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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 : 22-04-2020 23:59****. 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.

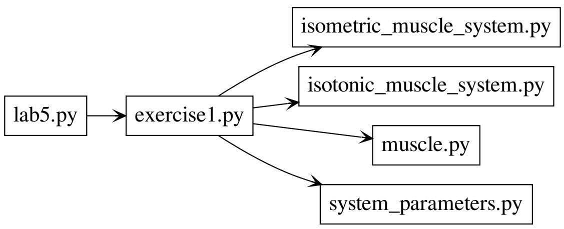

Figure 1: Exercise files dependencies. In this lab, you will be modifying `exercise1.py`.

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 (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.

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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`

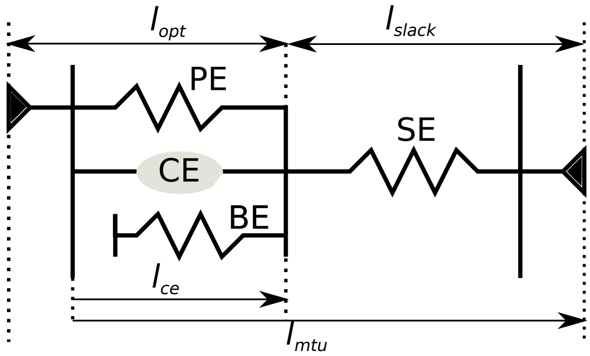

Figure 2: Hill muscle model

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

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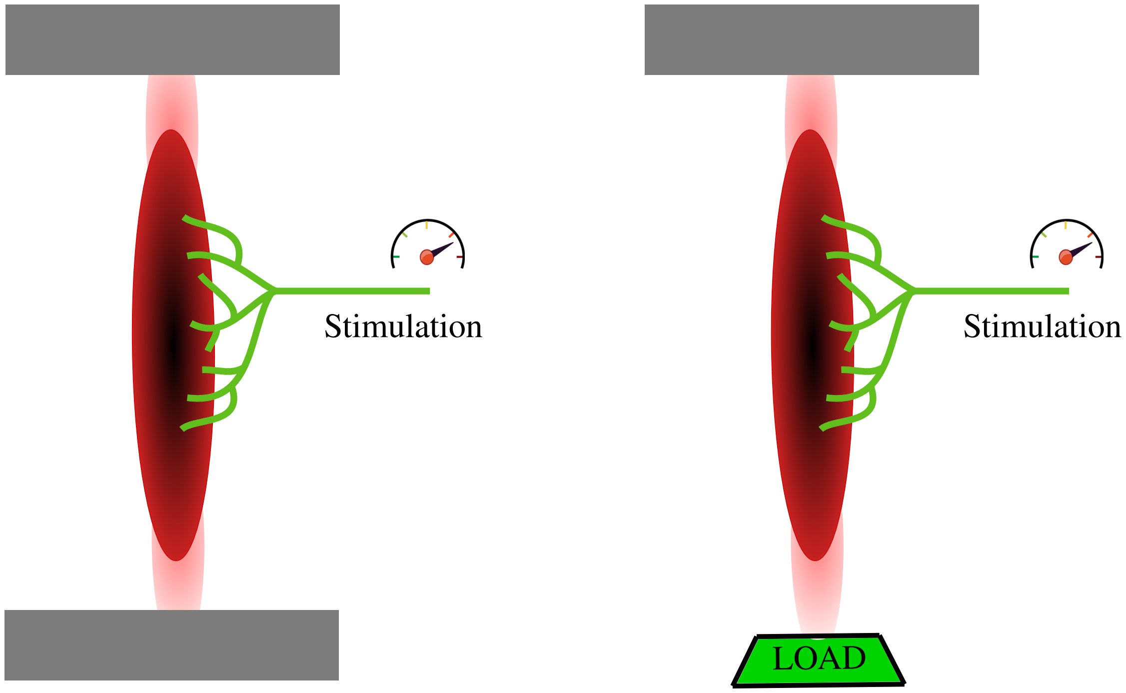


(a) Isometric muscle setup :
To study the relationship between Force-Length.

(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 5.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`

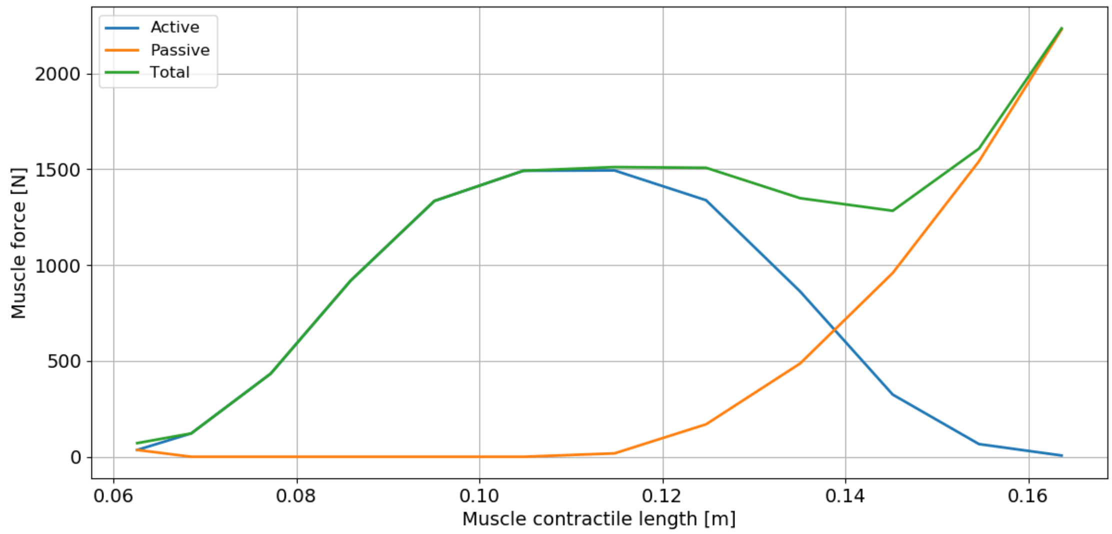
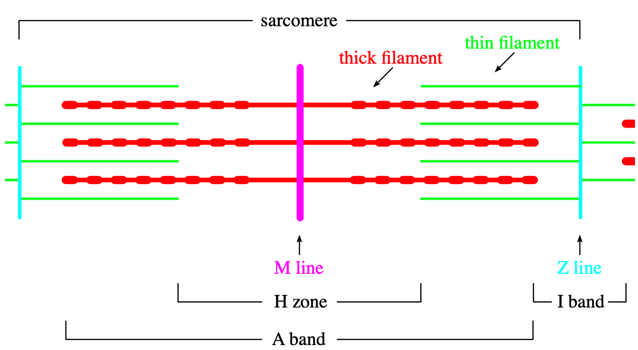


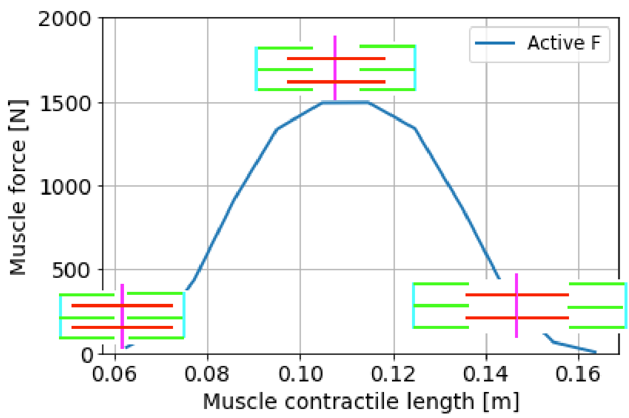
Figure 4: Isometric muscle experiment, muscle forces vs length of contractile element, stimulation = 1

According to figure 2, l_{opt} is the muscle optimal fiber length. The muscle emits passive and active forces. Passive forces come from the spring behavior of the muscle. This means that when it is stretched, it will tend to go back to its initial length, with a certain spring constant. Here, $l_{opt} = 0.11$ m. Thus, if the length of the contractile element (CE) is less than 0.11 m, the CE is not stretched, and no passive force occurs. If the CE length is bigger than 0.11 m, stretching occurs, and the passive force will increase with the stretching.

To understand the active force - CE length relation, we will need to look at the structure of a sarcomere, which is the contractile unit of a muscle.



(a) Sarcomere unit



(b) Contractile element length vs active force

Figure 5: Sarcomere stretching vs active F
source Figure 5a: https : //commons.wikimedia.org/wiki/File : Sarcomere_diagram.svg

The myosin (thick filament) interacts with the actin (thin filament) during a contraction. As visible in figure 5b, when the CE length is close to 0 m, the actin filaments totally overlap the myosin filaments. In this position, the myosin cannot pull the Z line towards the M line. In other words, it cannot contract and thus, no or small active forces are produced. On the opposite way, when the muscle is stretched too much (here around 0.16 m), the myosin cannot interact with the actin anymore. Thus, no active force is produced either. Finally, when the CE length is around l_{opt} (= 0.11 m here), the position of actin and myosin is optimal for active force generation.

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.

First of all, we need to remember that the passive force is not supposed to vary with the stimulation intensity. Indeed, the material intrinsic properties of the muscle normally do not change for different stimulations. Therefore, we only consider the active component of the muscle force to answer this question.

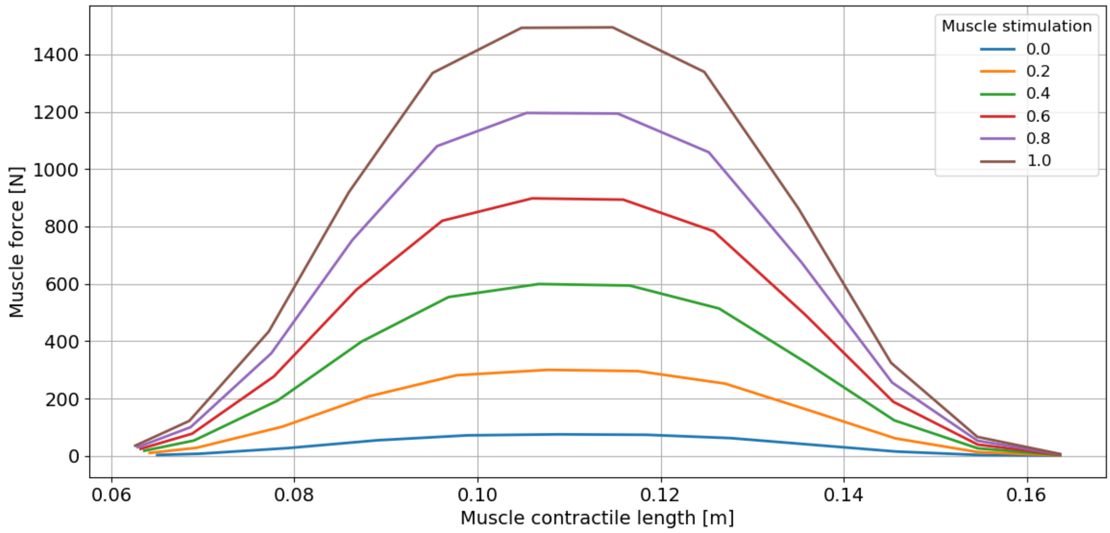


Figure 6: Isometric muscle experiment, muscle forces vs length of CE for a set of different stimulations

As the number of muscle fibers recruited is supposed to augment when the electrical stimulation of the muscle increases, we expect the active force developed by the muscle to also increase with the stimulation. This is coherent with figure 6, where we can see in addition that the global shape of the curves for different stimulations looks roughly the same. Indeed, the basic behavior of the muscle is not supposed to change in function of the stimulation intensity. We can also notice that the curve of the active force corresponding to no stimulation is not perfectly flat (does not remain null), which is in fact due to numerical implementation issues (in the activation_dadt() method of the muscle.py::Muscle class, the minimum stimulation is set to 0.05).

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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.

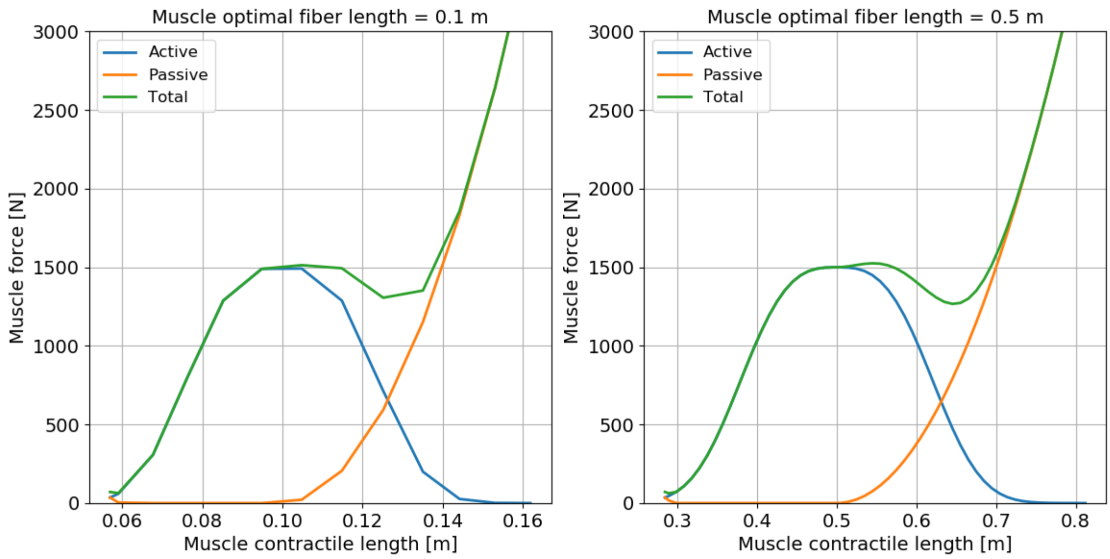

Figure 7: Isometric muscle experiment, muscle forces vs length of contractile element for two different l_{opt}, stimulation = 1

As it can be seen in figure 7, the value of the optimal fiber length does not change the shape of the muscle passive and active forces plotted in function of the muscle contractile length. It does not change either the magnitude of these forces: for example, the maximum of the active force is 1500 N for both experiments.

However, it is visible that an increasing l_{opt} translates the F-CE length curves to the right and dilates them. So the optimal fiber length changes:

- the muscle contractile length value at which the active force is maximal and the passive force begins to increase: it is equal to l_{opt}, as explained in question 1.a
- the maximal muscle stretch: fibers with a l_{opt} of 0.1m enable a maximal stretch of around 0.16 m while fibers with a l_{opt} of 0.5m allow for a maximal stretch of around 0.8 m.

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 5. 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`

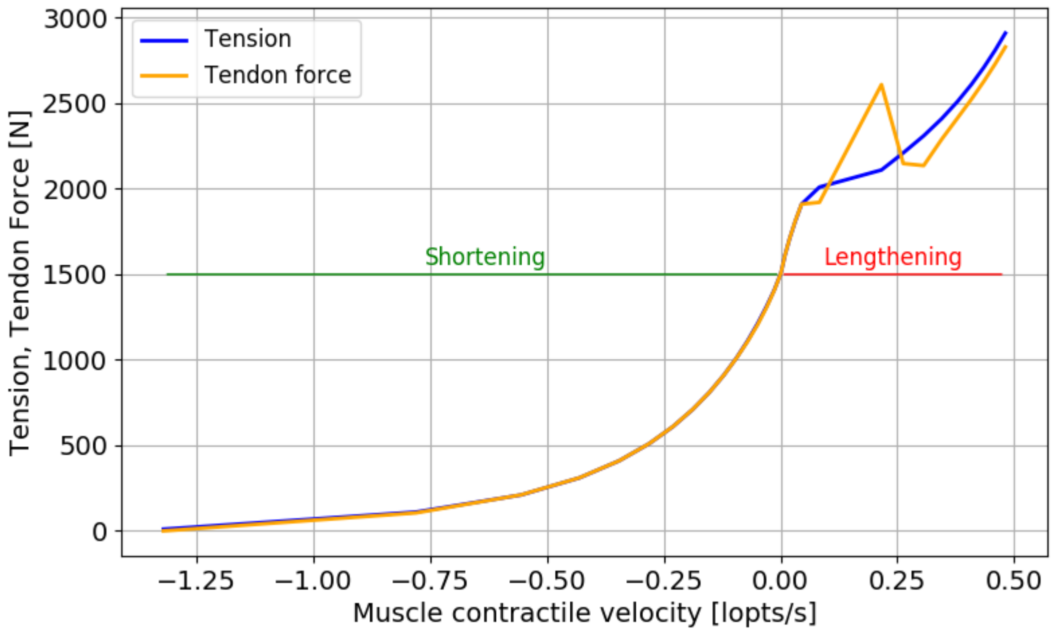

Figure 8: Isotonic muscle experiment, relationship between the muscle contractile element velocity and the tension/tendon force applied to it.

First notice that for this isotonic experiment with constant stimulation, we consider the velocity as negative during contraction (shortening) and positive during stretching (lengthening).

As expected, we can observe in figure 8 that for low loads, the muscle contracts and lifts the load. As the load increases, the difficulty to lift the load is bigger. Therefore, the maximum contractile velocity reached during the muscle contraction decreases in absolute value, until reaching an equilibrium for a tension of 1500 N (null muscle contractile velocity). Beyond this equilibrium state, the muscle stretches and the force developed by the muscle is not sufficient to lift the load anymore, which moves downwards. As the load increases, both the length and the velocity increase until the muscle tears. It seems that fibers begin to break for a tension of around 2100 N in this experiment.

For negative muscle contractile velocities, the tension and the tendon force are exactly the same. However, for velocities larger than around 0.05 lopts/s, the tendon force curve starts to adopt a less regular behavior than the tension. Indeed, as said before, the muscle stretches for positive velocities.

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

The force generated by the muscle depends on the degree of interaction between thin actin filaments and thick myosin motor proteins. So if the muscle is lengthened (i.e. velocity increases), it seems that the lengthening works against the direction of the formation of actin and myosin cross-bridges, leading to high forces. On the contrary, it seems that the shortening of the muscle (i.e. velocity decreases) counteracts too much the interactions between actin and myosin filaments such that no large forces can be generated.

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.

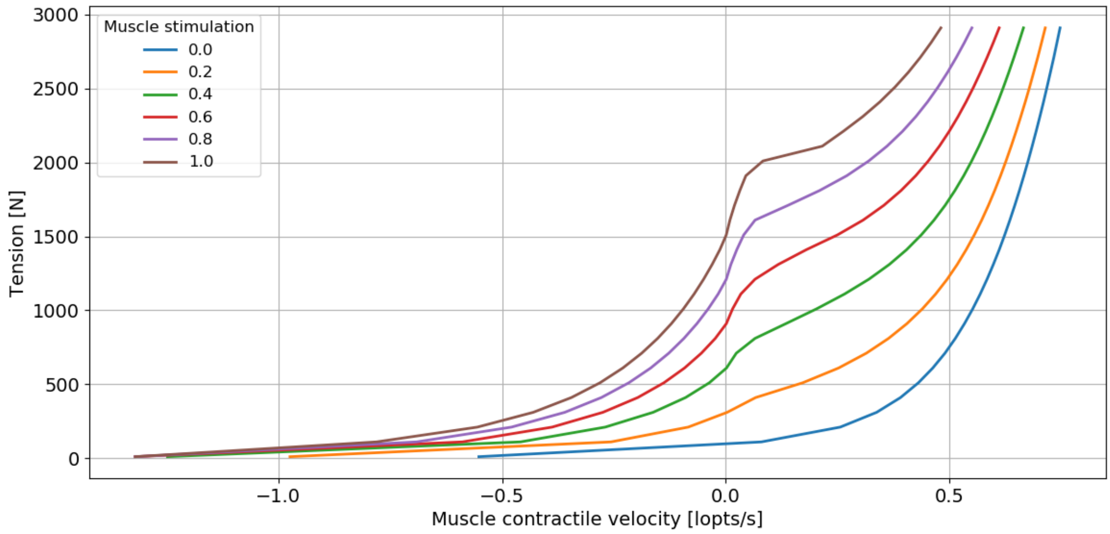

Figure 9: Isotonic muscle experiment, relationship between the muscle contractile element velocity and the tension applied to it for a set of different stimulations.

Figure 9 shows that decreasing stimulations flatten the Tension-Muscle contractile velocity curve. That means that a smaller stimulation reduces the range of loads that the muscle can lift. For example, with a stimulation of 1, the muscle can contract and support a tension up to 1500 N, whereas with a stimulation of 0.2, the muscle can only support a tension up to 300 N before elongating.

This is due to the fact that the number of muscle fibers recruited depends on the electrical stimulation of the muscle. For a big stimulation, lots of muscle fibers are activated and thus the muscle can contract enough to lift big loads. On the other hand, for a small stimulation, only few muscle fibers are recruited and their contraction cannot counter-balance the tension applied by the load, thus the muscle begins to elongate with very small loads.