Control of biped locomotion inspired from walking in monkeys

June 18, 2010

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Acknowledgements

Special thanks to :
My supervisors Sarah Dégallier, Jesse van den Kieboom and Solaiman Shokur, who focused me on what needed to be done for my project, gave me a lot of information and feedback and encouraged me to do the best,
Auke Ijspeert, who supervised my project at high level.
Nicolelis Lab in Duke University who produced the data concerning the monkeys which were necessary to complete this project,
and also to all the others who helped me and were not mentioned here.

Contents

1 Introduction

1.1 Research questions

Brain-machine interfaces are a promising way for the the rehabilitation of persons impaired by the loss of any of their limbs due to physical causes (i.e. spinal cord lesions). In an experiment of Fitzsimmons[1], the activity of certain cortical area are recorded in order to be able to predict the positions of the legs' joints. This method provides the ability to position the legs with great precision but needs a large population of neurons in order to be able to produce accurate predictions.

There are three main questions addressed here. First, is it possible to build a central pattern generator based model for predicting the gait of a rhesus monkey. And secondly, if it is possible to extend this model with little changes to fit the gait of other monkeys of the same species walking in the same direction at different speeds. And finally, if it is possible to it use to predict both backward and forward gait.

1.2 Goals

The goals of this project are multiple. The first one being the development of a model which could be used to reproduce the walking gait of a monkey. Furthermore, this model should use the least amount of information possible in order to be able to use more robust predictions of predictions of the wanted movement.

This done, another goal would be to know if the new model could be generalized for :

1. The same monkey over different sessions but with a given speed, meaning the monkey always walk with the same gait given a certain speed;
2. The same monkey but with different speeds going in the same direction, meaning the monkey will always go forward or backward;
3. Different monkeys;
4. Represent the backward and forward moving gaits.

For now, Fitzsimmons' model[1] can accurately represent only forward or backward walking. If the subject is to change its direction, it is necessary to switch from one model to another, resulting in the need to have another model responsible of deciding when the switching from forward to backward is needed. Thus it would be a great discovery if the cpg based model and the webots model were able to simulate both of them.

1.3 Advantages of CPG

The advantage of a CPG based approach is that the model would need only key parameters from the brain to be able to predict a correct gait. And as they need only directional and speed information, they can record smaller neuronal ensembles and thus gain in robustness.

Another great advantage consists in the fact that, as they are based on oscillators, they are resistant to perturbations and can as such naturally react and adapt to small ones and bigger ones will quickly fade.

Finally, as they are easily scalable by changing some constants, they can adapt to different speeds and individuals as long as the different gaits are close enough.

1.4 Long term goals

The goal of this project is to provide a way for paraplegics to regain the mobility of their lower limbs with the use of an exoskeleton for their legs and a BMI to convey the information of the brain.

As it would also need less data to provide the same accuracy in movement prediction, it could allow the development of BMI which would read smaller populations of neurons and thus could be smaller and/or less invasive.

Another advantage would be a gain in the robustness of the predictions. Neurons appear and disappear near the electrodes. And as we need less neurons the prediction will be accurate even when some neurons will be gone.

2 Short introduction to BMI

2.1 What it is

Brain-machine interfaces can be of three forms.

Invasive BMI The invasive BMI consists of electrodes which are directly implanted in the grey matter of the brain during neurosurgery. As they are directly in contact with the brain. This form of BMI produces the highest quality of signals but are prone to scar-tissue build-up, which can cause the signal to become weaker or even lost.

Partially-invasive BMI Similar to the invasive ones, that sort of BMI is implanted inside the skull but reside outside the brain. They produce rather good quality signals but have a lower risk of forming scar-tissue in the brain than the invasive ones.

Non-invasive BMI This last form uses non-invasive neuroimaging to allow observation of the signals. Those interfaces reside outside of the head and may consist in electrodes placed on the scalp (Electroencephalograph (EEG)) or big machines scanning the brain with magnetism (Functional Magnetic Resonance Imaging (FMRI)). Unfortunately, they procure lower spatial over temporal resolution and makes it hard to determine the area of the brain that created the signal or the actions of individual neurons.

2.2 Uses

Firstly, we should note that there are two type of BMI. The first one is the motor BMI and the second one is the sensory BMI[2]. The motor one consists in recording the activity of chosen parts of the brain. Then, after having decoded the signal, we can use it to move some machine like a robotic arm for instance. The sensory one consists in recording an activity and then to encode it such that the signal can be comprehended by the brain. For example, a camera could record images which would then be encoded and sent to the visual cortex.

2.3 Operating principles

The main principle of the BMI is to to measure the firing rate of neurons in a predefined area of the cortex or neuronal ensembles. For example, if we want to reproduce movements of the hand, we would need to measure the activity in the cortical area responsible of this behaviour. This could be done with any of the three previously described types of BMI.

Then we would need to decrypt the data we have obtained to be able to precisely determine which movement corresponds to a particular cortical activity. To this end, we can use the subject to perform some tasks which would allow us to have a better vision of the correspondence between a particular action and its corresponding neuronal behaviour.

Then the final part consists in being able to map a the signal obtained from the firing neurons to the right behaviour which can be computationally very intensive.

3 CPG for locomotion

In this section I will explain why we use central pattern generator for locomotion and what are the particular advantages to use them in this project.

3.1 Why CPG?

CPGs come from biology. They are neural networks that can produce rhythmic patterned outputs without rhythmic sensory or central input[3]. CPGs underlie the production of most rhythmic motor patterns and have been extensively studied as models of neural network function.

The use of CPG for locomotion comes naturally with the observation of the natural joint angle patterns of the lower limbs of bipedal like humans.

This taken into consideration, it is important to note that CPG are able to prevent the harmful effects of perturbations on a system. As such it allows to build a model with smoother constraints as small perturbations will be naturally compensated. And with bigger perturbations we will simply need to compensate them with the adequate coupling.

3.2 Advantages

3.2.1 Amount of information needed

The main advantage of this method is that it needs only a very small amount of information in order to be able to function correctly. As we do not use feedback, we only need speed and direction information. Thus, given that the more neuronal data you need, the lesser it will be precise, CPG allow us to design a model for which the signals which make it advance will be much more precise causing it to behave more realistically.

3.2.2 Scalability

Another great advantage to using CPG is that due to their nature, it relatively easy to scale them to correspond to others similar signals. For example, if we were to change the frequency of the signal, it would lead to a greater (or smaller depending of the change) speed of movement. Then if the gait is similar independently of the speed, then it means that the model using central pattern generators can be used as a representation for each of those.

3.2.3 Resistance to perturbations

Finally, central pattern generators are relatively immune to perturbations. In fact they will always feel them but their impact will fade very fast, almost annihilating small ones in an instant. Bigger ones would still need some time to disappear but nonetheless, with adequate coupling allowing to reflect the change of state in the equilibrium, they would have a minimum impact and would not be visible anymore in little time.

4 Presentation of the monkeys

The monkey used to build the webots model is a female rhesus monkey (Macaca mulatta) called Nectarine. Another male monkey is used to validate the portability of the model for different individuals.

4.1 Mesurments

4.1.1 Size and weight

The known measurements of Nectarine are its hand size - 12 cm - and its weight - 6.1 kg. All the other measurements data have been extrapolated from this by using the data from Hamada and al[4] which represent the average sizes of a population of monkeys. So, we transformed those by an appropriate factor obtained with the known size of the hand and the average one from Hamada.

4.1.2 Experimental setup

The monkeys have been recorded while walking on a treadmill. In this setup, the monkeys are holding themselves to an horizontal bar for a stability aid. The records are done with a camera filming the monkey walking.

The positions of the joints are obtained with the help of white dots painted on the monkeys. A classical session lasts thirty minutes.

4.1.3 Kinematic data

Multiple runs of data have been provided by Nicolelis Lab in Duke University. There are data of two rhesus monkeys, a male one (Idoya) and a female one (Nectarine). Data about forward and backward walking at different speeds are provided for each monkey.

The data used to build the CPG model are taken from the monkey Nectarine. They have been extracted from a typical swing of the left leg taken at a slow forward speed. The remaining data is used to ensure that the shape of the gait remains similar for the two monkeys whatever the session, speed or direction.

Those data consists in the cardinal positions the three joints of the leg (hip, knee and ankle), the speed of the treadmill on which the monkey walk and if the recorded foot is touching the ground or not.

4.2 Gait

The gait of the monkeys is rather different to the one of humans as they are not naturally bipedal. The first difference is that they will lean forward as they are holding themselves to a bar. Another big difference is that their knees will almost never go behind their hips, meaning they will do something which could look like half-steps.

In Figure 1, let α be the angle between the vectors coming from the hip and going to the neck and to the knee, this angle will almost never be greater than π. This is really different to humans where it would go beyond that value.

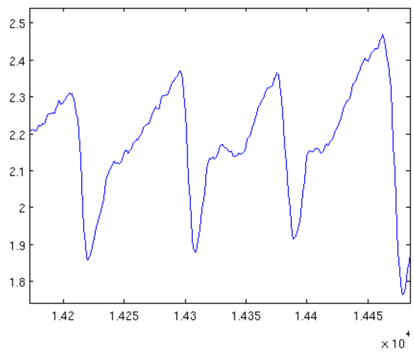

Figure 1: Some typical angles occurring for the joint of the hip during the walking.

4.3 Variability in measurements

Furthermore, the monkey's behaviour is not always predictable. Thus it will sometimes change its actions and start to play by hanging its legs on the bar on which it should holds only its hands.

Another problem is that, as it is not naturally bipedal, it has some difficulties to walk. Thus creating a great variability in the measured data as seen in Figure 2

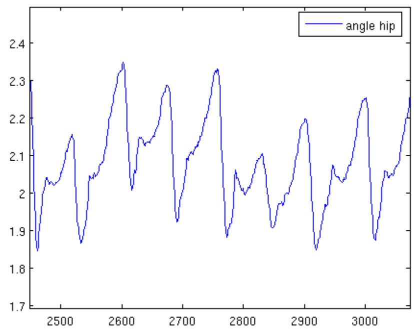

Figure 2: Typical variations in terms of amplitude and shape.

5 Methods, models and results

5.1 Webots model

The physical model of the monkey was built using webots. It was chosen because of its possibilities in reproducing good physical behaviour. This is done through the possibility we have to specify precise mass, body mass distribution, precise measurements, specify maximum degree of freedom of joints.

5.1.1 Methods

To build the model we need information about the measurements of the subject monkey. And as the only known ones are its hand size and its weight, we needed to extrapolate the others. This was done with the help of the data from Hamada[2].

Body part	Size (mm)
Crown-rump	576.83
Anterior trunk	391.18
Tail	207.06
Upper arm	167.32
Forearm	171.49
Hand	120
Thigh	189.17
Leg	170.28
Foot	175.55
Head	101.88
Foot width	39.52

Figure 3: The sizes extrapolated and used to build the webots monkey model.

Once this was done, we had to build the webots model. For this part, the human model from Jesse van den Kieboom was adapted to be like the subject monkey.

This was done by modifying the length of its body part to correspond to the data obtained with Hamada's information[2]. Once this was done, we also needed to add a new body part : the tail.

Then we also needed to adapt the weight of all its body parts from the human ones to the monkey ones. Due to the fact that I have not been able to find data concerning the body mass distribution of rhesus monkeys, we used the same than the human one. Another subtlety of the model is that the head was lightened more than it should if we were to have followed the logical way of dividing each body part by a certain coefficient. This was done to reflect the fact that the human head is much more heavy than the one from other primates[5]. To find the correct weight, we used the difference between the logical cranial capacity of the monkey and the real one. Then put the good weight in the model and used the remaining weight for the tail.

Also, being much lighter than the original human model, the monkey one was able to walk on its toes. This was due to the fact that the maximal force that the joints can apply were still set to human values, causing abnormal behaviour. So we also had to adapt those values.

5.1.2 Model

To reflect the fact that the subject monkeys are recorded while walking on a treadmill on which they holds on a bar, we have done one particular arrangement to the model.

We are using a a webots physics plugin, built by Jesse van den Kieboom, which fixes the hands on their z-axis positions. As such, the monkey is not completely free as its hands are as if they were on a grannywalker which would prevent it to fall on its side.

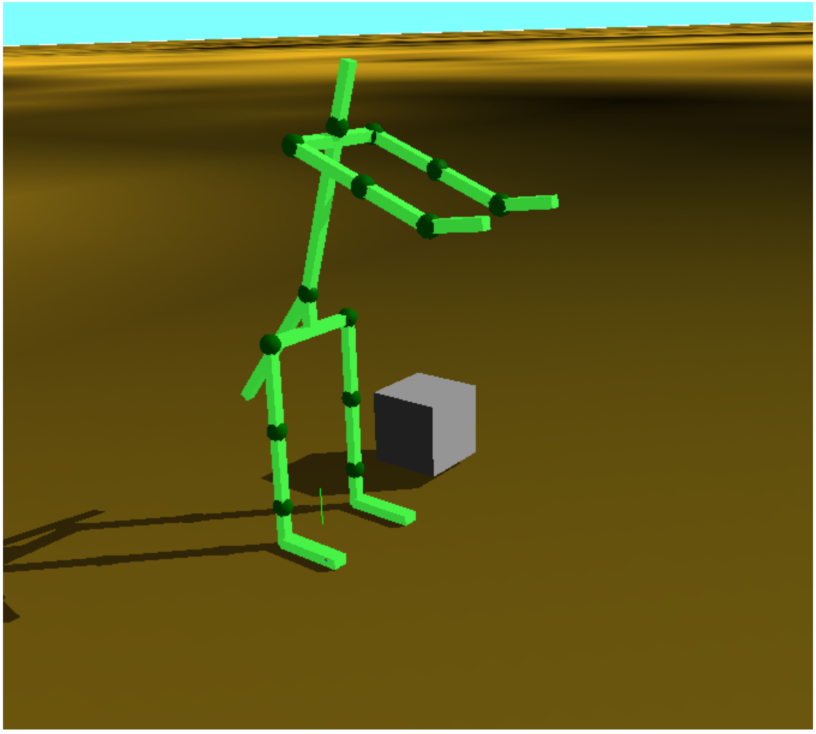

Figure 4: The model before it starts to move.

5.2 CPG model

5.2.1 Methods

Which CPG for this project? The following oscillator has been used for the CPG. The reason it was chosen is because of its simplicity. Its form being

$$\dot{x}_i = \gamma_i(f_i(\theta_i) - x_i) + \frac{df_i}{d\theta_i} \cdot \dot{\theta}_i + K_i$$

with f being the function reproducing the joint angle pattern, x being this angle, γ being a constant determining the speed of convergence, θ being the time value modulo the interpolation range of the driving function and K an arbitrary perturbation in the system. Also the first part of the equation is used to make the equation converge to the desired shape despite eventual perturbations.

The driving function is derived from polynomials obtained from the signal coming form the motion tracking system. An easy way to get them is to break the significant part (the period) of the signal into small parts which can easily be approximated through polynomials of divers degree. Then we only have to reproduce the original curve with those polynomials.

The CPG was built from the Cartesian data of the measured positions of a rhesus monkey during a walking session. The data comes from the left leg.

The first thing to do was to transform those coordinates into joint angles. We used vectorial algebra to resolve the value of an angle between two vectors. Thus we obtained the joint angles for the hip and for the knee.

$$\alpha = acos(\frac{\vec{v_1} \cdot \vec{v_2}}{\|\vec{v_1}\| \cdot \|\vec{v_2}\|})$$

Once those were obtained, we plotted them and looked for an average cycle. Note we must take care while choosing it as the behaviour of the model will depend on this choice. So it is necessary to choose a phase with a representative shape as it will condition the behaviour of the CPG.

To know if it is good, we must take care of two things. The first one being that there should be as little perturbations as possible. This is to ensure that the equations that will be used can give a representation as close as possible to the real joint angle pattern. Then the second one consists in being sure that it has average values. By that I mean that it should not have the extreme values - minimals as well as maximals. This will ensure that the shape reproduced will be as close as possible to a real and regular one.

Once we have a good cycle we need to obtain the driving function from it. To do so we simply need to break the chosen cycle into smaller pieces which can be easily approximated with polynomials. The obtaining of those polynomials is done with matlab and its polyfit function.

The knee and the hip functions have been cut into three parts. Those parts were chosen by hand in such a way that a polynomial fitting could be done easily. The chosen degree of the polynomials was three for all the part as this degree is high enough to correctly approximate the real curve

Now with those polynomials, it is possible to build the central pattern generator in order to be able to reproduce the trajectories previously observed.

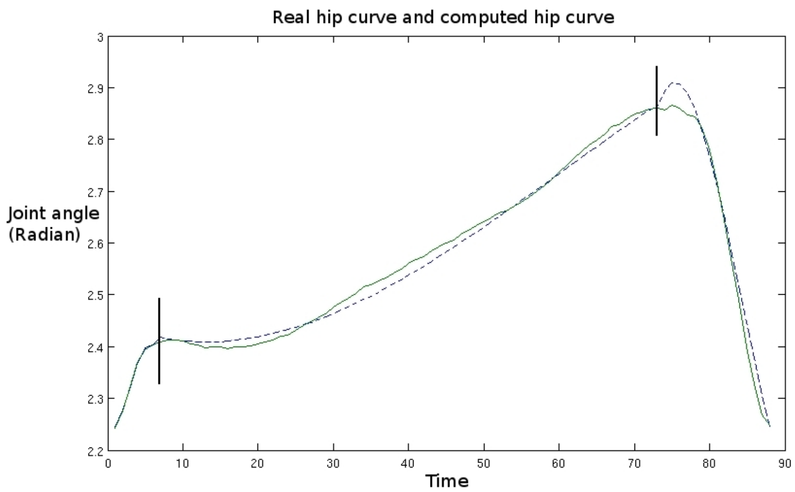

Figure 5: The hip joint angle computed with the polynomials (dashed line) and the real one.

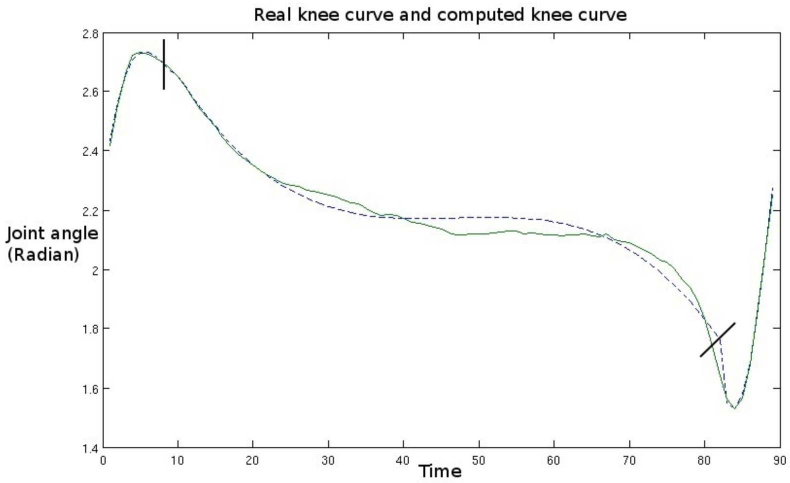

Figure 6: The knee joint angle computed with the polynomials (dashed line) and the real one.

In Figure 5, a little bump can be seen on the right side of the curve. This is due to the way the polynomials were chosen and could be reduced or even deleted by changing the starting points of the interpolated curves and / or by changing the degree of the polynomials. In a more general way, it would be possible to obtain curves which would be really close to the real ones by doing those changes.

5.2.2 Cpg model

The building of the central pattern generator model was done with the help of the libcpg and cpgstudio of Jesse van den Kieboom. Cpgstudio is a program allowing the easy creation and modification of central pattern generators and their respective coupling. The libcpg being mainly used through webots to be able to read and use the built CPG.

The first task was to enter the previously obtained polynomials into cpgstudio. Then it was necessary to represent each joint (called state) and its properties. Those properties being the time value and the angle of the joint. It is also necessary to add the coupling between the joints and to precise how the angles should change over the time.

This is done by using links between one state to another. Then, in those links, it is possible to precise some properties. The most useful operation in our case is to precise how the joint angle should change over the time. It is here that we use the oscillator.

Once all this has been done, all that remains to do for the central pattern generator is to test it through the model previously built under webots.

5.3 Results

The first and easiest way to test the central pattern generator and the webots model consists in simply looking if the model can walk. So with both our models we can use them through our webots environment and observe if it is able to walk. in Figure 8, you can see a set of snapshots depicting the first step of the monkey.

And so, we can conclude that in its actual shape, the webots model associated with

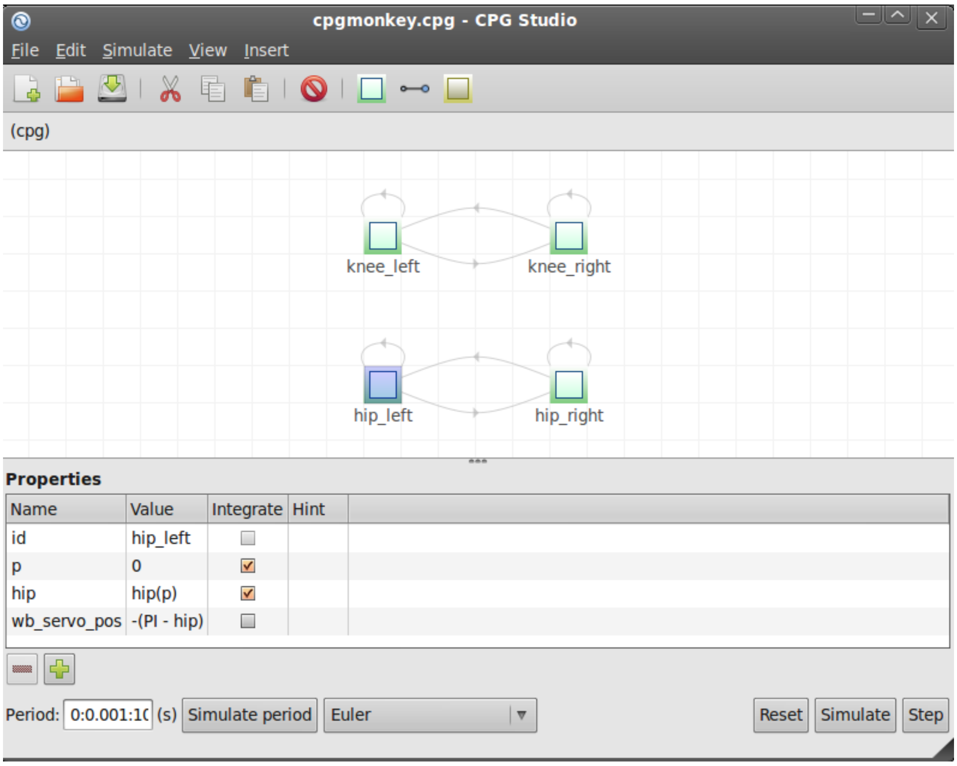

Figure 7: Screenshot of Cpgstudio.

the central pattern generator is able to walk forward at different speeds. It can also walk backward.

However, note that there are some limitations to this statement. Extreme values for the frequency will cause the model to loose adherence on the ground and to fall down. The maximum values after which a clear loss of adherence is visible are at 1.6 and -1.6. Also, as everything was computed using a grannywalker, removing it would most assuredly cause the model to fall.

As said, it is an easy way to see if the model is valid. Nonetheless, this way of testing despite providing some information lacks of numerical information about the differences between multiple records.

5.3.1 Numerical testing

For more rigorous and general tests, it is necessary to resort to more efficient methods like mathematical and statistical analysis. Here we will first use the duty factor and then use the least squares error method.

Duty factor The duty factor is the duration of stance divided by stride duration. This is used to know the amount of time the foot is on the ground. A value of one would indicate that the foot is always on the ground while a value of 0 would mean the opposite. Also, a value below 0.5 would mean that there are moments when both feet are not the ground.

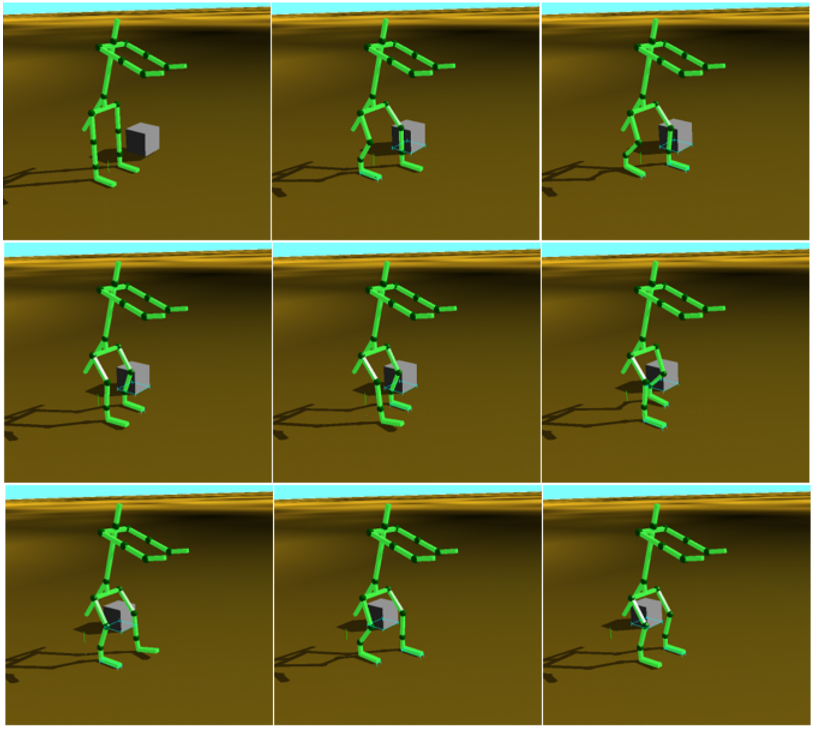

Figure 8: Nine images of the monkey model while it performs a step. It starts still.

Also, if the duty factor is very different for two legs going at the same speed, it could point to the fact that the monkey uses a asymmetric walking. As such, it could suggest that it is pulling one of its leg and in this case, the measured data would loose much of its significance.

The computation of the duty factor was done by using the data indicating when the foot of the subject monkey was on the ground. To prevent too short steps (i.e. when the monkey lifts its foot and put it down right after this), we used only the steps which were longer than twenty time units (ten for the stance and ten for the swing).

As expected, we can see in Figure 9 that duty factor deacreses as the speed increases[6]. This is due to the fact that the monkey must make more frequent steps in order to be able to follow the speed of the treadmill. Also it is approximatively identical for the backward moves than for the left ones for the left leg.

Also, the variance diminishes as the speed increases. This could indicate that the monkey has to make more regular and identical steps the faster it goes. As such, it means that the use of CPGs is even better with high speeds in the case of a bipedally walking monkey as its steps are more stereotypical.

An interesting feature is that the duty factor is lower for the right leg than for the left one, meaning the right one is more often not on the ground than the left one. Also, when the monkey is going backward, the difference is much lower. Moreover, the variance is greater for the right leg than for the left one for the forward walking.

All these could indicate that the right leg might be doing longer steps than the left one. And this would cause the right leg to somewhat mimic a greater speed than the one it should have from walking on the treadmill.

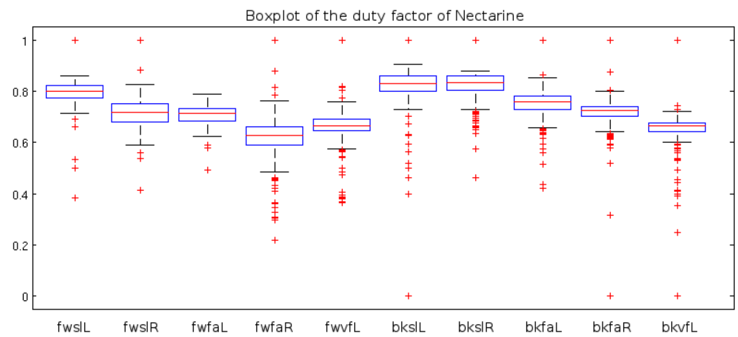

Figure 9: Duty factor for each piece of data from Nectarine. The vertical axis is the duty factor. The meaning of the legend is : fw = forward, bk = backward, sl = slow, fa = fast, vf = very fast, L = left leg and R = right leg.

Least squares error The least squares error method is used to ensure that the shape of individual cycles of the joint angle has a minimum of differences between the different sessions / monkeys / speeds. The first thing to do in order to be able to use this test is to normalize the measurements according to amplitude and frequency.

To do so, we need to lengthen or shorten each swing in order to make them correspond to the length of a reference swing. The detection of a particular swing is made with the help of one particular field of the data of the monkeys. It tells us if the foot is on the ground or not. We can then use this data to separate individual swings.

Now that they are separated, we can scale them accordingly for their length. This done, the only remaining thing to do for the preparation is to modify their height such that they are between zero and one. To do so, we need to do the following :

$$\hat{y} = (y - \bar{y})/(y_{max} - y_{min})$$

y being the angle value to normalize, $\bar{y}$ the mean of all values for this step and y_{max} and y_{min} being the maximum and minimum values for this step.

Then, once all this work is done, we can compute the least squares error in order to verify if a steady step exists. A steady step consists in a regular shape of the step which is repeated over the time.

To do this, we test the joint angles of one run with a chosen part of its own data. With this, we can verify that a particular step is approximatively equivalent to any other steps of the same individual done at the same speed.

As you can see in Figure 10, the mean error is approximatively at 0.08 and 0.1 for the hip and the knee respectively. Note that there is a greater variability for the knee than for the hip. This might be explained by the fact that the knee is subordinated to the hip. And as such, any variability happening for the hip will be passed to the knee causing it to adjust in order to maintain equilibrium.

Nonetheless, the error being relatively small, this may be indicating that a steady step does exist and as such, that the usage of a central pattern generator is a good way to represent the walking gait of a monkey.

But we should also verify it for different speeds and monkeys. Do do this easily, I propose to simply use the central pattern generator with different speeds. As the CPG is valid only if a steady step does exists, if it is able to accurately represent different

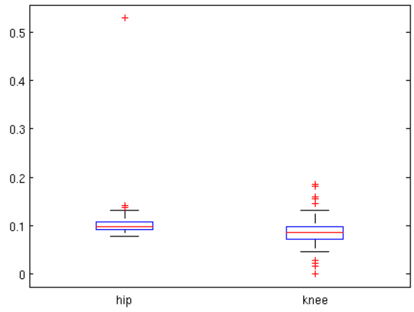

Figure 10: Least square errors of hip and knee joint angle for Nectarine while walking at a slow speed.

speeds and monkeys, then it would prove that a steady step does exist and that it can model it accurately.

If it were not able to model the different speeds, then this would mean that a steady might in fact not exists and that a central pattern generator based approach is not valid.

In order to verify this, we computed the least square errors for each speed against the signal obtained with the central pattern generator.

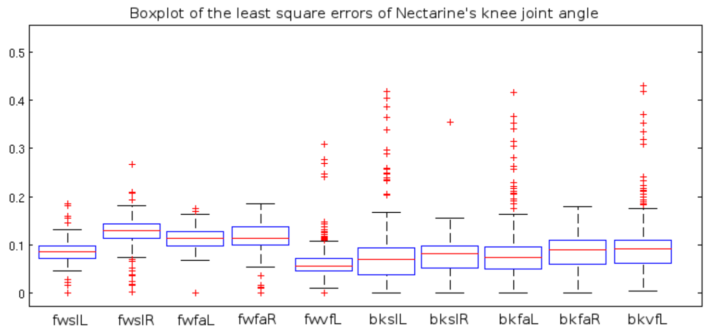

Figure 11: Least square errors of hip and knee joint angle for Nectarine for all the different speeds. The meaning of the legend is : fw = forward, bk = backward, sl = slow, fa = fast, vf = very fast, L = left leg and R = right leg

As you can see in Figure 11 and 12, the mean error remains small for all the speeds. The variance also remains relatively the same for a given direction. But note that it increases when the monkey is walking backward.

A precision is needed here. The kinematic data for all backward walking was reversed (i.e. tested from the end to the beginning). This particularity was done in order to reflect that the backward walking gait is in fact similar to the forward one excepted that it is reversed. This is because the monkey is doing the same steps but in the reverse direction. Almost like if it were in movie which would be rewinding.

Those numbers in our possession, we can assume that the central pattern generator is able to accurately model the walking of a particular monkey and that this one has

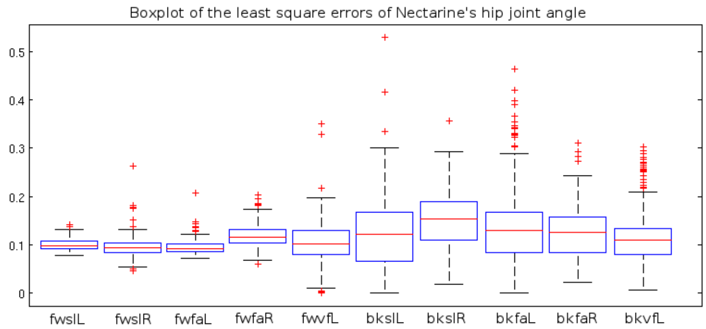

Figure 12: Least square errors of hip and knee joint angle for Nectarine for all the different speeds. The meaning of the legend is : fw = forward, bk = backward, sl = slow, fa = fast, vf = very fast, L = left leg and R = right leg

a steady state walking. Now all that remains is to see if it is also able to model the walking gait of another monkey.

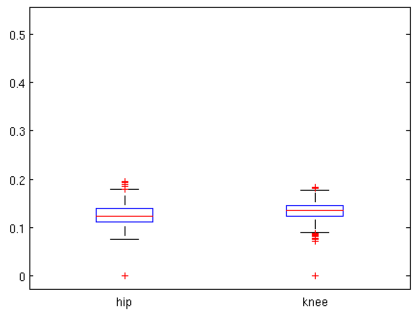

Figure 13: Boxplot of the least square errors of Idoya walking forward at two different speeds.

In Figure 13 we can see the least square errors of the monkey Idoya walking forward. During this session two different speeds were recorded. The least square errors have been computed with both of them.

Even though the error is greater than for Nectarine, it remains small with little variance. The fact that the error is greater might be caused by physiological reasons causing the gait to be slightly different. For instance, it could be that it has longer legs causing bigger but less frequent steps). Nonetheless, we can state the central pattern generator is a good representation of the walking gait of Idoya.

And thus, as it can represent accurately the gait of different monkeys, then it means that they have a steady step and at the same time indicates that the central pattern generator is a good approach to model the gait of rhesus monkeys.

5.4 Conclusion

So, as we have just seen, the monkeys have a steady step. Accordingly, the use of a central pattern generator for the representation of the walking gait of rhesus monkeys is entirely appropriate. Furthermore it can also accurately represent both the forward and backward walking gaits of both the monkeys for which we have kinematic data.

Further improvements could consist in the adding of a CPG for the ankle to decrease even more the distance between a real and a reproduced gait. Note that in this case, it would be necessary to also add a damped spring joint between the metacarpals and the phalanges. This would serve to reflect the fact that the feet of a monkey is much more flexible than ours. As such, it will lift its heels sooner than a human would. Consequently, if the damped spring is not implemented, it might cause the model to loose stability as the ankles would try to push it away from the ground.

Nonetheless, for now, we have already a working representation of the walking gait of rhesus monkeys. As such, the central pattern generator can be used for further development of BMIs which would use it to make exoskeletons to walk efficiently.

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Notes

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