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Exercise 1 : Hill muscle model

Muscle Force-Length Relationship

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 experimentation results are found in Figure 1. We decided to modify two parameters:

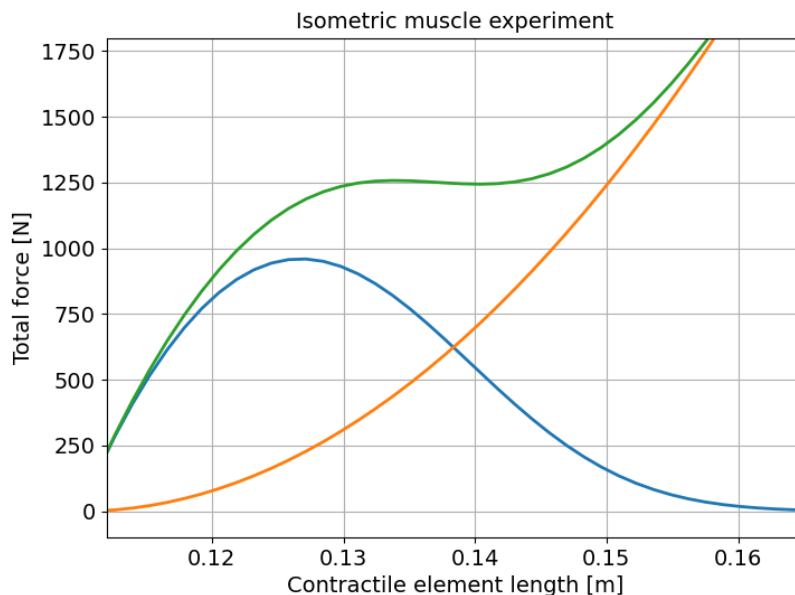- muscle_stretch = 0.5

- muscle_stimulation = 0.7

Figure 1: Result of experimentation 1_a. Blue: active force [N]; Orange: passive force [N]; Green: total force [N]

As shown in slide 34 of Lecture 2, the passive force behaviour can be observed when the muscle is stretched from a certain length (when it is not slack anymore) - here this slack region does not exist - due to the spring resistance in the sarcomeres. The harder we pull on the muscle, the stronger the reaction force is, just like a non-linear Hooke law (non-linear spring behaviour), until the sarcomere/fiber/muscle ruptures.

As for the active force, it also depends on the length of the sarcomere, but this time on the overlapping ratio of the actin over the myosin. If the fiber is too contracted, the sarcomere cannot contract that much and does not produce a lot of force. If the fiber is too stretched, there is not enough overlap between the two components to produce a good traction force. By adding the two forces together, we can observe that the total force reaches a local maximum (when applying a high enough stimulation, because otherwise we don't have a lot of active force available) at the optimal muscle length, which in our case is 0.13[m].

The total force graph has three main regions:

- From $l_ce = 0$ to about 0.13[m]: first fast rise of the total force due to predominance of rising active force due to the fact that there is more and more space between the two Z-rings of each sarcomere to allow a good contraction of the myosin relatively to the actin.

- from $l_ce = 0.13$ to about 0.143[m]: plateau of the total force, where the decrease of the active force is compensated by the increase in the passive force. (the negative effect of the decreasing overlap actin-myosin on the active force overtook the positive effect of the space increase between the Z-rings since before we reached the optimal length).

- from $l_ce = 0.143$ to the muscle rupture: new rise of the total force, for the increase of the non-linear spring-reactive passive force is bigger than the decrease of the active force.

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.

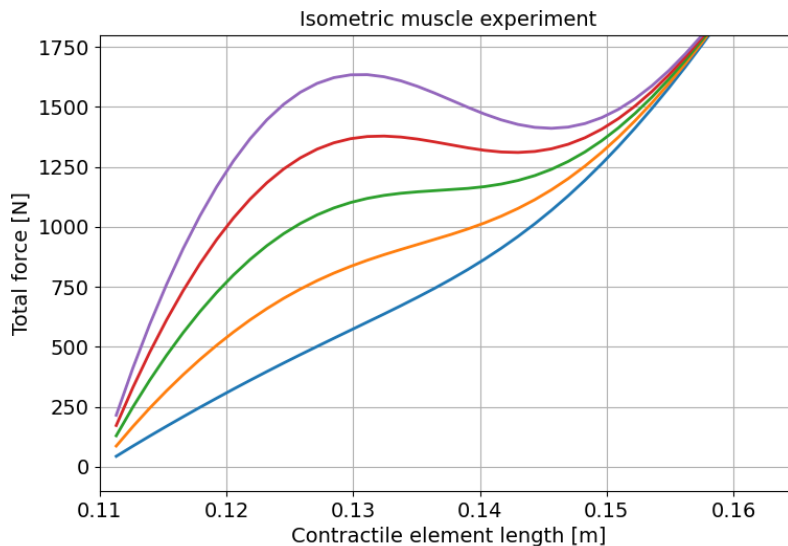The measurements on different stimulation values can be found on Figure 2.

Figure 2: Result of experimentation 1_b. stimulation = 0.2[N]; stimulation = 0.4[N]; stimulation = 0.6[N]; stimulation = 0.8[N]; stimulation = 1[N]

As explained in part 1.a, a lower stimulation implies that the active force will be lower at the same muscle length, which means that the predominant force will be the passive one.

1.c Describe how the[N] 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.

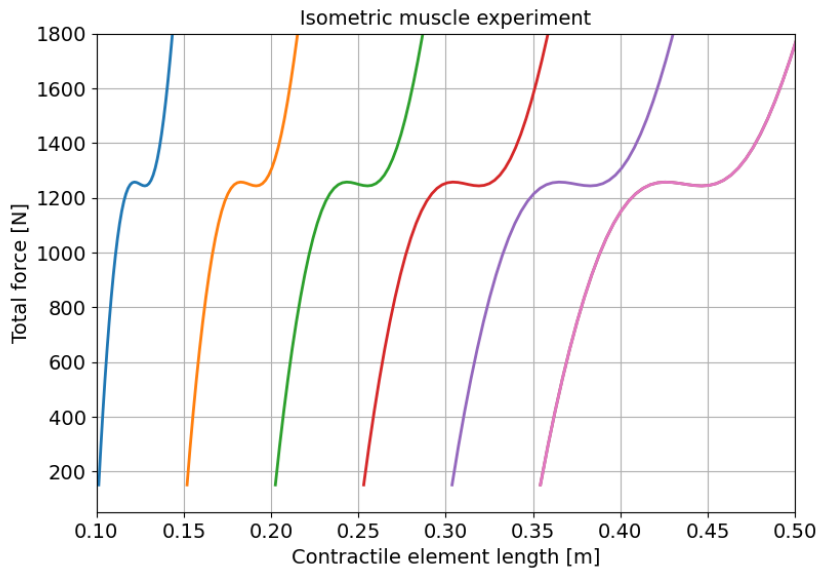The result of the exercise 1.c can be found on Figure 3.

Figure 3:   Result of experimentation 1_c: L_opt =: 0.10[m]; 0.15[m]; 0.2[m]; 0.25[m]; 0.3[m]; 0.35[m]

We can observe that a longer muscle fiber has a bigger plateau near the optimal fiber length, which is in turn further away from the initial fiber length than for a shorter muscle fiber. This can be explained by the fact that the active force will decrease less rapidly because the myosin and actin will be overlaped for a longer period of time after exceeding the optimal length.

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 **??**.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.

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

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`

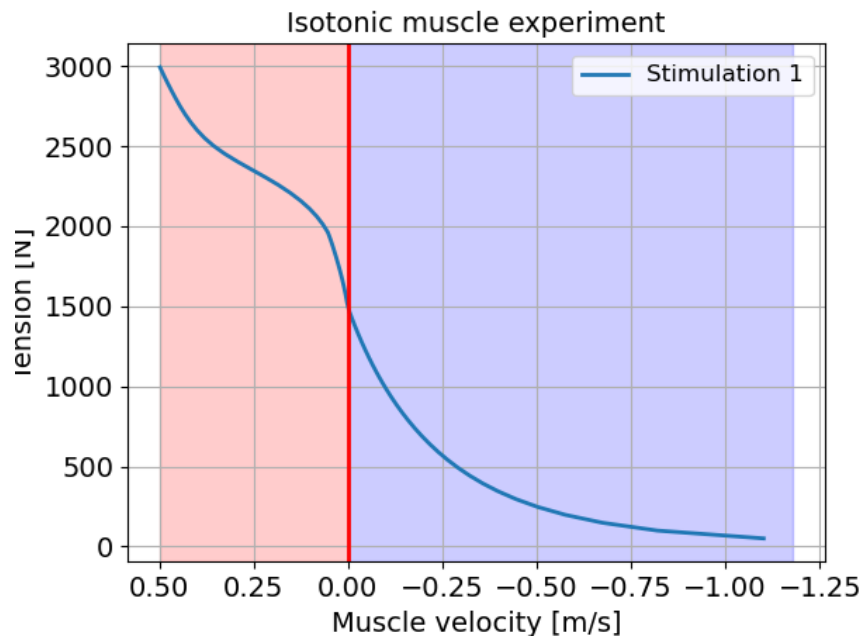The result of the exercise 1.d can be found on Figure 4.

Figure 4: Result of experimentation 1_d. In red: lengthening region, in blue: shortening region

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

As explained graphically in slide 35 of the lecture 5, when the muscle is being lengthened, we are working against the actin-myosin interaction direction, which means that we need a higher force to obtain the same deformation velocity than in the shortening direction.

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.

The result of the exercise 1_f can be found on Figure 5.
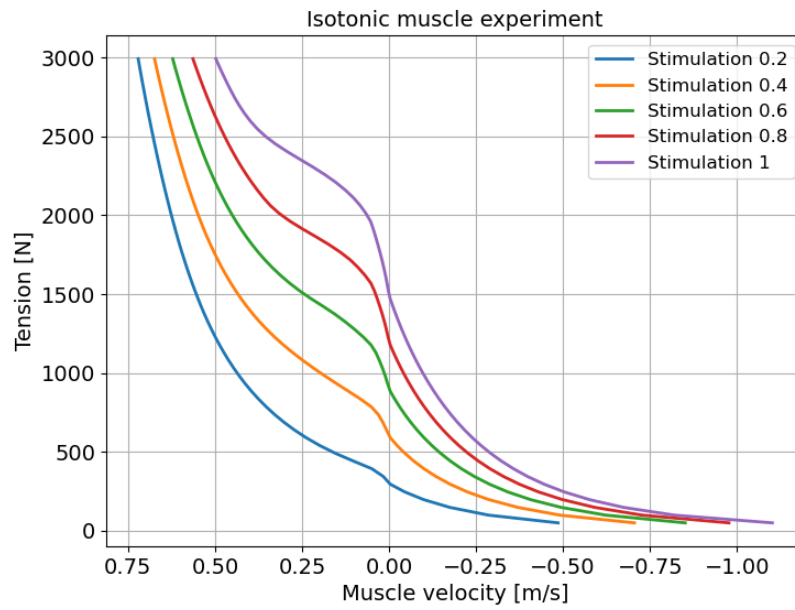
Figure 5: Result of experimentation 1_f

A more stimulated muscle fibre needs more force to be lengthened and shortened because the actin-myosin interaction will be stronger, therefore harder to act upon.