Scone Assignement

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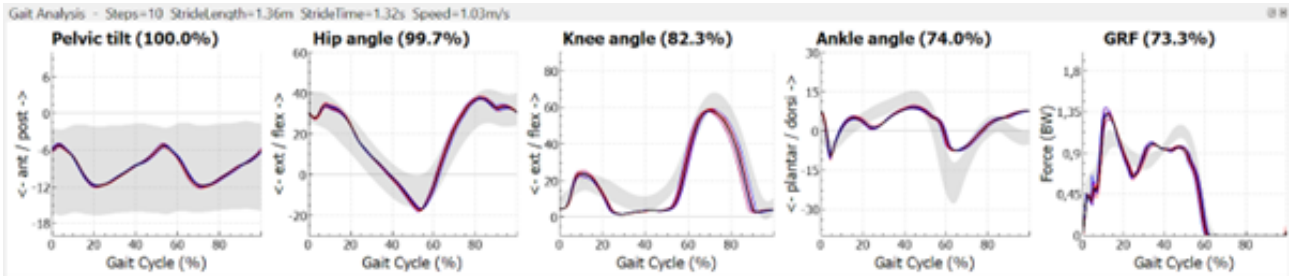
Deliverable 1

1. First, run three optimizations, one for normal, and one for slow and one for fast gait by changing the measure file.

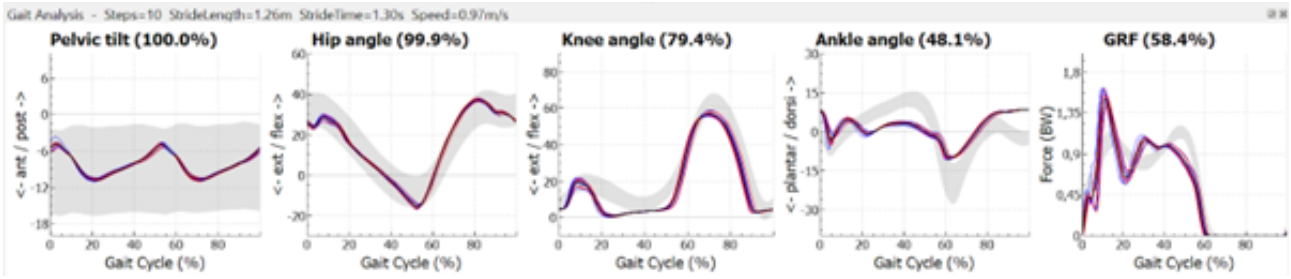
In order to run the optimisation at the corresponding speed, we need to change the measure file in the main file, as it defines the target speed as min_velocity. For slow, normal and fast gait we use respectively *"MeasureGait**05**Grf15.scone"*, *"MeasureGait**10**Grf15.scone"* and *"MeasureGait**15**Grf15.scone"* files.

2&3. Please comment on the results obtained from the values of the objective functions (see the message window) and gait analysis tool comparing the three solutions.
What can be improved in terms of gait properties (please elaborate)? First of all we recall that during a gait cycle, using the foot strike of one limb as the limit of the gait by convention, the stance phase of this limb is from 0% to 60% of the cycle, and the swing phase from 60% to 100%.
Also, on each graph, the light gray curves represent the ranges for a healthy gait at normal speed, and is there to make comparisons.

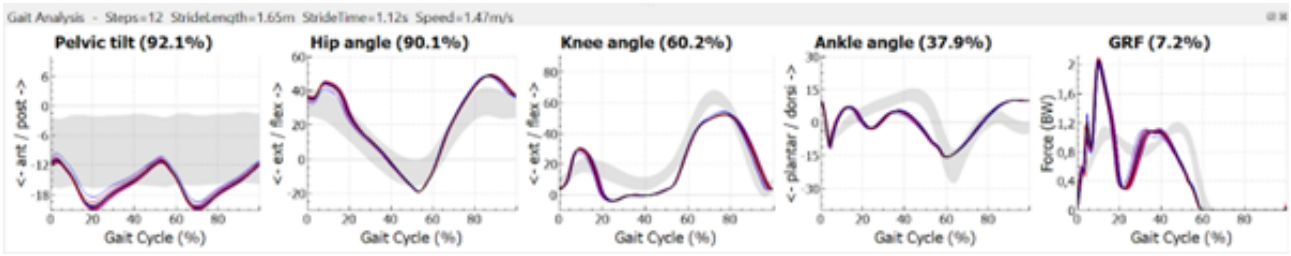
In figure Fig.1 we displayed the results of the *Gait Analysis Tool* obtained for the slow, normal and fast gait of the healthy model. In general, we observe similar behavior accross the different gait speeds for a given parameter (e.g angle, ground Reaction Force). However, their is a shift when the speed increase making the values deviate from the ideal range. Furthermore, a very good value of the objective function (R<0.7) was obtained under 50 generations for the slow and normal gait. In contrast we had to wait until generation 88 to only get R=1.17 for the fast gait, a acceptable but higher value. This difference may be caused by the optimisation variations across computers.



(a) slow gait, objective function: R=0.6 at gen 39 and R=0.567 at gen.125



(b) normal gait, objective function: R=0.693 at gen 23



(c) fast gait, objective function: R=1.17 at gen 88

Figure 1 : Slow, normal and fast gait analysis results for a healthy gait

For the pelvic tilt, the results are almost similar between normal and slow gait, and the scores are very good compared to expected values (metric of 100% or almost). But for fast gait, we observe that the pelvic tilt curve is significantly shifted toward the anterior side. It is understandable that if the gait is fast, the pelvic angle behaves like this as the model leans forward. What could be improved is that the model should absorb more energy in the tigh and make larger steps in order to compensate for the fast gait, rather than tilting the torso forward.

For the Hip Angle, the only significant change occurs at fast gait : the hip flexion is higher, especially at 80% during the swing phase. This brings the thigh to be too high during the swing phase and the hip makes a too big abduction (=movement away from the body line).

For the knee and ankle angle, we observe the same gait deterioration with increasing speed. The ankle angle goes down to 37% for fast gait, and we can observe an abnormal exaggerated oscillation of the ankle when the foot is on the floor (between 10% and 40% of the gait cycle). That causes jiggling/quivering of the foot, as it could be observed in the viewer window. This is why the ground reaction Forces (GRF) are chaotic at the same time (about 20% of the gait cycle), leading to a very poor score of 7.2% of similarity against normal values. Also, the ankle angle doesn't reach its maximum at the end of stance (at 50% of the gait cycle).

The Knee angle gets too high during the stance phase, and too low during the swing phase. In addition, during the swing phase the knee flexion is a bit delayed, leading to an abrupt swing phase.

Deliverable 2.1

1. Optimize the scenario in Tutorial 5b - Short Hamstrings – OpenSim.scone. Please comment on the results obtained from the values of the objective functions and gait analysis tool after evaluating your solution. What are the main kinematic adaptations (please elaborate)?

With optimization_length = 0.5, no working optimization could be found in 200 generations. The highest score was found in the 183th generation, with a score of 88.67.

With optimization_length = 0.75, a working gait was rapidly found, the score of 1 having been passed already on the 54th generation. Final score was about of 0.709 at the 192th generation and generated following gait cycle:

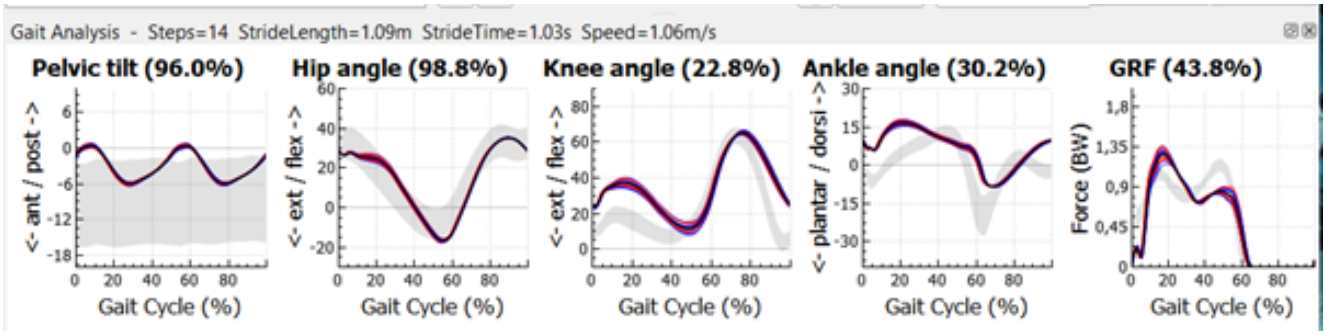


Figure 2 : Gait cycle features for optimization_length = 0.75

Compared to healthy gait modelling with the same min_speed parameter, the general speed and stride length is lower with crouch gate in early stable generation, but it reaches similar values in later generations. While the pelvic tilt has 99% overlap with the "normal" gate area, it has more posterior and smoothed pattern relative to the healthy gate: as the leg swings forward, the contracted hamstring will push the pelvic backward i.e more posteriorly. In early non stable generation, the model usually finished his trajectory because of a super-posterior pelvic tilt that made the upper body crash on the back (see Fig.3).

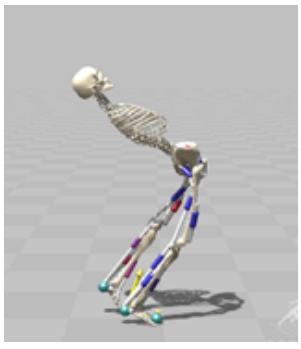


Figure 3 : Typical unstability in posterior pelvic tilt

Hip angle has also lost some specific features but is relatively similar, whereas knee and ankle angle are at 22.8% and 30.2% of overlap. They are both more extended than in healthy patients, and show less variability during the gait. GRF are again smoother, but retain general similar shape, with sensibly lower values in the second part of the stance: contracted hamstring restrict the push power on the ground, which therefore reduces GRF.

To further dig out the feature of crouch gait, shorter and shorter optimization length was tried, while retaining a complete final gate cycle within the 200 generations. Optimization_length = 0.68 was already too much, with a final score of 85.172. For 0.7, a score of R=1.1 has been achieved at the 129th generation with the following gait cycle in Fig.4.

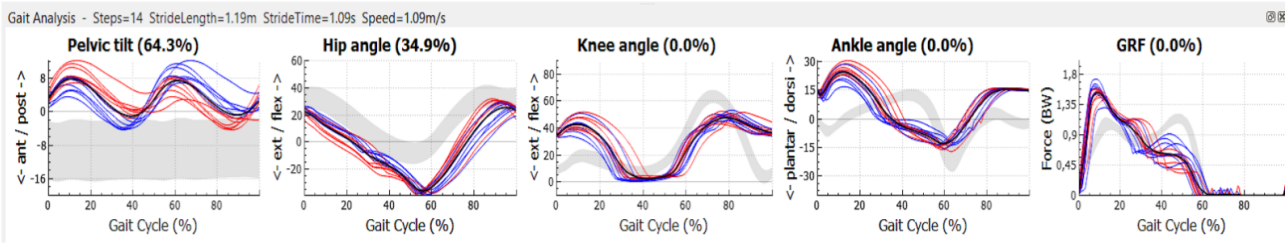


Figure 4 : Gait cycle features for optimization_length = 0.7

As expected, the general results are more drastic, with much lower overall overlap, 0% for knee and ankle angle, as well as for GRF. Hip angle is also much more extended than before.

2. After performing a hamstring lengthening surgery, please comment on the results obtained from the values of the objective functions and gait analysis tool after evaluating your solution. What are the main kinematic adaptations (please elaborate)?

With the simulated surgery, the model could stabilise much quicker, with a score of 0.609 at the 49th generation, that gave following gait cycle in Fig.5.

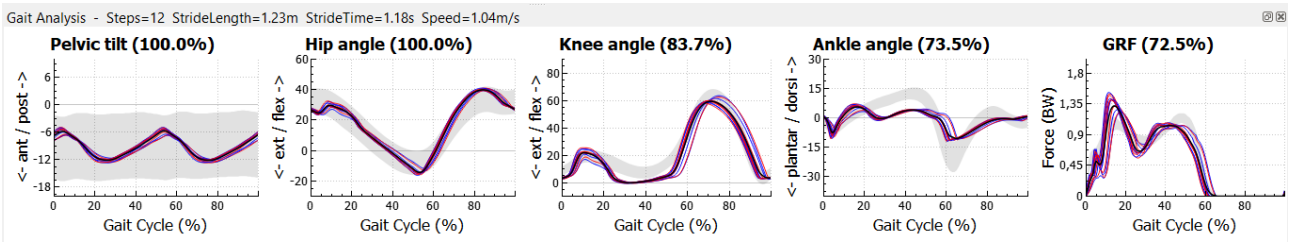


Figure 5 : Gait cycle features for optimization_length = 0.7, after surgery

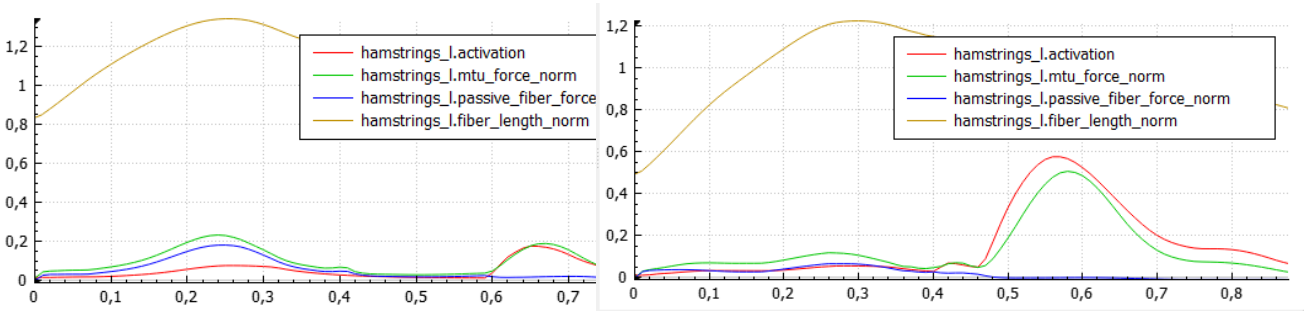
The overlap percentages with the normal grey gait area are much higher and comparable with the ones of healthy gate simulation. Compared to before surgery, pelvic tilt is back to more anterior oscillation, hip angle is higher, knee and ankle extend less and GRF has a much more typical form.

3.Using the analysis tool in SCONE, plot the hamstring activation, normalized fiber length, passive and total forces for the contracture condition and after surgical intervention. Compare the two plots and comment in detail how the pathological condition and the surgery affect the hamstring muscle.

Results are found in Fig.6.

- **Fiber length normalized**: Is longer, and quicker longer in contracture condition: this can be explained as the muscle is more relaxed thanks to the lengthening of the tendon, and is therefore less stretched.

- **Passive fiber force**: In contracture, they are much greater during the stance phase: as the muscle is too short, the passive fibers are stretched and exercises therefore more force.
- **Total force and hamstring activation**: Probably influenced by the passive force (and as the hamstring activation is not enhanced here), there is a little bit greater total force in the first part of the stance before surgery, but the force in late stance and swing stance is much greater after surgery than before, which is another sign toward better muscle functioning, confirmed by the greater hamstring activation.



(a) Before surgery (b) After surgery

Figure 6 : With muscle contraction, optimization_length = 0.7

Surgery let the contracted muscle relax a bit, as it is not as stretched as before. This led to a reduction of the passive fiber force and a better activation of the muscle, which influence positively the active force and gait cycle.

Deliverable 2.2

1. Using the scenario Tutorial 5a - Plantarflexor Weakness – OpenSim.scone, you can model heel walking with muscle weakness to plantarflexor muscles. Please comment on the results obtained from the values of the objective functions and gait analysis tool after evaluating your solution. What are the main kinematic adaptations (please elaborate)?

We obtain a heel walking pattern.

We first optimize the solution with 0.2 of the maximum force for the plantarflexor muscles, by shortening the optimal fiber length. The simulation starts with a cost of 90. After 200 generations, we obtain a cost of 63.264 for the best iteration (177). The model walked 4 steps, reaching a velocity of 0.95m/s, and fell on the back.

To visualise an extreme case we increase even more the pathological condition. With 0.1, the score fonction stay higher than 50 after 100 generation. The model start by hitting the ground strongly and do big step with the knee flexed. He then reduces progressivelly the step length, hit the ground with the heel, and finally fall on the back after a few step.

We tested an intermediate value with 0.3. The model is able to walk without falling, we obtain a score of 0.9 in 7 iterations. The ankle angle and the knee angle are not good. Especially the

ankle angle is too high.

We increase the maximum force to 0.4 of the healthy value. The model reaches a good cost of 0.7 in 3 iterations, a value comparable to the healthy model. However, the gate is not natural. The step are small, the knee is advanced and the model tend to slow down with time. The center of mass is on the back and the model is likely to fall (as the most drastic one did) on the back.

All result are shown in Fig.8.

In pathological case, the pelvic tilt is normal, the hip angle is almost normal.
The knee angle is way higher at the beginning of the gait cycle, as is the ankle angle and it increases even more during the gate. The change in the knee and ankle angle help to maintain balance. Since the model hit the ground with the heel, it need to lower and move forward his center of mass to maintain the balance.
The GRF double from normal at the beginning of the gate cycle and half the normal at the end. In fact, the subject hits the ground strongly at the foot strike using the gravitational force to compensate his muscle weakness during the rest of the gait.
Fig/7 show a example of the heel walking pattern.

In could be interesting to change the velocity in the objective function. With a pathological condition, the subject may prefer to reduce the speed to have a better gate for example.

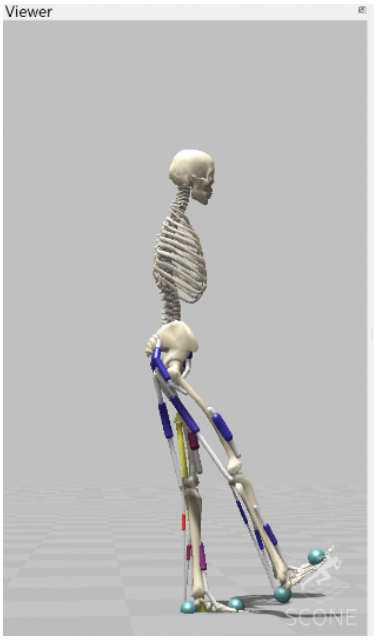
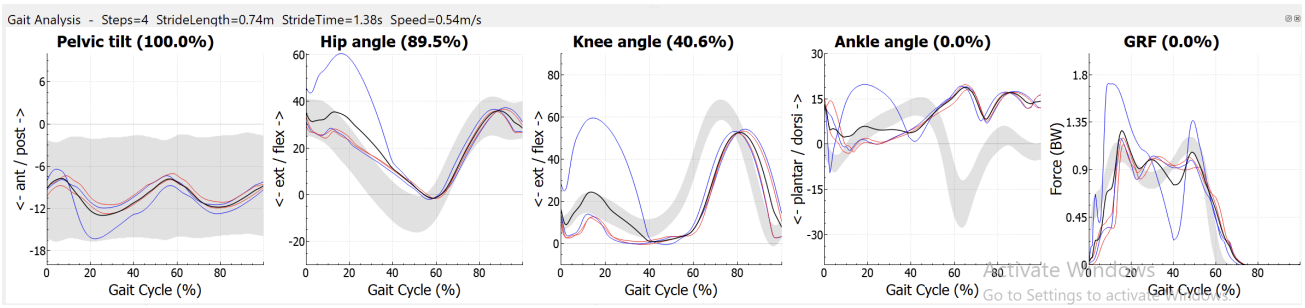
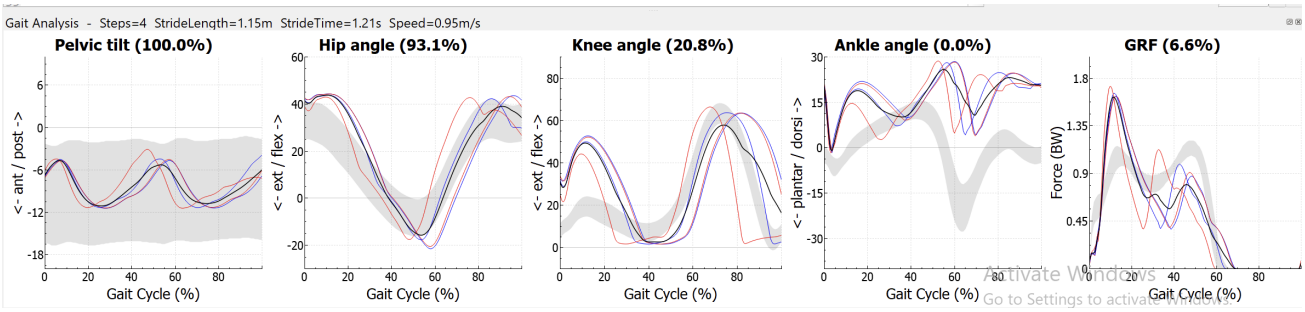


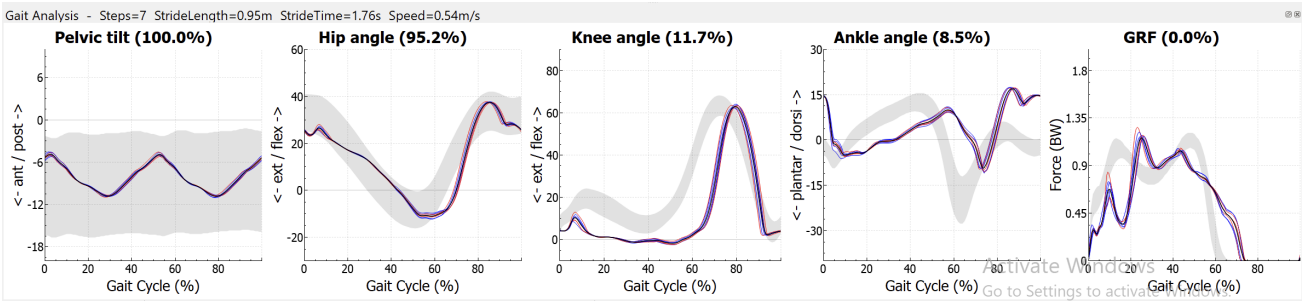
Figure 7 : Heel walking pattern



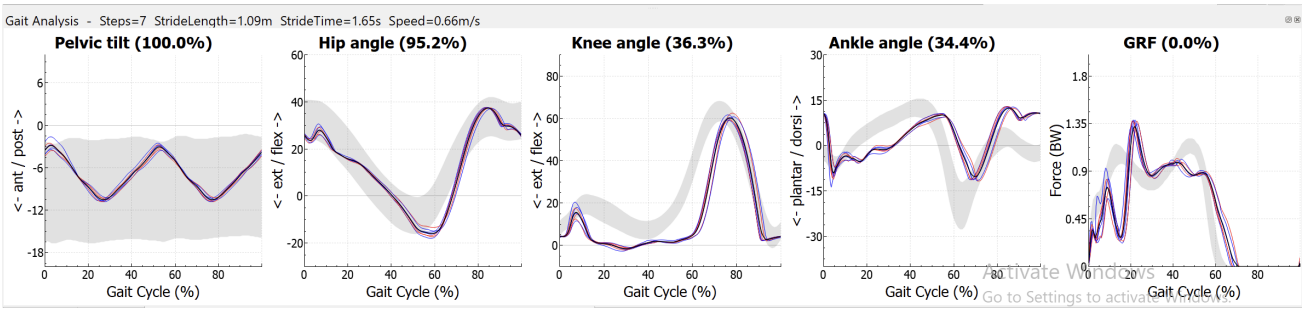
(a) Gen 126, score 54.846, factor 0.1 [fall]



(b) Gen 177, score 63.264, factor 0.2 [fall]



(c) Gen 7, score 0.926, factor 0.3



(d) Gen 3, score 0.738, factor 0.4

Figure 8 : Gait analysis for different degree of weakness

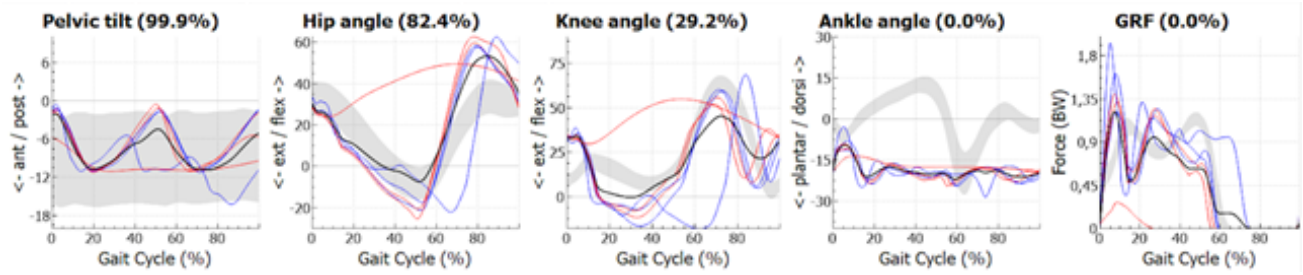
2a. Increase the gain of plantarflexor muscles to model toe gait due to hyper-reflexia. Please comment on the results obtained from the values of the objective functions and gait analysis tool after evaluating your solution. What are the main kinematic adaptations (please elaborate)?

The constraint was set as follows :

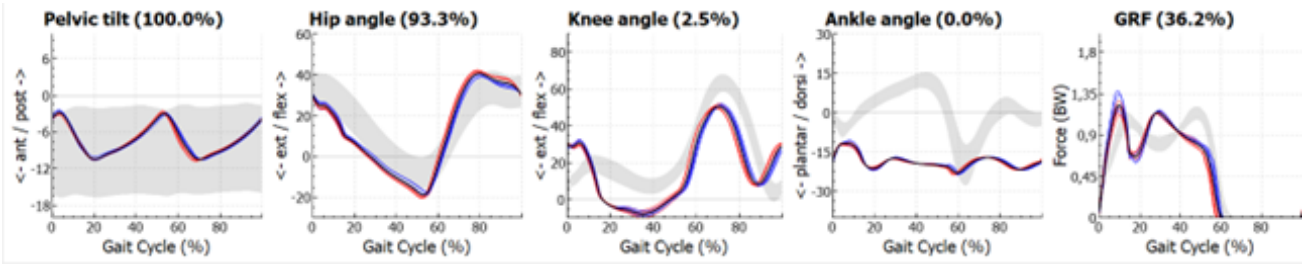
```
MuscleReflex { target = soleus delay = 0.020 C0 = 0.1 KF = 1 }
MuscleReflex { target = gastroc delay = 0.020 C0 = 0.1 KF = 1 }
```

First of all, the 3D viewer display a clear pathological toe gait.

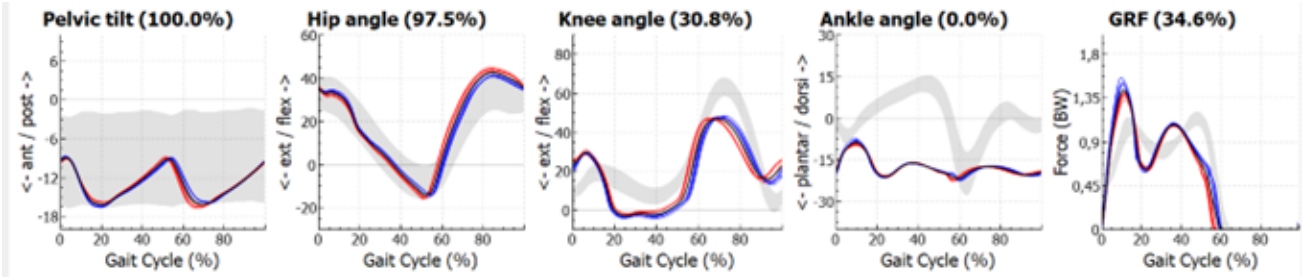
The Force muscle gain (KF) is fixed to 1, which is a positive value, meaning that the muscle will tend to be activated after receiving a force. This is useful to promote pushing on the toe during the stance for forward walking. But here the value of KF = 1 is relatively high, causing hyper reflexia, and thus the gastrocnemius and soleus are always activated, leading to plantarflexion of the foot and toe walking.



(a) Gen. 120, objective function : R>25



(b) Gen. 141, objective function drops to R=1.331, speed of 0.67 m/s



(c) Gen. 211, objective function: R=0.906, speed of 0.90 m/s

Figure 9 : Slow, normal and fast gait analysis results for a healthy gait

Before 100 generations, the model is not able to make one step, so we cannot obtain the curves on the gait cycle, and the value of the objective function is still above 25. After 120 generation, R drastically drops to R=1.331 and the model is stable. Finally, we stopped the simulation at generation 211 where R=0.906.

We can clearly observe across all the generations that the ankle angle angle is almost constant around a value of -15°, meaning there is no dorsiflexion of the foot, leading to toe walking.

The behaviour of the Hip angle is preserved in this pathology, and the GRF has the correct shape but is too strong during the stance phase. However, it is noticeable that the knee angle remains constant and low throughout the swing phase, it indicates the leg remains straight. This observation aligns with the fact that toe walking on the opposite leg eliminates the necessity for knee flexion during the swing phase.

We observe that between the R=1.331 and R=0.906 generations, the pelvic angle has shifted down, meaning the torso is leaned forward, this can be explained as in question 1 because the model has accelerated from 0.67 m/s to 0.9 m/s.

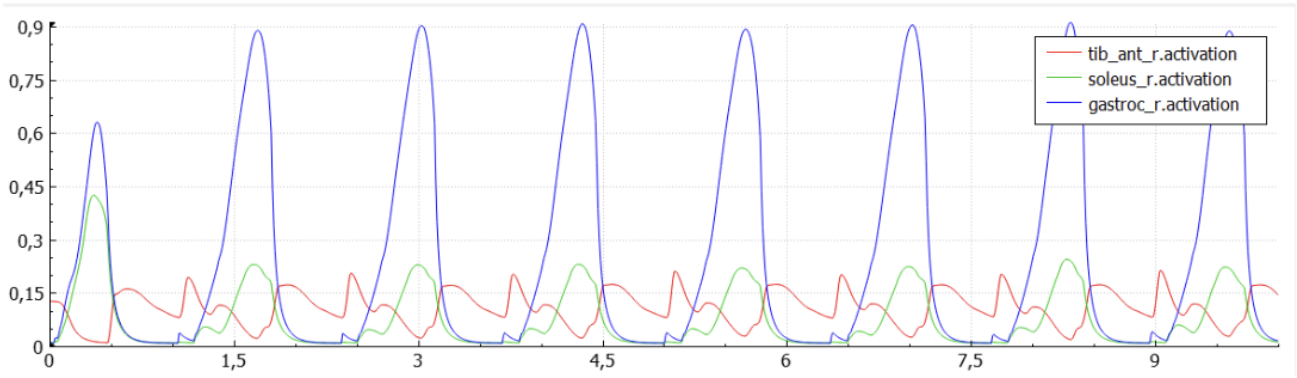
2b. What are the controller's limitations to properly model spasticity (i.e. hyperreflexia)? What additional reflexes would you implement to more accurately model spasticity to the plantarflexor muscles?

From the online documentation, we see that in Scone, the Reflex based on muscle length (KL), muscle velocity (KV), muscle force (KF), or muscle spindle sensor (KS) Of the output excitation corresponds to:

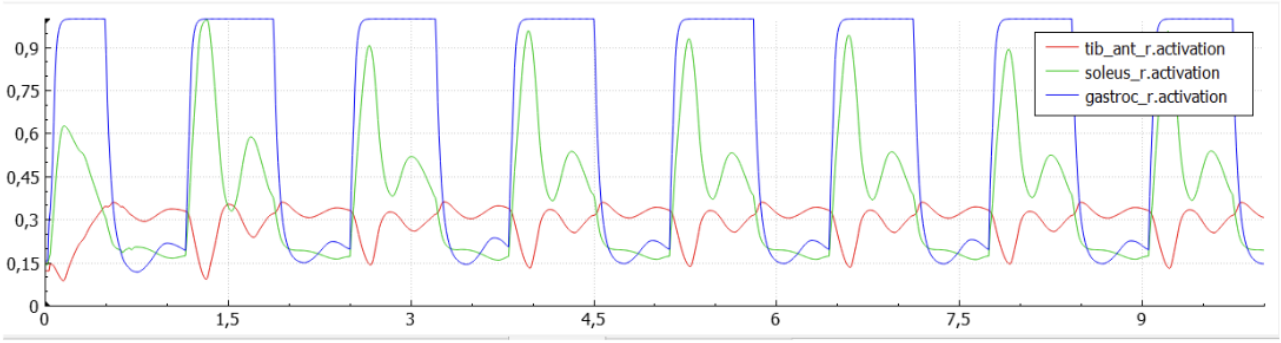
$$U = C0 + KF[(F - F0)]' + KL[(L - L0)]' + KV[(V - V0)]' + KS[(S - S0)]'$$

Where [ ]' correspond to a positive value Se we can see that only the Force reflex was parameterized

The soleus and the gastrocnemius are constantly activated in the pathological toe walking, with at least 15% of constant activation for an optimised toe gait. In addition the soleus is highy activated (reaching 90% at some point) in the pathological state, while the healthy gait reaches a maximum of activation of 20%. Above, Fig.10, a comparison between toe gait (objective function of 0.906) and normal gait.



(a) activation in heathy walking



(b) activation in pathological toe walking

Figure 10 : comparison between activations in normal gait and toe gait

Hyperreflexia is mainly a combinaison of two conditions. Firstly to a increased stretch reflex gains from muscle spindle, secondly to a lack of reciprocal inhibition from the antagonist muscles.

The controller we provide change the reflex involving only the muscle with himself. The current state of the muscle can trigger the reflex. By changing the value of C0, we activate the reflex all the time, even if the state of the muscle will not activate any reflex in the healthy individual.

The first condition is well modelised. However, we didn't really modelised the reduction of the reciprocal inhibition (even if a omnipresent responce of the reflex modelise a combinaison of the two)

This is a limitation of this controller. To improve the modelisation, and represent the reduction of the reciprocal inhibition, we need to reduce the reflex loop that update the state of the antagonist in function of the state of the agonist.

In this case, we need to reduce the reflex with the tibialis anterior as source and the soleus as target.

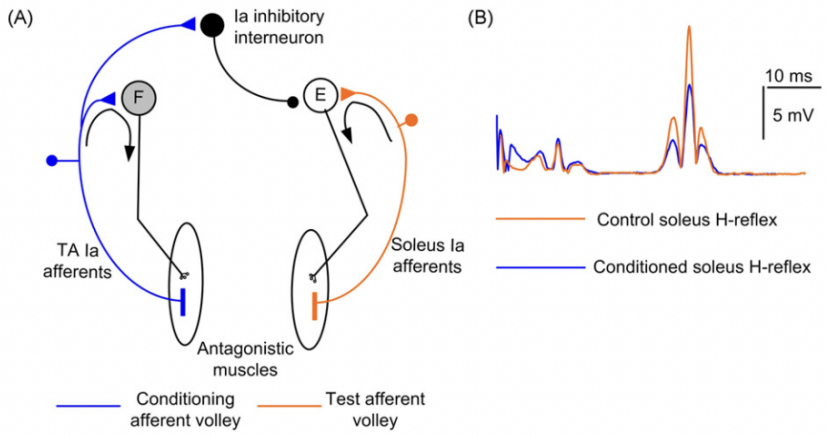


Fig. 4. Reciprocal Ia inhibition. (A) Spinal circuit designates the pathway of reciprocal inhibition exerted from ankle flexors following common peroneal (CP) nerve stimulation onto the soleus H-reflex. Reciprocal inhibition involves the Ia inhibitory interneuron and is exerted at a postsynaptic level and (B) waveform averages of 20 control and conditioned (by CP nerve stimulation) soleus H-reflexes evoked every 5 s at a conditioning test interval of 2 ms are illustrated for a healthy subject while seated at rest. Conditioning stimulus intensity was delivered at the tibialis anterior motor threshold level (data adopted and modified from Knikou and Taglianetti, 2006).

Figure 11 : paper : doi:10.1016/j.jneumeth.2008.02.012

In this figure, we modelise the effect of the orange loop and will improve by modelising the influence of the blue loop on the soleus by the biais of the interneuron.

To do so, we tried a new modelisation where we removed the antagonist inhibition of the soleus muscle coming from the tibialis anterior by setting KF =0. In the first generations, the model is unstable.

Deliverable 2.3

1. Propose a biomechanical and neural model to reproduce contracture and hyperreflexia to a specific muscle of your choice. You can modify biomechanical and neural parameters as you did in Derivable 2.1 and 2.2. What are the main kinematic adaptations (please elaborate)?

Firstely, hyperreflexia is modeled by increasing the gain of reflex parameters in the controller section. Secondely, contracture is modeled by decreasing the optimal muscle length.

For a biomechanical and neural model that reproduces these behaviours, we need to combine these two effects for a specific muscle.

We choose the soleus, because it is a central muscle in walking.

We tested several set of parameters for the model before finding a stable one.

With c0 = 0.05 and KF = 0.9, and optimal lenght 0.85 the model was falling after 200 generation. Surprisingly, the modelisation of the surgery was restoring a normal gait. We cannot use this set-up to answers because it's not stable. We tested c0=0.1, KF=1 and optimal length 0.9, it was even worse, so we decided to reduce the hyperflexia conditionning by setting the following parameters : CO = 0.05 and KF = 0.5. The following gate cycle was found:

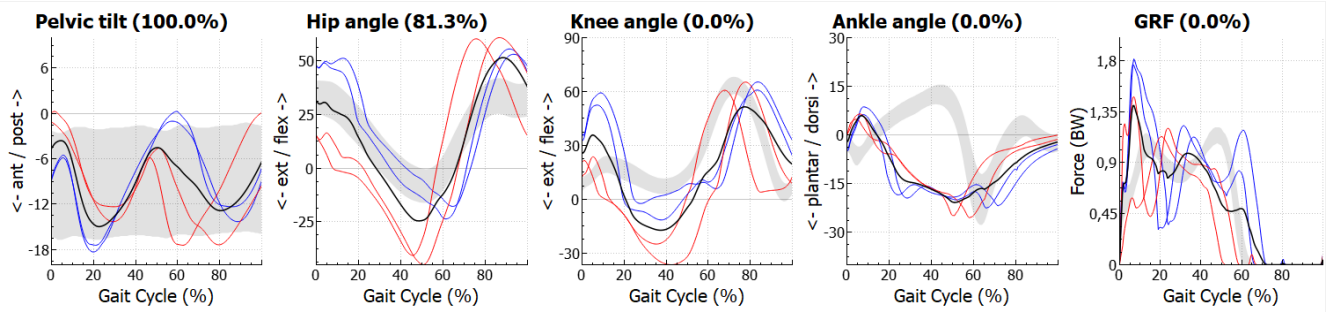


Figure 12 : Gait cycle with soleus contraction and hyperreflexia

Gait is visibly still not very stable, and quite far away from normal values for healthy gate, especially for knee and ankle angle pattern, are completely disrupted by the combination of contraction and hyperreflexia.

2. Apply a virtual muscle-tendon lengthening surgery to the impaired muscle as you did in Derivable 2.1. What are the main kinematic adaptations (please elaborate)?

To modelize the surgery, we increase the tendon_slack_length to 1.1 and we reduce the maximum force to 0.9. Even for the condition where the model wasn't able to take a step, the surgery restored the gate nearly to normal, and generated following gate:

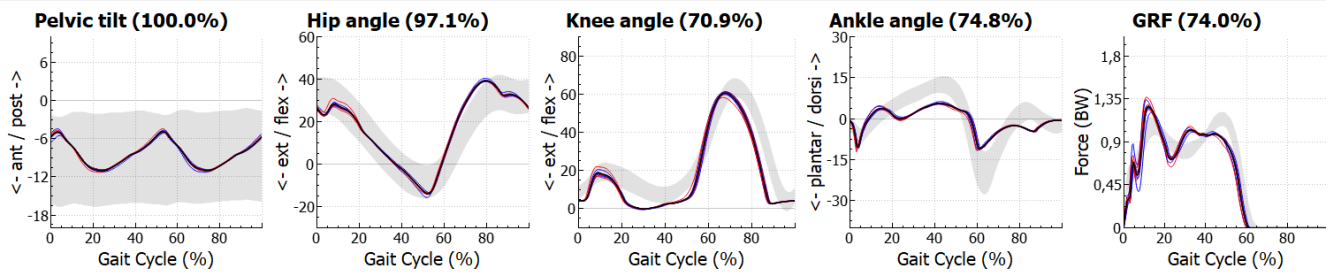


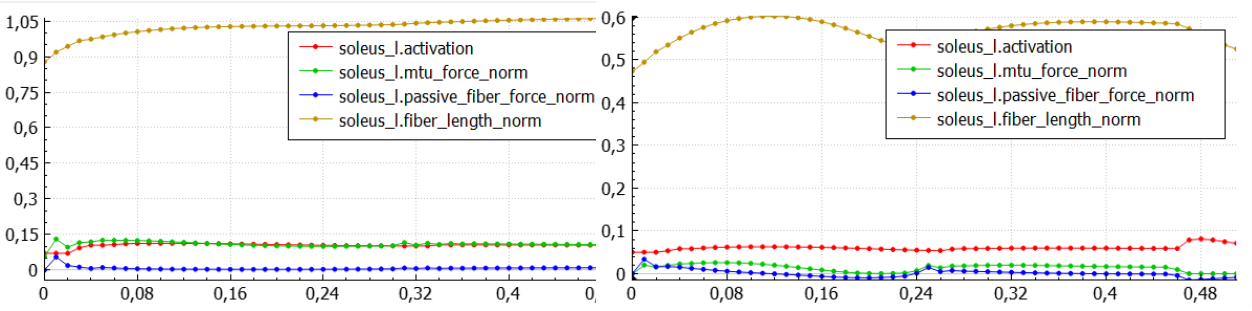
Figure 13 : Gait cycle with soleus contraction and hyperreflexia after operation

The gait is comparable to healthy ones, with high grey zone overlap and similar feature as in the healthy model.

3. Using the analysis tool in SCONE, plot the chosen muscle activation, normalized fiber length, passive and total forces for the contracture condition and after surgical intervention. Compare the two plots and comment in detail how the pathological condition and the surgery affect the chosen muscle. What is the efficiency of the surgery compared to the treatment of contracture condition alone that you studied in Derivabe 2.1?

As can be seen in fig. Fig.14 , there is quite a difference between before and post-surgery. Operation seems to have decreased up to the half of the fiber length, overall muscle activation is also decreased from an average of 0.1 to an average slightly above 0.5, which leads to a consequent drop of total force. Passive fiber force are in both cases very low. While the surgery in this case led to less muscle activation, the improvement for the hamstrings was mostly shown through much better muscle activation and force. But the soleus was probably overactivated due to the

contraction, while it had the inverse consequence on the hamstring. Overall, the surgery is in this case as "successfull", as it permitted non-stable model to stabilize.



(a) Before surgery (b) After surgery

Figure 14 : With soleus muscle contraction and hyperreflexia