Ecole polytechnique fédérale de Lausanne

Biorobotics Laboratory (BioRob)

Spring Semester 2018

Semester Project: Bipedal passive dynamic walker with lateral stability

Authors:
Tristan Abondance

Teacher:
Auke Ijspeert

Supervisor:
Amy Wu

June 8, 2018

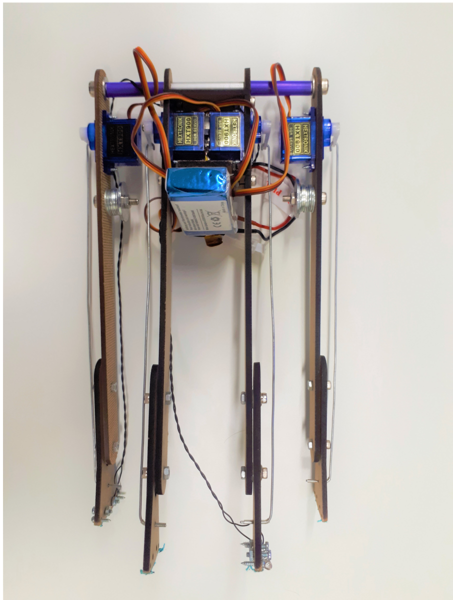
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

BIOROB
EPFL Biorobotics Laboratory

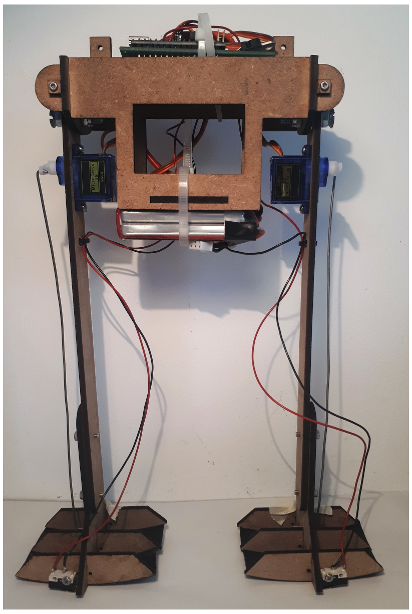
Contents

Abstract

The goal of this project was two make a two-legged version of a four legged dynamic walking robot, Rando created by Matthew A. Robertson and Amy R. Wu (figure 1a). The robot being created in this project, "Rando/2", kept the same mechanisms, and while the robot was running, the trailing leg was actuated to restore the appropriate amount of energy that was lost between each step so that it could continue walking. It also kept the same functionality, as it walked and demonstrated the principles of inverted pendulum. Finally, it should be accessible by using maker-style techniques and having a relatively low manufacturing cost. With these requirements, a first lateral stabilisation mechanism was tested. However, that was not actually necessary, as the simple action of the feet push-off gave enough strength to the robot to swing on each side. Subsequently, two designs of the upper body were tested to obtain different distances between the two legs in order to better manage the tilt angles. The best design was the one that had a distance of 115mm between the two legs. Walking performance was increased by modifying the shape and length of the robot's feet. The best robotic foot was the one with a curvature radius of 200mm and an arc length of 72mm in the sagittal plane. The lateral parts had a curvature radius of 150mm and an arc length of 76.49mm. Finally, the robot (figure 1b) successfully walked a distance of over 1.5m in less than two minutes.



(a) Inital version of the four-legged dynamic walker, Rando



(b) Final two-legged version of Rando

Figure 1: The two walking robots, on the left "Rando" and on the right "Rando/2"

1 Introduction

The graphs present in this report were generated using *Matlab* and the prototypes design was created with the Computer Aided Design (CAD) software *Solidworks*.

1.1 Static vs dynamic walking

First, one should distinguish the two main categories of legged locomotion techniques: static and dynamic. Static robots are always balanced, meaning their centre of gravity is within the polygon that is formed by the ground contact point of the legs [MI18]. This type of robot requires at least four legs, which are easy to control but inefficient because they need to be powered at each step. In contrast, motion is required to maintain balance for dynamic walking and are increasingly more complex to control. In regards to the energy level, this instability is very interesting because the gravity can be used as source of power to move the robot forward. Therefore, the robot studied in this report uses dynamic locomotion.

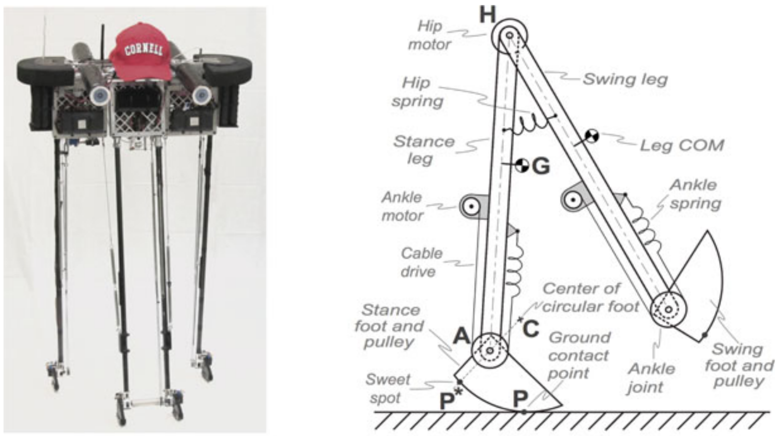
1.2 Passive vs active dynamic walking

The main energy issue for walking robots is the loss of energy with each step. When the foot of the robot hits the ground, energy is lost due to the collision [DKK02]. There are two different methods for restoring this lost energy, which are regrouped into two different classes of dynamic walking robots. Passive dynamic walking, in which no external inputs or control are needed since they only use gravity and inertia as a source of power [McG90]. As a result, these robots can only work on sloping ground. Active dynamic walkers, use actuators to add energy to the system to compensate for this energy loss. These robots no longer have this environmental constraint and can also walk on flat surfaces.

1.3 Background

1.3.1 Cornell Ranger

Cornell Ranger is a four legged bipedal robot that was created at Cornell university (figure 2). It is known to have continuously walked during 65.2km in an ultra-Marathon from May 1st to 2nd, 2011 [And12]. Ranger walks with the principle of the inverted pendulum, using gravity as its main source of energy. Therefore, an actuator is used to rotate the feet, which makes either the inner or outer legs shorter in order to create instability.



(a) (b)

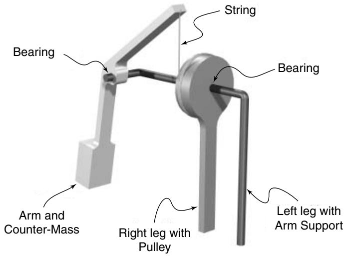
Figure 2: (a) The Cornell ranger, (b) Schematic diagram of the walking mechanism [HBM15]

1.3.2 Passive Biped with Knees

Steven H. Collins, Martijn Wisse and Andy Ruina, were inspired by the four-legged robot created by Tad Mc Geer [McG90] to create their "Passive biped with knees" (figure 3). Specifically, this walker has arms and knees, which gives it more human characteristics. This robot is completely passive, and uses only gravity as its form of energy, therefore it can only walk in a decreasing slope surface. By using only two legs, the walker has a new degree of freedom and makes the robot more unstable on the sides. The inventors, based its design on four important ideas thus differentiating it from the original four-legged version. Firstly, by adapting the shape of the feet to guide the lateral movement and moving the centre of mass to the left or right on the support foot. Secondly, by adding a heel damping system to reduce instabilities when placing the foot so that both edges of the foot touch the ground at the same time (figure 4a). Thirdly, by swinging one arm attached to its opposite leg at a time, their movement countered the rotation around the yaw axis. Finally, by making both arms swing laterally, the walker becomes more stabilised (figure 4b) [HWR01].

Figure 3: The passive biped with knees [HMA01]

(a) Schematic diagram of the foot of the walker [HWR01]



(b) Arm mechanism for lateral stability and yaw compensation [HWR01]

Figure 4: Key features of the walker

1.3.3 Powered Biped with Knees

A new version of this biped with knees was created and allowed it to walk on a flat surface (figure 5). For this, motors powered by batteries and controlled by electronic circuits were been added [CR05]. These motors created a push-off at the ankle to restore the energy lost during the heel-strike collision. However, its displacement and stabilisation is based on the same factors as the passive biped with knees (figure 4) [S+05].

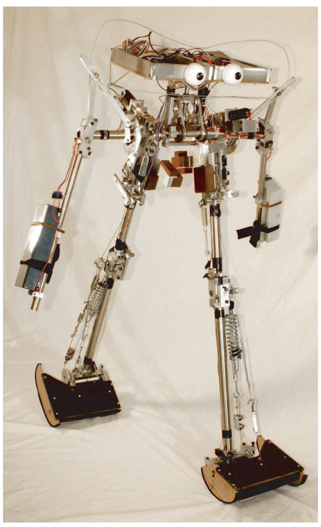


Figure 5: Powered biped with knees [S+05]

1.3.4 MIT learning biped

The toddler robot was developed at the Massachusetts Institute of Technology (MIT), for studying learning control (figure 6). The goal was to find a control policy that allowed the robot to stabilise itself. It was designed from a passive model and can walk down a slope without the use of the actuators. The two actuators control the roll and pitch at each ankle. The yaw is countered in the same way as the biped with knee (figure 4), and two arms are mechanically coupled to the opposite leg to create an opposite torque. Even with these four motors present, the trajectory of the robot is difficult to control because it has nine degree of freedom, making it under-actuated. Another interesting feature is the shape of the feet, they are large and curved in the front plane, while the three robots previously studied have their feet bent in the sagittal plane [TWS18; Ted+04].

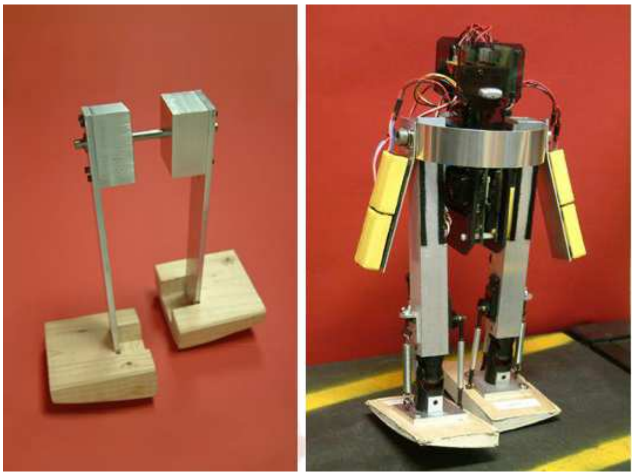


Figure 6: MIT learning robot on the right and the passive dynamic model on the left [TWS18]

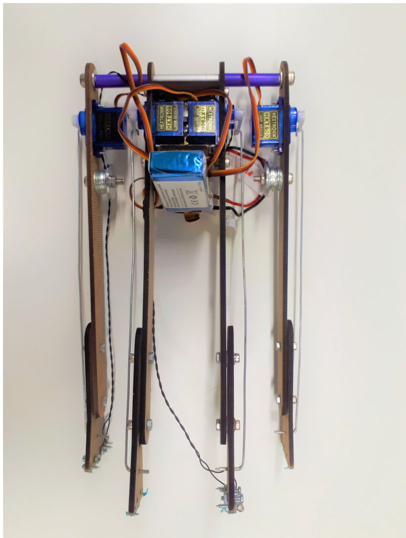
1.4 Rando the Walking Robot

The walking robot named "Rando" was created by Matthew A. Robertson and Amy R. Wu for the “Dynamic Walking 2017 Dynamic Robust Actuated Passive Ambulation (DRAPA) Challenge”. The goals of this challenge was to “build a robot that is accessible (open-source) and enables researchers and private individuals to explore and verify scientific questions without the hurdles of a huge budget” [Wor17]. Rando sufficiently met this criteria; it was a very accessible robot which could be manufactured for less than $ 50 [Wu+17a]. Electrical or mechanical components are easily found in shops. The material used for the parts is the medium density fibreboard (MDF), which can be easily laser cut. Welds can be made with a commercial soldering iron. If you do not have access to a laser cut, the pieces can be cut with a saw and then filed to obtain the desired shape. The holes can be made with a drill. This robot is very simple to manufacture and can be rapidly assembled. Moreover, this robot allows people to explore and verify scientific domains, such as fundamental principles of legged locomotion and more specifically the inverted pendulum principle. It is an active dynamic walker, which uses gravity for energy and actuators to restore lost energy during the collision of the feet with the ground [Wu+17b].

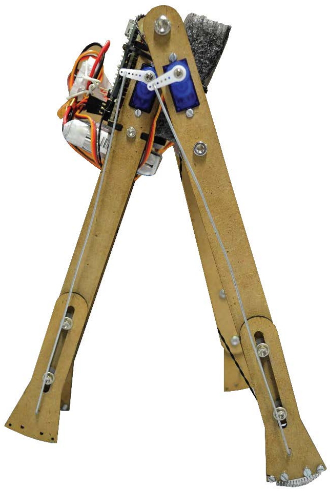
More specifically, Rando weighs 250g and has four legs that operate in pairs to maintain lateral stability. The lateral legs measure 240mm. The robot has feet with a curvature of 29.4 degrees and an arc length of 45.78mm, which optimises the energy used for each steps. On these feet a switch is attached to detect contact with the ground.

Finally, this robot is easily controllable and an algorithm is used to move the feet vertically at the right time. A push-off event is triggered on the supporting legs when the opposite legs touch the floor. The push force is proportional to the step time, for example, if the robot has taken a wide step, the force will be greater than if the step was weaker.

However, to ease the control and avoid the possibility that Rando will fall sideways, Rando only moves two legs at a time. A second version with lateral control was later created in order to make Rando more similar to human behaviour.



(a) Front view of Rando



(b) Lateral view of Rando [Wu+17a]

Figure 7: Rando the walking robot

2 The project: Rando/2

This new version was called "Rando/2" which reads "Rando slash two" in reference to the fact that this new version has a leg number divided by two compared to the first version. The number 2 can also refer to the fact that this robot is the second version of the Rando robot.

2.1 Goal of the project

The goal of this project was to make a two legged version of the Rando robot. The design could be changed to fit the new version, but the robot would keep the same mechanisms. While the robot is running, the trailing leg is actuated to restore the appropriate amount of energy lost between each step, so it could continue walking at a steady state. The robot kept the same functionality as Rando, through walking it demonstrates the inverted pendulum principle. Moreover, the robot was developed with the same intentions that Robertson and Wu had, making a robot accessible to everyone while maintaining the educational aspect. Thus, maker-style techniques were used, which included laser cutting and readily accessible materials, to create a low-cost robot.

2.2 State of the art

2.2.1 Stabilisation methods

The robot already had a stable longitudinal motion, meaning that one should be more focused on the different methods of stabilisation of lateral motion in walking. By analysing human behaviour, five methods can be considered [Kuo99].
The two first methods use the same weight transfer principle. By adding a torque actuation to the ankle of the swing leg, the centre of mass of the robot is moved to this support leg (figure 8a). Another method is to add a mass on top of the robot that can be moved laterally. This mass allows the weight compensation of the moving leg and helps the robot avoid falling on its side (figure 8c).
The third method is based on the control of the angular momentum. The overall angular momentum of the system is to be preserved, as it is possible to control the angular momentum of the robot by creating a tunable angular moment. In order for that to occur, a reaction wheel is installed on top of the robot and will spin at an appropriate speed (figure 8b).
The last method is based on step width. During the swing phase, the leg in motion moves both in the direction of travel and laterally to stabilise movement (figure 8d).

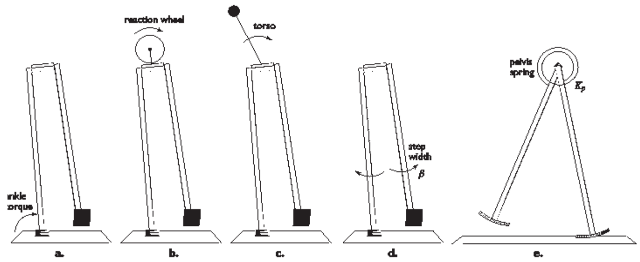


Figure 8: Different stabilisation methods: (a) ankle torque, (b) reaction wheel, (c) torso motion and (d) lateral step width control [Kuo99]

2.2.2 Foot shape

Peter G. Adamczyk, Steven H. Collins and Arthur D. Kuo have analysed the role of foot length and curvature [ACK06] [AK13] on the mechanical and metabolic costs of walking. Their analyses showed that the arc length of the foot has a greater effect on the mechanical work and the overall energetic cost of walking, in comparison to the radius of the foot. Nevertheless, it is still necessary that the foot is minimally convexly curved in order to minimise this energy. Finally, they found that the minimum energy cost obtained for a foot arch length was about 29% of the leg length.

3 Design

In order to build a robot that could be compared with the old version, Rando figure 7, and facilitate the same design, certain parts had to be preserved. The length of the upper and lower parts of Rando's lateral legs and the position of two servo motors on each of his legs were kept to preserve similar movements. The electronic part and the control mechanism are also the same, they will be described in more detail in section 4.

3.1 Experimental setup

The installation is quite simple and can be easily reproduced. All you need is a ruler and a camera that can film in slow motion. For this experiment the camera filmed with a resolution of 240 frames per second and the ruler was graduated in centimetres. The ruler was placed horizontally on a vertical plane, the centre of the robot was placed in the middle of this ruler and the camera was aligned with its centre. Another graduated line was drawn on the ground perpendicular to the horizontal plane and aligned with the centre of the ruler. A picture of the assembly is visible in the figure 9.

This assembly allows to measure the maximum angle with respect to the vertical that the moving robot makes in the frontal plane as well as its number of steps. The graduated line on the ground allows distance estimation of the robot's movement. The maximum angle is measured only using the first three steps of the robot to have a measurement comparable to the others because after several steps the robot moves forward in front of the camera and makes it more difficult to measure the inclination. Another issue is that its inclination is amplified by oscillation and thus depends on the number of steps. The accuracy of the measurements is the order of half a centimetre, which is low, but suitable for determining if a certain design for a part is more advantageous over another.

All measurements have been made with this same setup to replicate the same conditions and be easily comparable. To have representative measurements, only one parameter was changed at a time and each experiment was conducted several times.

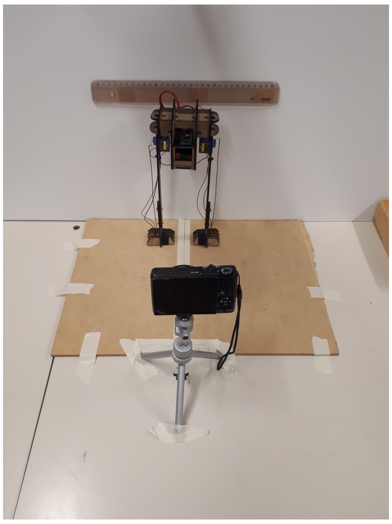


Figure 9: Experimental setup

3.2 First prototype

3.2.1 Stabilisation mechanism

Firstly, after analysing the state of the art of the different methods of stabilisation of lateral motion, it can be concluded that adding a controlled mass on top of the robot will be complicated to build, as it requires a solid structure. It will be also complicated to control and it's not similar to human behaviour, so it's less interesting to study. Moreover, the lateral step width control method is more closely related to the human behaviour but it will be more difficult to implement in that system. This method will certainly require a specific join, which cannot be easily crafted with wood and thus difficult to make them inexpensively. Additionally, the torque actuation at the ankle will be difficult to implement because the ankles are not fixed. Finally, the most feasible method that is easy to implement for the mechanism, is the torso motion. From a dynamic standpoint, this method is interesting because it is very similar to the human mechanism, which makes its a good fit when attempting to reproduce and study human behaviour. This mechanism was designed by connecting a servomotor to a rod on the stabilisation mechanism that will shift the weight horizontally. The centre of this mechanism is attached to the moving weight and can be easily changed to become adaptable to the system (figure 10).

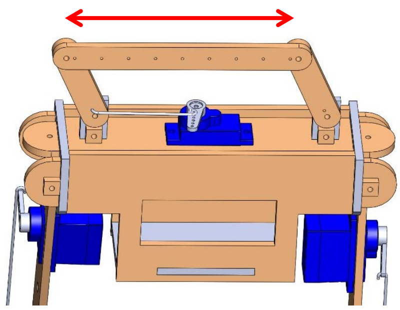


Figure 10: Stabilisation mechanism

3.2.2 Upper body

The robot no longer has the inner leg and a new upper body has been designed. This upper body had to be rigid enough so that the robot did not have too much backlash and resultantly became more stable and easier to control. The upper parts of the body also need to carry the new mechanism and allow the swinging of the weight. A T-shaped structure was chosen to adjust the position of the internal elements (battery and electronic circuit) and the robot's centre of gravity by varying the height. This shape gives sufficient space to the servo motor so that the movement of the legs are not constrained. It also allows to have a distance between legs sufficiently large, 115mm (figure 11).

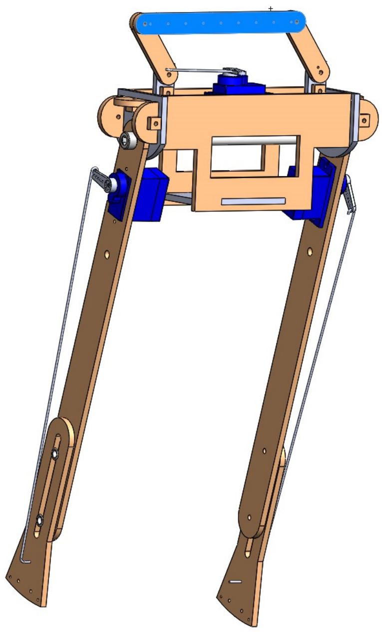


Figure 11: First prototype drawing

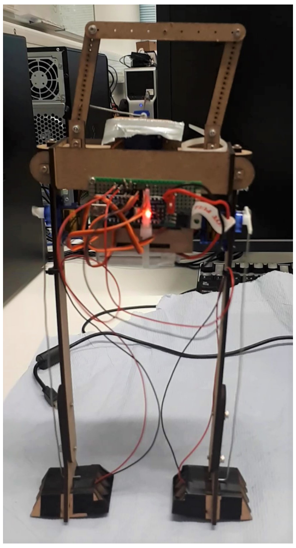
3.2.3 Foot shape

For the first prototype we kept the same foot as Rando, figure 7. However, after several tries, the robot keep falling, making it impossible to conduct measurements and led to modification of the feet design. They have been designed to make the robot increasingly more stable in order to study the lateral swing of the robot. As a result, their curvature was increased to become flatter, and pieces have been added on side to increase foot area and create better stability. These pieces have a curvature radius of 200mm, and the curvature of the foot in the sagittal plane can by modified by moving these pieces up and down (figure 12).

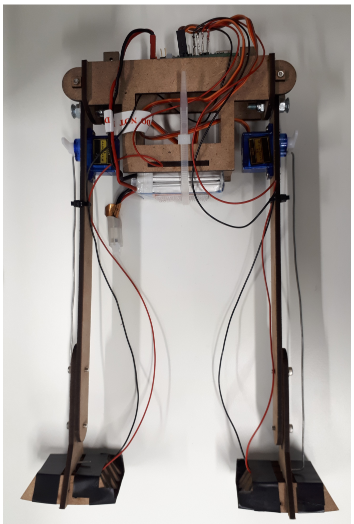
Figure 12: First feet prototype

3.2.4 First result

The first prototype can be seen in the figure 13a, the battery has been placed under the robot to counterbalance with the upper mechanism and vertically maintain the upper body. The electronic circuit has been fixed in front of the robot to create an imbalance and lean the robot forward to facilitate a walking direction.
To validate the design, two types of tests were performed, one by operating the upper mechanism to change the centre of mass and another by disabling this mechanism. It turned out that the mechanism was actually not necessary, the simple action of the push-off through the feet gives enough strength to the robot to swing on the sides. Resultantly, the mechanism was removed and the electronics circuit were placed on top of the robot to create a more stable robot (figure 13b).
Then, the robot was re-tested five times under the same conditions, in which the methods are further explained in section 3.1, to measure the angle of deviation and the number of steps. It had an average angle of deviation of 15.8 degrees and an average of 15.8 steps, but it only moved marginally (figure 14).



(a) First prototype of the robot with the stabilisation mechanism



(b) Second prototype of the robot without the stabilisation mechanism

Figure 13: First two prototypes

Measurements	Displacement_Max [cm]	Angle_Max [°]	Number of steps
1	7	15,6	7
2	7	15,6	4
3	6,5	14,5	18
4	7,5	16,8	26
5	7,5	16,8	24
Mean	7,1	15,8	15,8
Standard deviation	0,42	0,96	9,91

Figure 14: Table of the different measurements made with the large upper body

3.3 Prototype improvement

A new prototype has been made to increase the travel distance, and at first, an improvement of the upper body was tested. Afterwards, several tests were done with different foot shapes and lengths to determine the best compromise.

3.3.1 Upper body

A new design of the upper body was made to reduce the distance between the two legs of 30mm in order to better control the tilt of the robot. Thus, the new distance was 85mm. The design was inspired from Cornell ranger [HBM15], the battery and the electronic circuit have been placed perpendicular to their previous position in the central compartment (figure 15).

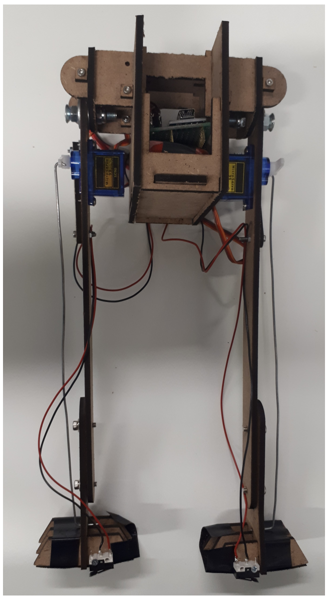


Figure 15: Third prototype of the robot with smaller upper body

As expected, the robot tilts more on the sides at each step with an average of 17.9 degrees (figure 16), compared to 15.8 degrees for the larger upper body (figure 17). However, the robot makes very few steps (4.2 steps on average) and often fell forward. Ultimately, the upper body design for this robot is not advantageous and will not be kept.

Measurements	Displacement_Max [cm]	Angle_Max [°]	Number of steps
1	7,5	16,8	4
2	7,5	16,8	6
3	8	17,9	4
4	8,5	19,1	3
5	8,5	19,1	4
Mean	8	17,9	4,2
Standard deviation	0,50	1,16	1,10

Figure 16: Table of the different measurements made with the small upper body

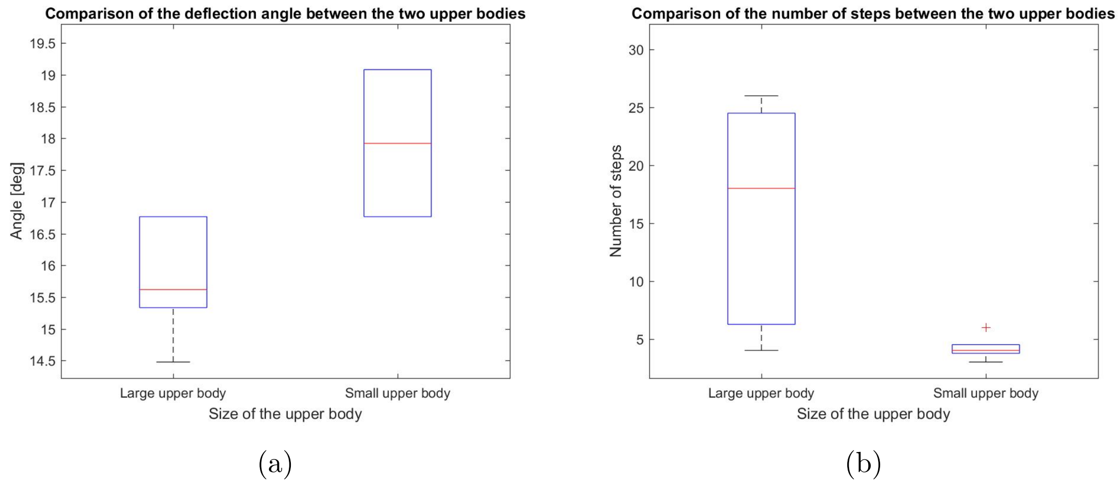


Figure 17: Comparison between the two body sizes

3.3.2 Foot shape

The new design for the upper body provided no improvement, so new feet shape and length were designed to increase the performance of the robot. These new feet have been compared to each other to determine which one is better. The sheet that contained all of the results was in the annex.
The arc length of each foot in the sagittal plane was 72mm, and was chosen in agreement with the study based on the foot shape analysed in section 2.2.2. This length corresponds to 30% of the leg length, which is 240mm.
The robot does not move to the side, and the length of the lateral parts of the feet were not constrained to a precise value. For this analysis, the radius of curvature was more important.

Four different foot designs have been created:

- **Foot_Sagittal_Curve**: its design was inspired by the feet of the Passive Biped With Knees 4a. This foot has a curvature radius of 100mm and allows the robot to tilt more easily forward (figure 18a).
- **Foot_Arc**: its design was inspired by the feet of the robot created by MIT that was analysed in the section 1.3.4. This asymmetric arch-shaped foot with a 70mm radius of curvature and an arc length of 62.47mm makes it more susceptible for the robot to tip over to the sides (figure 18b).

- **Foot_Circle**: The design goal was to see if the robot could tilt with a high angle on the sides and return to its original position, vertically. The foot has a radius of curvature of 50mm and its tip is at an angle that is greater than 90 degrees, relative to the horizontal plane (figure 18c).
- **Foot_R150**: this foot is used as a reference, it is similar to the ones created for the first tests, as it has the same radius curvature of 150mm. However, its arc length has been lengthened, as it measures 75.66mm, whereas it was 55mm for the old model (figure 18d).

(a) Foot_Sagittal_Curve

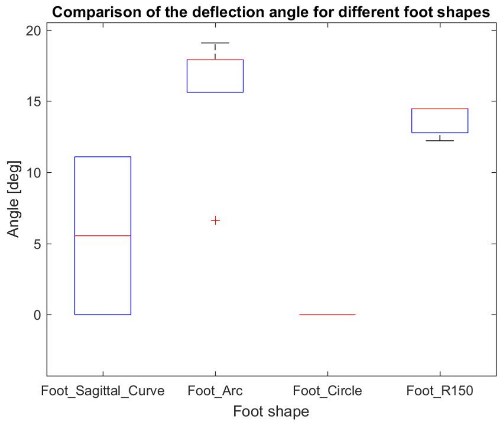
(b) Foot_Arc

(c) Foot_Circle

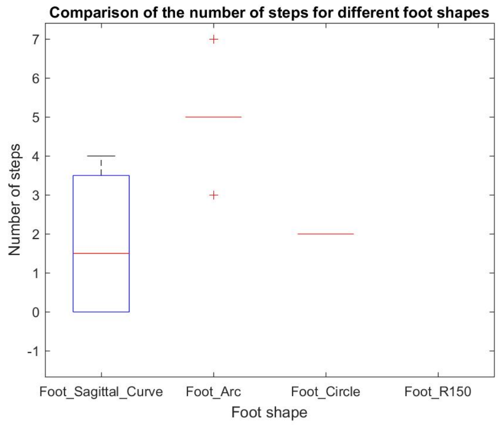
(d) Foot_R150

Figure 18: Different foot shapes

To determined which shape is the best, these four feet have been compared (figure 19). For these tests, the feet were flat in the sagittal plane, to not influence the measurements by making the robot less stable.
The foot "Foot_Circle" shape was the least successful because the robot was falling directly to the side without making any steps. With the foot "Foot_Sagittal_Curve" the robot was swinging very little on the sides, averaging 5.54 degrees and was unstable. It was difficult to make it stand up, it often fell forward or backward and took less than 2 steps on average. A better result was obtained with the foot "Foot_Arc", the robot averaged 5 steps and tilted at an angle of 15.8 degrees. Finally, the best results were obtained with the foot "Foot_R150", the robot never fell and swayed with an angle of 17.7 degrees. This shape for the lateral part of the foot is therefore the best for this robot.



(a)



(b) Comment: for Foot_R150, there is no value for the number of steps because the robot is walking continuously

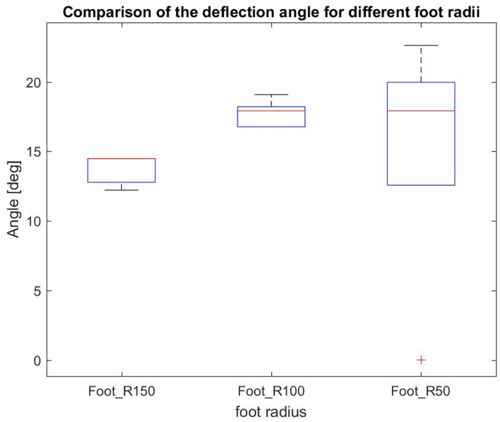
Figure 19: Comparison between different foot shape

Determining the best foot shape required an analysis of the different radii of curvature for the lateral part of the feet, in addition to studying their implications on the robot. Their names and parameters are listed in figure 20.

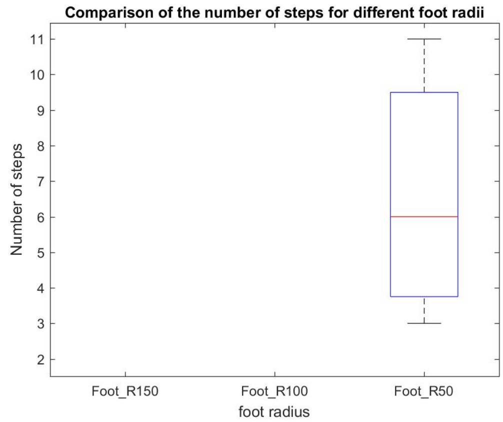
Name	Radius of curvature	Arc length
Foot_R150	150	76,49
Foot_R100	100	73,61
Foot_R50	50	68,17

Figure 20: Table of the parameters of each feet

As shown in the figure 21, a radius of 50mm proved to be too small and made the robot unstable, which resulted in less steps being taken (on average 6.6 steps). For a radius greater than 100mm, the robot remained standing and never fell. Regarding the angle, as expected, larger angles of inclination were obtained with a more curved foot. Therefore, the foot Foot_R100 with a radius of 100mm has been kept for this robot.



(a)



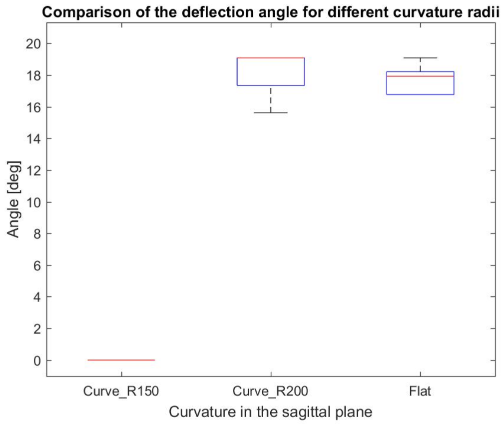
(b) Comment: for Foot_R150 and Foot_R100, there is no value for the number of steps because the robot is walking continuously

Figure 21: Comparison between different foot radii

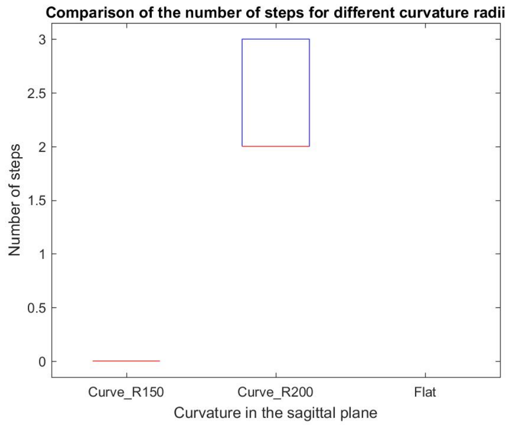
Another analysis was made to study the impact of the curvature radius of the foot in the sagittal plane, on the walking of the robot.

As stated in the figure 22 the robot is very sensitive to the radii of curvature. A radius of 150mm makes the robot completely unstable and it was not possible to make it stand up. With a radius of 200mm, it is a little better but the robot is still unstable and averages only about 2.4.

Although, it was noticed that the robot was falling because the legs did not move at the right time. To fix this issue, the sensor that was attached to the centre of the foot was then moved forward. As it can be seen in the figure 24, that was in fact the problem, the robot was now averaging 6 steps. Nevertheless, the robot was always falling back, though it was supposed that the switch sensor acted like small springs and pushed the robot backwards. Weights of 13g each were added to the front of the robot to try to compensate for this effect (figure 23). But, it did not improve the movement of the robot and actually resulted in less steps.



(a)



(b) Comment: for the flat foot, there is no value for the number of steps because the robot is walking continuously

Figure 22: Comparison between different foot curvatures

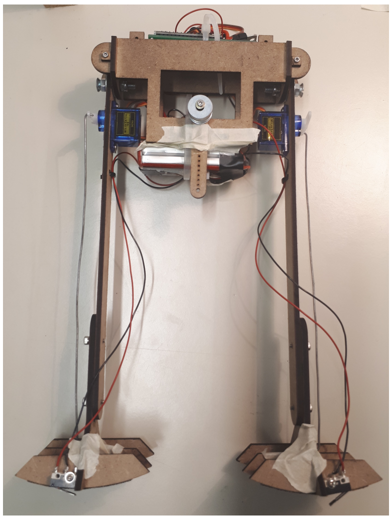
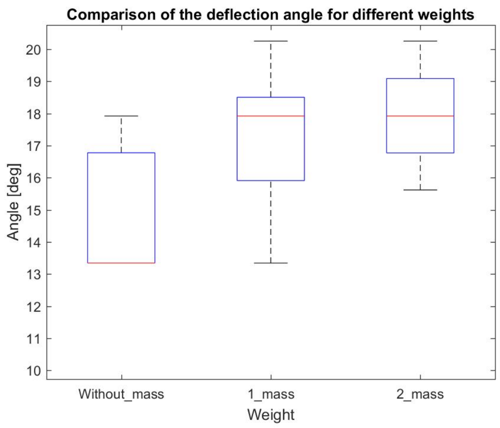
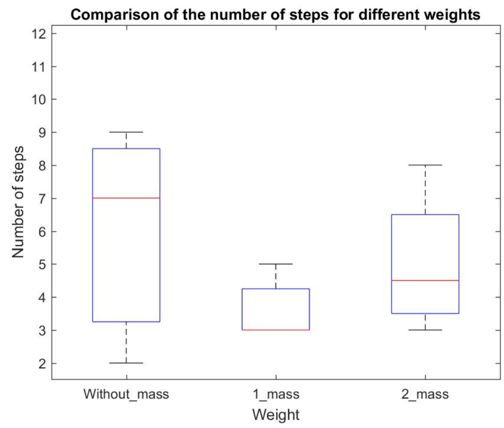


Figure 23: Robot prototype with one weight attached in the front



(a)



(b)

Figure 24: Comparison between different weights

Due to the issues with the added weight, the weights were then removed. Instead, switch sensors were attached to the back of the foot to compensate for the effect of the other switch sensor in the front. The robot would sometimes slide on the floor, and so non-slip tape was glued under the foot (figure 25).

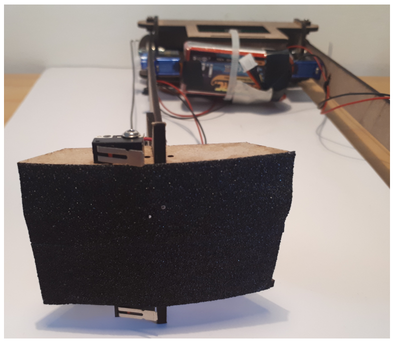
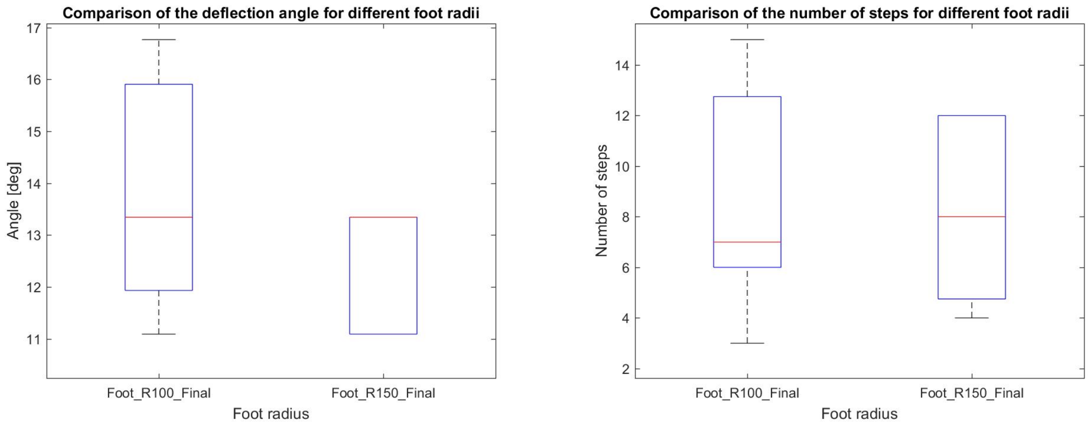


Figure 25: Foot with two sensors attached and non-slip tape glued

The robot was tested with these new feet "Foot_R100_Final", and it was noticed that the robot was swinging a little too much on the sides, which reduced the walking dynamics and caused it to fall. The feet with the lateral parts having a radius of 150mm were then tested with the same elements that were used for the previous feet "Foot_R100_Final". Sensor was attached to the back of the foot and non-slip tape was glued underneath the foot. As shown in the figure 26, the best result was obtained with these feet "Foot_R150_Final", which had a higher radii of curvature. Therefore, these foot "Foot_R150_Final" has been kept for this robot. Thus, the final version weighs 238 g and is shown in figure 27.



(a)

(b)

Figure 26: Comparison between different foot radii

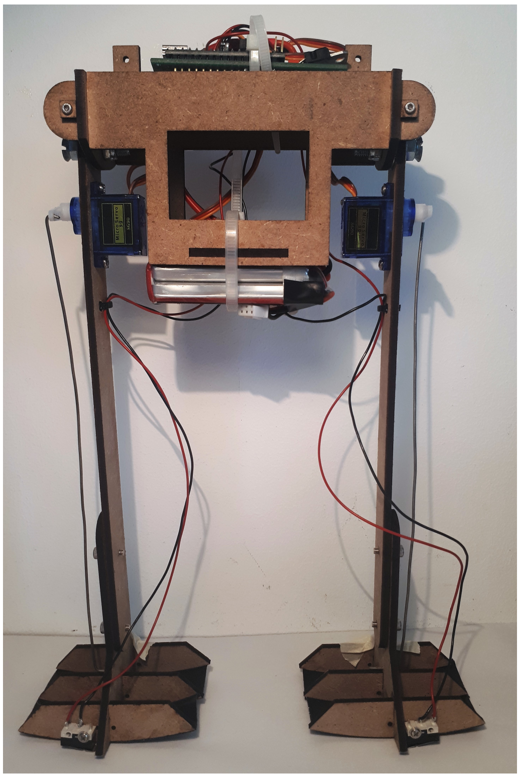


Figure 27: Final version of the new robot, Rando/2

3.3.3 Final result

Several other tests were conducted on softer ground and proved to be successful, the robot walked a distance greater than 1.5m for less than 2 minutes (figure 28). However, the robot walked over a distance greater than 1m in 4 out of 15 tests. These test proved that it was difficult to make the robot walk, and it depends significantly on the initial conditions, such as how the upper body of the robot is oriented as well as the position and spacing of the legs. spacing.

During these movements, the robot made a circular trajectory. This may be due to the fact that either the force during the push-off was not the same for each foot or the imbalance of weight between the two legs, which would create a torque at each movement and lead the robot to turn on itself.

Measurement	Time [s]	Approximate distance [m]	Comment
1	48	1 < and < 1,5	Fall at the end
2	18	0,5 < and < 1	Fall at the end
3	1	0-	Fall
4	5	0 < and < 0,2	Stay up
5	2	0 < and < 0,05	Fall
6	2	0 < and < 0,05	Fall
7	18	0,2 < and < 0,5	Fall at the end
8	2	0 < and < 0,2	Fall
9	3	0 < and < 0,2	Fall
10	6	0,1 < and < 0,2	Fall at the end
11	4	0,1 < and < 0,2	Fall at the end
12	104	1,5 < and < 2	Fall at the end
13	46	1 < and < 1,5	Stay up at the end
14	120	1,5 < and < 2	Kept walking
15	40	0,5 < and < 1	Kept walking
Mean	28	0,4 < and < 0,9	
Standard deviation	38	0,6 < and < 0,8	

Figure 28: Table of the different measurements made with the final prototype

4 Electric parts and control

4.1 Technical parts

4.1.1 Hardware

Most of the electronic components are the same as the ones used for the four-legged robot, Rando. A compact board, the Arduino nano powered by a 7,4 V battery was used to control the robot (figure 30a). The electronic diagram of the Rando is shown in figure 29. The differences with the previous version was that this robot only used two servomotors to operate its two legs and not four. The two inputs for the servomotors, "Right lateral" and "Right Medial" can be replaced by only two inputs, "Right" and "Left". The "Left Medial" and "Left Lateral" inputs can be deleted. In addition, on the right diagram, the blue and purple wires can be removed. Moreover, sensors to detect when the feet touch the ground that were previously a simple measurement of tension through a spring, have been replaced by micro switch sensor (figure 30b) to simplify assembly and electronics.

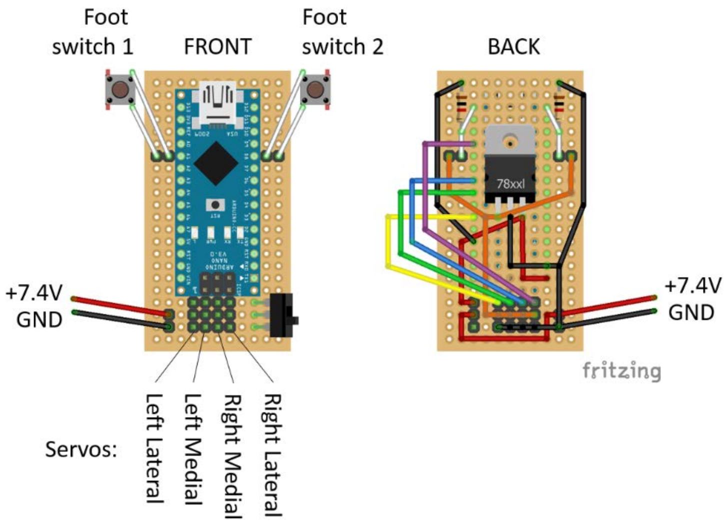
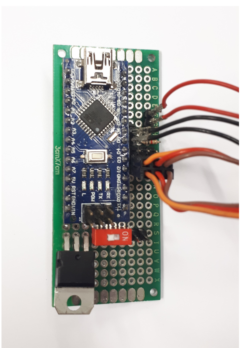
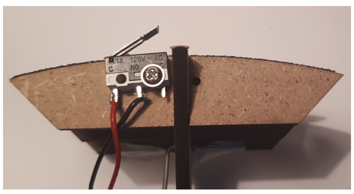


Figure 29: Diagram of the electronic circuit of the robot with four legs, Rando [Wu+17b]



(a) Electric circuit



(b) Micro switch sensor attached to the foot

Figure 30: Electronic components of the robot

4.1.2 Software

For the software, the same code as that created for Rando by Amy R. Wu and Matthew A. Robertson were used. To facilitate the control of the robot, the displacement of the leg during the push-off was constant unlike the previous version, which was proportional to the duration of each step.

Two important group parameters have to be defined as they are specific to the robot.

In the following explanation, the variable "i" can be replaced by "R" if one wants to act on the servomotor on the right and by "L" if one wants to act on the one on the left.

- The management of the position of the legs, the initial position of the moving leg is defined by the variable "mid_i". In the code it is initialised to 90, which corresponds to the angle that the servomotor will move from its reference position. The variable "down_i" gives the angle that will make the servomotor lower the leg a certain distance and the variable "up_i" gives the angle to raise it.

- The different time parameters: the variable "pushOff", defines the time in milliseconds for the leg that remains in the low position, and the variable "swing", defines the time in milliseconds for the leg that remains in a high position.

The complete code is present in the appendix.

For the robot, the parameters concerning the position of the legs were easily determined because they only depend on the design of the leg. Regarding the swing and push-off time, several tests have been done by varying these parameters in order to obtain the best performances. The best results were obtained for swing time and push of 150 milliseconds.

4.2 Control

The control of the robot is simple; it is based on the principle of the inverted pendulum. The robot not being statically stable, will lean forward under the effect of gravity. By well managing their sizes, the legs will swing in turn forward, allowing the robot to walk. In order for the legs to have enough time for this, the robot will first tilt to one side leaving the opposite leg free (figure 31).

More specifically, when the foot of the forward leg touches the ground, the micro-switch is activated. The other leg is lengthened to push-off the robot both forward and to the side. The robot will therefore tip on the support leg and transfer all its weight on it. The other leg will retract to not to rub against the ground, resembling the knee movement that is bent when human walks. The leg will swing forward due to gravity and will then be re-lengthened to return to it original size. The foot will touch the ground and trigger the sensor. This leg will be the support leg and the actuation will be on the other leg, and vice versa, as long as the robot walks.

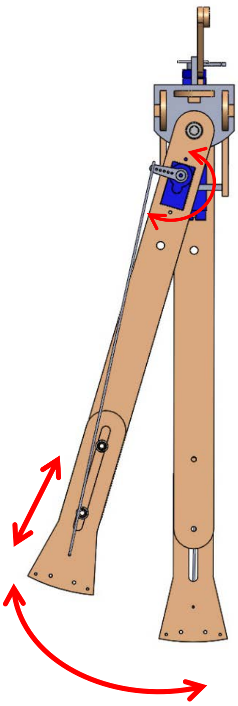


Figure 31: Diagram of the leg movement

5 Conclusion and future work

The goal of this project was achieved, a two legged version of the Rando robot was created. The robot was able to demonstrate that it could walk a distance of more than 1.5m in less than 2 minutes. Nevertheless, it was not easy to make the robot walk as it depended on many factors, such as the quality of the ground (i.e. if it is rough and flat enough), and the initial conditions such as the orientation of the upper body and the legacy spacing. It would be interesting to improve this robot to make it less dependent on these parameters. In addition, this project analysed the influence of different parameters on the movement of the robot. The different parameters being analysed included the distance between the legs and the shape of the feet, with greater emphasis on analysing the radius of curvature and arc length in the sagittal and frontal plane.
Although some parameters have been fixed to facilitate the construction of the robot, further analyse of the parameters' impact on the robot in the future would be beneficial to this area of research. Greater in-depth analysis could help identify and modify the issues of leg length and the position of the servomotors. In addition, more study on the kinematics of the robot could be interesting from different academic perspectives, and would enable making improvements on the robot more easily.

Acknowledgements

I would like to give a special thank you to my supervisor Amy Wu for her patience and valuable guidance with this project.

References

[McG90] Tad McGeer. “Passive dynamic walking”. In: *The International Journal of Robotics Research* 9 (1990).

[Kuo99] Arthur D. Kuo. “Stabilization of Lateral Motion in Passive Dynamic Walking”. In: *The International Journal of Robotics Research* 18 (1999).

[HWR01] Steven H. Collins, Martijn Wisse, and Andy Ruina. “A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees.” In: 20 (Jan. 2001), pp. 607–615.

[HMA01] Collins S. H., Wisse M., and Ruina A. *Passive Biped with Knees.* 2001. URL: http://ruina.tam.cornell.edu/research/topics/locomotion_and_robotics/3d_passive_dynamic/ (visited on 05/18/2018).

[DKK02] J. Maxwell Donelan, Rodger Kram, and Arthur D. Kuo. “Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking”. In: *Journal of Experimental Biology* 205.23 (2002), pp. 3717–3727. ISSN: 0022-0949. eprint: http://jeb.biologists.org/content/205/23/3717.full.pdf. URL: http://jeb.biologists.org/content/205/23/3717.

[Ted+04] R Tedrake et al. “Actuating a simple 3D passive dynamic walker”. In: 2004 (Jan. 2004), 4656–4661 Vol.5.

[CR05] S.H. Collins and A Ruina. “A Bipedal Walking Robot with Efficient and Human-Like Gait”. In: 2005 (May 2005), pp. 1983–1988.

[S+05] Collins S. et al. “Efficient Bipedal Robots Based on Passive-Dynamic Walkers”. In: *SCIENCE* VOL 307 (Feb. 2005). URL: www.sciencemag.org.

[ACK06] Peter G. Adamczyk, Steven H. Collins, and Arthur D. Kuo. “The advantages of a rolling foot in human walking”. In: *Journal of Experimental Biology* 209.20 (2006), pp. 3953–3963. ISSN: 0022-0949. DOI: 10.1242/jeb.02455. eprint: http://jeb.biologists.org/content/209/20/3953.full.pdf. URL: http://jeb.biologists.org/content/209/20/3953.

[And12] Ruina Andy. *Cornell Ranger, 2011-2012 4-legged bipedal robot.* 2012. URL: http://ruina.tam.cornell.edu/research/topics/locomotion_and_robotics/ranger/Ranger2011/ (visited on 05/18/2018).

[AK13] Peter G. Adamczyk and Arthur D. Kuo. “Mechanical and energetic consequences of rolling foot shape in human walking”. In: *Journal of Experimental Biology* 216.14 (2013), pp. 2722–2731. ISSN: 0022-0949. DOI: 10.1242/jeb.082347. eprint: http://jeb.biologists.org/content/216/14/2722.full.pdf. URL: http://jeb.biologists.org/content/216/14/2722.

[HBM15] Seyed Javad Hasaneini, John Bertram, and C.J.B. Macnab. “Energy-optimal relative timing of stance-leg push-off and swing-leg retraction in walking”. In: (Sept. 2015).

[Wor17] Wordpress. *Dynamic Walking presents: The DRAPA Challenge*. 2017. URL: `https://dwdrapa.wordpress.com/` (visited on 06/04/2018).

[Wu+17a] Amy R. Wu et al. "A Powered Dynamic Walking Robot for under $50". In: (2017).

[Wu+17b] Amy R. Wu et al. *DRAPA Challenge, Dynamic Walking 2017. Rando the Walking Robot*. 2017. URL: `http://www.bot-hed.com/` (visited on 05/18/2018).

[MI18] Prof. Francesco Mondada and Prof. Auke Jan Ijspeert. "Locomotion". In: *Mobile robots* (2018).

[TWS18] Russ Tedrake, Teresa Weirui Zhang, and H Sebastian Seung. "Learning to walk in 20 minutes". In: (June 2018).

A Measurements

Measures for the different upper body.

	Displacement_Max [cm]	Angle_Max [°]	Number of steps
Large Body			
N=1 :MVI_1162	7	15,6	7
N=2 :MVI_1164	7	15,6	4
N=3 :MVI_1165	6,5	14,5	18
N=4 :MVI_1166	7,5	16,8	26
N=5 :MVI_1167	7,5	16,8	24
Mean	7,1	15,8	15,8
Standard deviation	0,42	0,96	9,91
Small Body			
N=1 :MVI_1153	7,5	16,8	4
N=2 :MVI_1154	7,5	16,8	6
N=3 :MVI_1156	8	17,9	4
N=4 :MVI_1157	8,5	19,1	3
N=5 :MVI_1158	8,5	19,1	4
Mean	8	17,9	4,2
Standard deviation	0,50	1,16	1,10

Measures for the different foot shape.

Foot shape	Déplacement_Max [cm]	Angle_Max [°]	Nb of step	Comment #1	Comment #2
Foot sagittal curve					
N=1 :MVI_1179	0	0,0	0	Falls	
N=2 :MVI_1180	5	11,1	3		
N=3 :MVI_1181	5	11,1	4		
N=4 :MVI_1182	0	0,0	0	Falls	
Mean	2,5	5,5	1,75		
Standard deviation	2,5	5,5	1,8		
Foot arc-flat					
N=1 :MVI_1196	3	6,6	3		
N=2 :MVI_1197	7	15,6	5		
N=3 :MVI_1198	8	17,9	5		
N=4 :MVI_1199	8	17,9	7		
N=5 :MVI_1200	8,5	19,1	5		
N=6 :MVI_1201	8	17,9	5		
Mean	7,1	15,8	5		
Standard deviation	2,1	4,7	1,3		
Foot circle-flat					
N=1 :MVI_1186	0	0,0	2	Falls	
N=2 :MVI_1187	0	0,0	2	Falls	
N=3 :MVI_1188	0	0,0	2	Falls	
Mean	0	0	2		
Standard deviation	0	0	0		
Foot R150-flat					
N=1 :MVI_1203	5,5	12,2	stay up		
N=2 :MVI_1204	6,5	14,5	stay up		
N=3 :MVI_1205	6,5	14,5	stay up		
Mean	6,2	13,7			
Standard deviation	0,6	1,3	0		
Foot R100-flat					
N=1 :MVI_1206	8	17,9	stay up		
N=2 :MVI_1207	7,5	16,8	stay up		
N=3 :MVI_1208	8,5	19,1	stay up		
N=4 :MVI_1209	8	17,9	stay up		
N=5 :MVI_1210	7,5	16,8	stay up		
Mean	7,9	17,7			
Standard deviation	0,4	0,9			
Foot R50-flat					
N=1 :MVI_1211	10	22,6	11		
N=2 :MVI_1212	0	0,0	3		
N=3 :MVI_1213	7,5	16,8	6		
N=4 :MVI_1215	8	17,9	4		
N=5 :MVI_1216	8,5	19,1	9		
Mean	6,8	15,3	6,6		
Standard deviation	3,5	7,9	3,0		
Foot R100-R150					
N=1 :	0	0,0	0	Falls	
N=2 :	0	0,0	0	Falls	
N=3 :	0	0,0	0	Falls	
Mean	0	0			
Standard deviation	0	0	0		
Foot R100-R200					
N=1 :MVI_1218	7	15,6	2		
N=2 :MVI_1219	8,5	19,1	3		
N=3 :MVI_1220	8,5	19,1	3		
N=4 :MVI_1221	8,5	19,1	2		
N=5 :MVI_1222	8	17,9	2		
Mean	8,1	18,2	2,4		
Standard deviation	0,6	1,3	0,5		
Foot R100-R200-Sensor-front+mass					
N=1 :MVI_1230	8	17,9	3		
N=2 :MVI_1231	7,5	16,8	3		
N=3 :MVI_1232	6	13,3	5		
N=4 :MVI_1233	9	20,3	3	Falls back	
N=5 :MVI_1235	8	17,9	4	Falls back	
Mean	7,7	17,2	3,6		
Standard deviation	1,0	2,3	0,8		
Foot R100-R200-Sensor-front+2masse					
N=1 :MVI_1236	8	17,9	5		
N=2 :MVI_1237	9	20,3	3		
N=3 :MVI_1240	8	17,9	4	Falls back	Falls back
N=4 :MVI_1241	7	15,6	8	Falls back	Falls back

Mean	8	17,9	5		
Standard deviation	0,7	1,6	1,9		
Foot R100-R200-Sensor-front					
N=1 :MVI_1244	8	17,9	2	Without mass	Falls back
N=2 :MVI_1245	6	13,3	7	Without mass	Falls back
N=3 :MVI_1247	6	13,3	9	Without mass	Falls back
Mean	6,7	14,9	6,0		
Standard deviation	1,2	2,6	3,6		
Foot R100-R200-Sensor-front+back+masse+grip					
N=1 :MVI_1255	6	13,3	7		
N=2 :MVI_1254	5	11,1	15	Stay up without moving	
N=3 :MVI_1253	5,5	12,2	12		
N=4 :MVI_1252	7,5	16,8	3		
N=5 :MVI_1251	7	15,6	7		
Mean	6,2	13,8	8,8		
Standard deviation	0,9	2,1	4,2		
Foot R150-R200-Sensor-front+back+masse+grip					
N=1 :MVI_1258	6	13,3	12	Stay up without moving	
N=2 :MVI_1259	6	13,3	8	Stay up without moving	
N=3 :MVI_1262	6	13,3	4		
N=4 :MVI_1263	6	13,3	5		
N=5 :MVI_1266	5	11,1	12		
N=6 :MVI_1269	5	11,1	15+	Keep walking	
Mean	5,7	12,6			
Standard deviation	0,5	1,2			

B Code implementation

Code for controlling the robot.

```
/* RandoWalkerTall
  created by Amy R. Wu and Matthew A. Robertson in 20 May 2017
  modified by Tristan Abondance in 7 June 2018
*/

#include <Servo.h>

Servo servoR;  // create servo object to control a servo
Servo servoL;

// settings
// Right
int down_R = 60;
int mid_R = 90;
int up_R = 130;

// Left
int down_L = 60;
int mid_L = 90;
int up_L = 130;

const int footSwitchR = 6; // PIN 8
const int footSwitchL = 5; // PIN 12
int switchState = 1;

// Delays
int contactDelay = 0;
```

```
int pushOff = 150;
int swing = 150;
int temps = 0;

void setup() {
  pinMode(footSwitchR, INPUT);
  pinMode(footSwitchL, INPUT);

  servoR.attach(2);  // attaches the servo on pin X to the servo object
  servoL.attach(3);  // attaches the servo on pin X to the servo object

  servoR.write(mid_R);  // tell servo to go to position in variable 'pos'
  servoL.write(mid_L);

  delay(2000);
}

void loop() {

    int buttonStateR = digitalRead(footSwitchR);
    int buttonStateL = digitalRead(footSwitchL);

    if(buttonStateL == HIGH && switchState){
      delay(contactDelay);

      servoR.write(down_R);    //PUSH OFF
      delay(pushOff);

      servoR.write(up_R);      //RETRACT for swing
      delay(swing);                //SWING

      servoR.write(mid_R);     //RESET
      delay(temps);

      switchState = !switchState;

    }
    else if(buttonStateR == HIGH && !switchState){
      delay(contactDelay);

      servoL.write(down_L);    //PUSH OFF
      delay(pushOff);

      servoL.write(up_L);      //RETRACT for swing
      delay(swing);            //SWING

      servoL.write(mid_L);     //RESET
      delay(temps);

      switchState = !switchState;
```

```
        }
}
```