows the force-length relationship for the above l_{opt} values. One observation is that the shape of the curves do not change. Which means, in order to observe the difference in two conditions we need to plot the forces against the actual l_{ce} length

With short fiber, the range of active force development is much smaller compared to the long fiber. This means short fibers produces higher muscle force in a small range of muscle length change and then quickly drop to zero. While the long fibers have a bigger range and there by can produce sustained max force for a larger change in muscle length. This has a direct implication on the Range of Motion(ROM) of the joint on which the muscle operates.



(a) Force-Length relationship for short fiber

(b) Force-Length relationship for Long fiber

Figure 6: Effect of fiber length on muscle force-length relationship

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.

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

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 shows the relationship between muscle force and muscle velocity. The plot can be divided into three sections. The shortening region marked as concentric condition. The lengthening region marked as eccentric condition. And finally the isometric condition. NOTE : Students might observe slightly different looking curves depending on whether they plot velocity versus tendon-force or active-force or external load. The main observations should be the above mentioned three regions present in the plots.

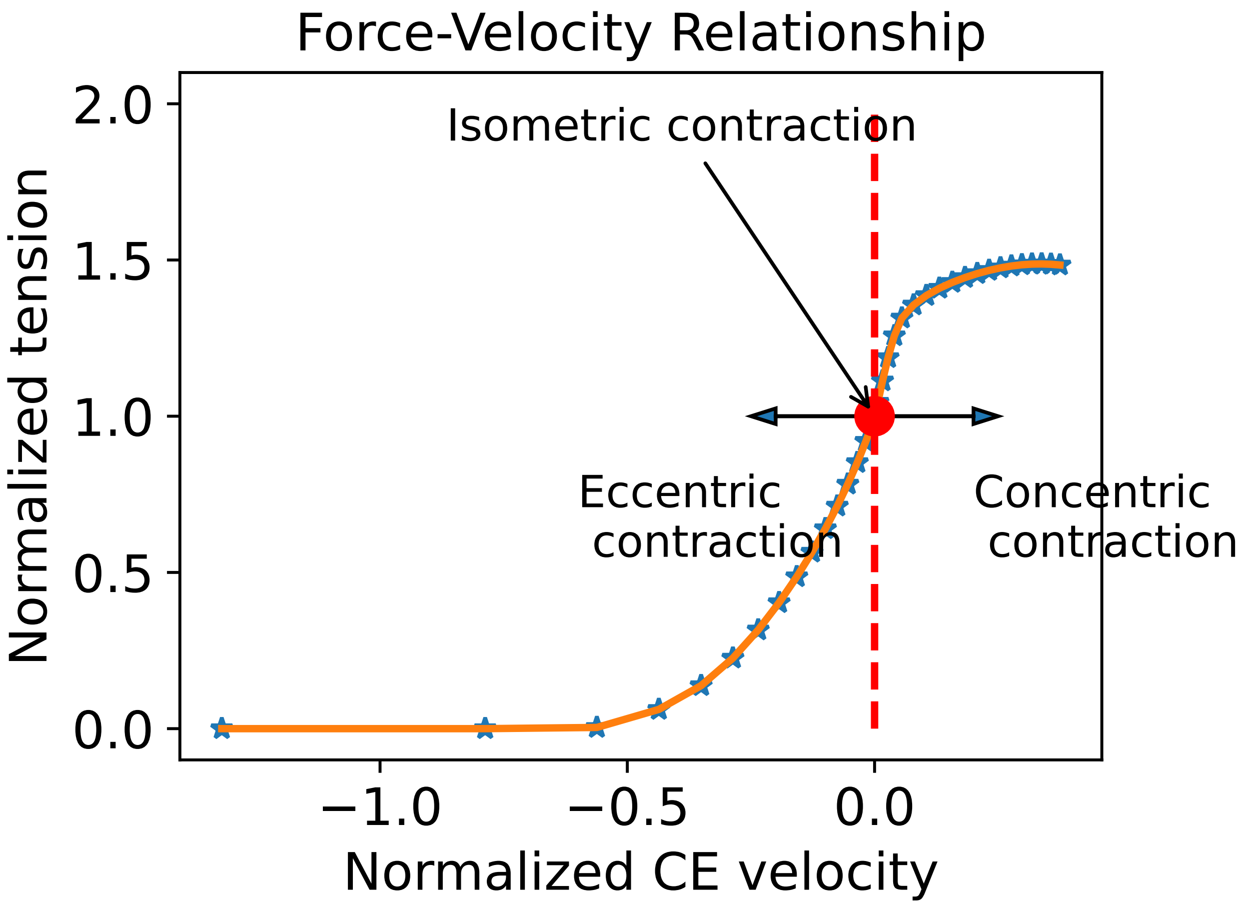


Figure 7: Muscle Force Velocity Relationship under isotonic condition for a muscle stimulation of 1.0

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

Figure 7 shows the relationship between muscle force and muscle velocity. When the external load is greater than what the muscle can produce, the muscle begins to stretch even while fully activated. This is called as muscle lengthening and the region is found under eccentric contraction. While the external load is smaller than the maximum muscle force, muscle shortens quickly and this is the shorterning region and is found under concentric contraction. During eccentric contraction/lengthening, the muscle is stretching due to the load while the active element is trying to shorten. Under this condition muscle builds up passive forces due to the elastic nature and results in a higher tension. Where as during concentric contraction, the muscle force is only due to the active element and no passive tension is generated which results in a lower force during shortening.

The students can also explain this using the muscle filament model, that is using sarcomers and the how they bind together during these conditions. This can be found under the lecture notes.

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 shows the force velocity relationship with under multiple stimulation levels. Like we observed in the force-velocity relationship, changing the stimulation only affects the magnitude of the force and the shape of the force-velocity profile. Under lower stimulation, the muscle velocity saturates much quicker than while it is fully stimulated.

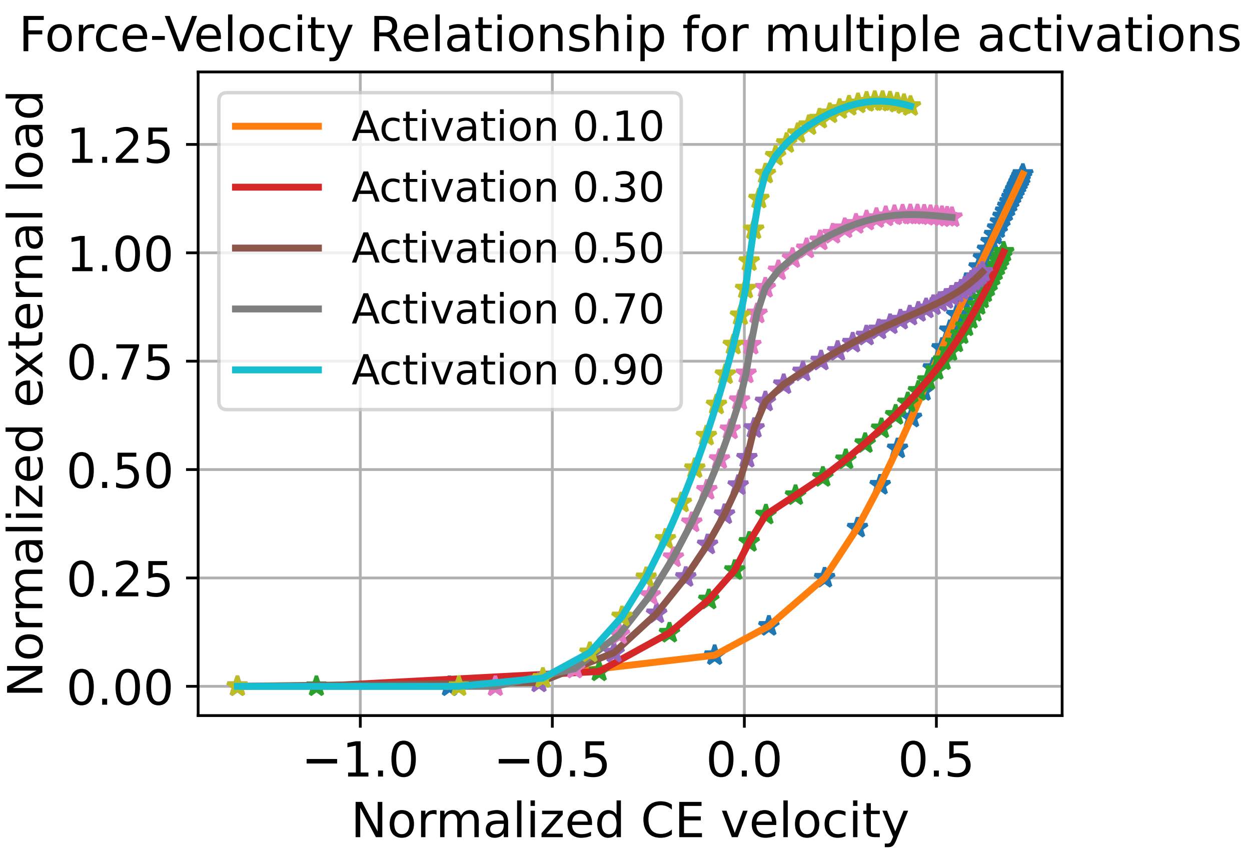


Figure 8: Muscle Force Velocity Relationship under isotonic condition for multiple muscle stimulations