Passive Dynamic Walker

2 4 / 0 8 / 2 0 1 4

Passive dynamic walking is a phenomenon originally described for bipeds having straight legs that are able to walk down a gentle slope with no external control or energy input. A humanlike pair of legs will settle into a natural gait generated by-passive interaction of gravity and inertia. Due to time constraints we will be modelling, simulating and constructing the simplest walking 2D walker (without knees). To put it simply, dynamic walking means to constantly fall, but to bring forward the swing leg in time to prevent tilting over. The forward swing of the leg has to meet two conditions: the foot must clear the ground, and the leg must arrive in front of the body in time to act as next swing leg. The simulation used is based upon ["First Steps in Passive Dynamic Walking", Climbing and Walking Robots, Springer Berlin Heidelberg, P 745-756, 2005]. It provides the basic tools to simulate a simple, two-dimensional walking model, to find its natural cyclic motion, to analyse the stability, and to investigate the effect of parameter changes on the walking motion and the stability.

CONTENTS

INTRODUCTION

The system that we will be modelling is a Passive Dynamic Walker (PDW), which is a gravity powered walking machine. Due to time constraints we will be modelling, simulating and constructing the simplest walking 2D walker (without knees). The project aim is to design and build a passive dynamic walker (PDW), without any on-board sources of energy. The main objective is to configure the PDW to walk consistently and this is not a trivial task, hence the necessity for modelling and design is useful.

BACKGROUND

RESEARCHING

WHAT IS A PASSIVE DYNAMIC WALKER?

A mechanism with human-like pair of legs will settling into a natural gait generated by passive interaction of gravity and inertia given only a downhill slope as a source of energy. No muscular input is required (McGeer 1991).

CHALLENGES IN DESIGNING AND IMPLEMENTING A PASSIVE DYNAMIC WALKER

INSTABILITY

It must be ensured that instability remains temporarily. To put it simply, dynamic walking means to constantly fall, but to bring forward the swing leg in time to prevent tilting over. This allows for higher velocity by larger step size, shorter double support phase, and less time consuming adjustment of weight distribution (Luksch 2010).

LEG SWING

The forward swing of the leg has to meet two conditions: the foot must clear the ground, and the leg must arrive in front of the body in time to act as next swing leg. Ground clearance can be achieved through shortening the leg by bending the knee, and by keeping the foot oriented level to the ground. Uneven terrain makes this task even more difficult (Luksch 2010).

CONTROL OF FORWARD VELOCITY

The system acts like an inverted pendulum while traversing over the stance leg, enough kinetic energy must be present to be transferred to potential energy. In contrast, if the velocity is too high, the time for the swing leg to travel before the place it’s supposed to might be too short and the biped tumbles. During walking, energy is consumed by damping and by foot impact. Measuring or estimating the proper forward velocity is not easily achieved.

The forward velocity can be influenced by many factors: the further back the centre of pressure is located in the stance foot during single support, the faster is the resulting forward movement. Bending the trunk forward accelerates the biped; leaning backwards slows it down (Luksch 2010).

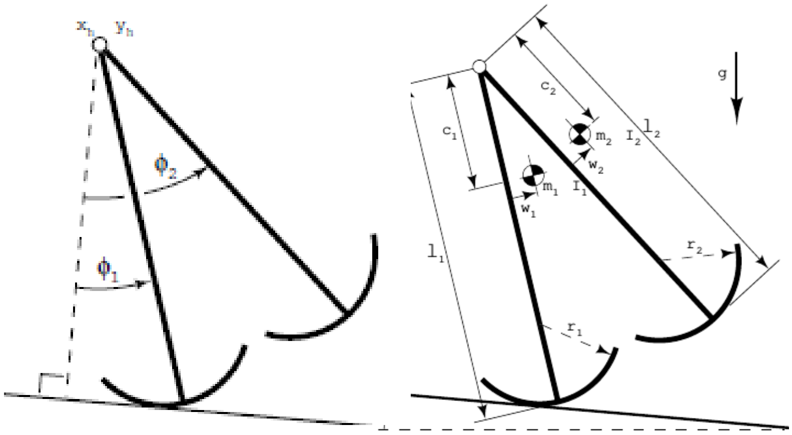
MODELLING

The model used in the simulation is realistic enough to enable the construction of a physical prototype with corresponding behaviour. The simulation is based upon ["First Steps in Passive Dynamic Walking", Climbing and Walking Robots, Springer Berlin Heidelberg, P 745-756, 2005] (Wisse and Schwab 2004).

It provides the basic tools to simulate a simple, two-dimensional walking model, to find its natural cyclic motion, to analyse the stability, and to investigate the effect of parameter changes on the walking motion and the stability. The simplest system that can perform a Passive Dynamic Walking motion consists of two rigid legs interconnected through a passive hinge as demonstrated in the simulation.

We are using a simulation so we are able to gauge/predict how something will behave without actually testing it in real life. Its purpose is to develop data as a basis for making the final PDW design decisions. An advantage of this is that it’s generally cheaper and safer than conducting experiments with a prototype and can often be conducted faster than real time. A downside to this is that it can often be even more realistic than practical/traditional experiments because of the various assumptions made by the simulation.

Fig.1 right – parameters of the PDW model. Centre of mass of each leg is shown as circle with shaded sectors.



Symbols	Meaning
$\Phi_1\Phi_2$	initial leg angle in radians
l_1, l_2	leg's length in meters
r_1, r_2	foot radius in meters
c_1, c_2	vertical distance of hip from centre of mass in meters
w_1, w_2	horizontal distance of hip from centre of mass in meters
m_1, m_2	leg mass in kg
I_1, I_2	leg's moment of inertia

The simulation makes a number of assumptions to keep it manageable. First, we assume that the legs suffer no flexible deformation and that the hip joint is free of damping or friction. Second, the contact between the foot and the floor was idealize, assuming perfectly circular feet that do not deform or slip, while the heel strike impact is modelled as an instantaneous, fully inelastic impact where no slip and no bounce occurs. Finally, the floor is assumed to be a rigid.

There is one problem due to oversimplification of the model. Contrary to humans who have knees, the legs of the model cannot extend or retract, which inevitably leads to foot-scuffing at mid-stance. In a real-world prototype this problem is solved by covering the floor with a checkerboard pattern of tiles that provide foot clearance for the swing foot (Wisse and Schwab 2004, Tucker 1975).

It uses some very interesting modelling techniques in it namely:

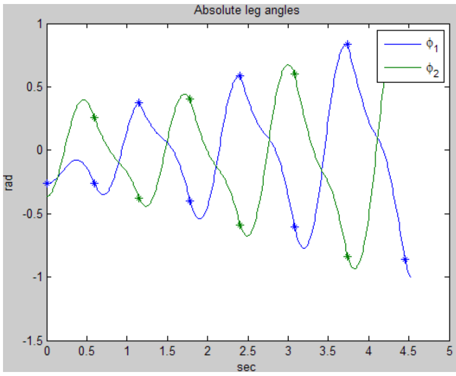
- **Divide and Conquer**: it splits the walking cycle into several stages to model each one 'simply'.
- **Physical laws**: identify Newton's second law (F = ma)
- **Matrices**: rather than consider each dimension separately matrices are used for compactness and clarity
- **Vectors**: identify where vectors are resolved in horizontal and vertical directions
- **Numerical integration**: identify where dynamic changes at any instant are converted to a continuous motion (time response)
- **Visualisation**: see where diagrams and figures assist with modelling
- **Linearization**: identify where the system is linearized around a fixed point

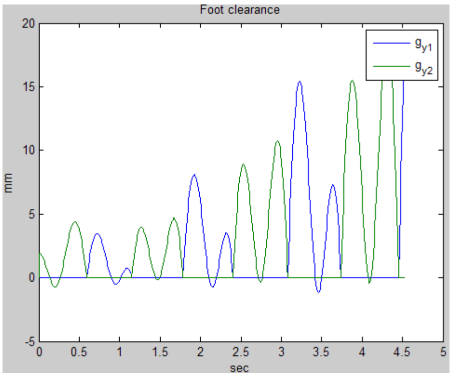
METHOD

MY DESIGN

Provisional Design Initial Values		Provisional Design Parameters	
initial angle leg1	- 15*pi/180	leg length - m	250/1000
initial angle leg2	- 21*pi/180	foot radius - m	190/1000
initial speed of rotation leg1	0	vertical distance hip -CoM -m	150/1000
initial speed of rotation leg2	0	horizontal distance hip -CoM -m	0
NOTE: The slope angle is set to 5^{O}		leg mass – kg	0.4

The resulting graphs on the following page illustrates that the provisional PDW can be made to walk 7 steps based on the initial /provisional simulation. These values though are only configurable given the said slope angle [see appendices]. In the simulation animation when the said slope is decreased, the PDW walked back and forth i.e. stayed stationary in one spot. Incrementing the slope lead to it achieving only fewer steps. This is because the cumulative momentum in the PDW (change in 'oomph') tends to be greater provided the slope increases as the speed increases as well in the latter condition while there was a lack of increase in speed in the former condition.





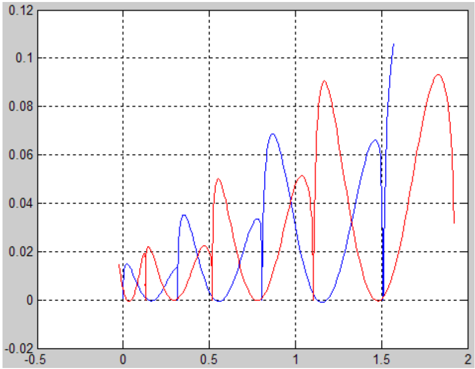


Fig.2 above left – leg angles (phi1 and phi2) as functions of time

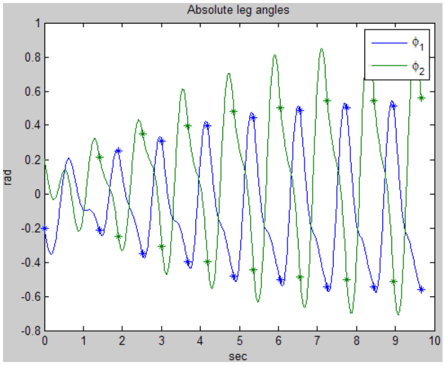
Fig.3 above centre – feet clearances [mm] as functions of time

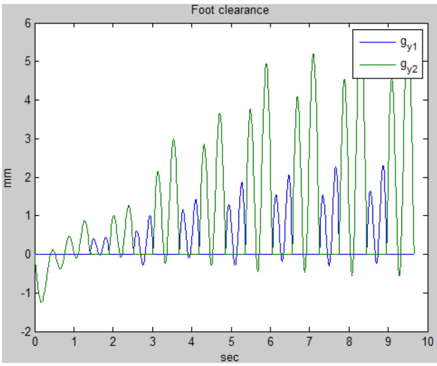
Fig.4 above right – PDW heel trajectories (to assist in determining heel impact points)

- Horizontal axes: heel x-coordinate[m]
- Vertical axis: heel y-coordinates[m]

Final Initial Values		**Final Parameters**	
initial angle leg1	11.5450*pi/180	leg length - m	120/1000
initial angle leg2	- (11.5450*pi/180)	foot radius - m	100/1000
initial speed of rotation leg1	-1.4052	vertical distance hip -CoM -m	100/1000
initial speed of rotation leg2	-1.1205	horizontal distance hip -CoM -m	0
NOTE: The slope angle was reduced to 2.155^{O} instead of 5^{O}		leg 1: mass – kg	1
		leg 2: mass – kg	0.7

The resulting graphs are as follows:





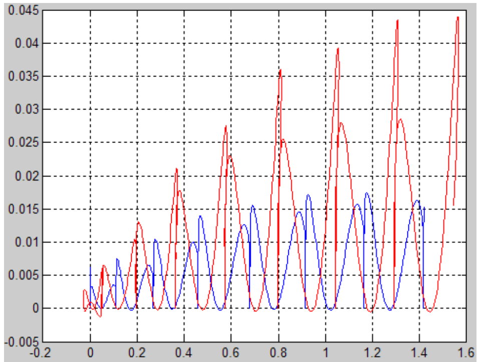


Fig.5 above left, Fig.6 above centre, Fig.7 above right – same as Fig.2, Fig.3, Fig.4

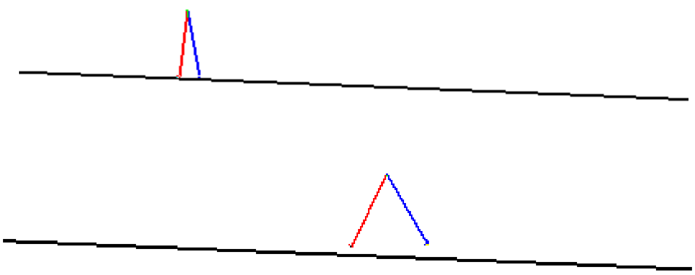


Fig.8 left – shows simulation after 8 steps

This design managed to do 15 steps in the simulation animation and it shows that it was capable of so-called 'ballistic walking' c.f. (McGeer 1991). That is, if the limbs were given appropriate speeds and angles at the start-of-step, then they would swing passively through to heel strike in a perfectly natural style. But the problem with my design is that there is a fixed foot radius of 0.19 metres, mine was just 0.1 metres (I found this out later than supposed to be). A solution would be to 3D print a custom-made feet but due to time constraints, this idea was not pushed through.

MEASURING (IMPLEMENTATION)

Weighting Matrix	Weights	My Design	Alternate Design 1	Alternate Design 2	Alternate Design 3
Steps in Simulation	10	8	4	10	10
Human-like gait	9	8	6	8	9
Stability	8	5	4	3	8

Ease of assembly	5	4	4	2	4
Total		25	18	23	31

It has been decided that the steps in the simulation of each design would be taken with the utmost importance during the final design considerations as it is the only sound and nearest evidence of the PDW workability. Secondly, a PDW with a human-like gait and its stability would be considered for the aesthetic side of things. These three criteria would be the most importance criteria as the aim of the project would fail if these things would not have been considered.

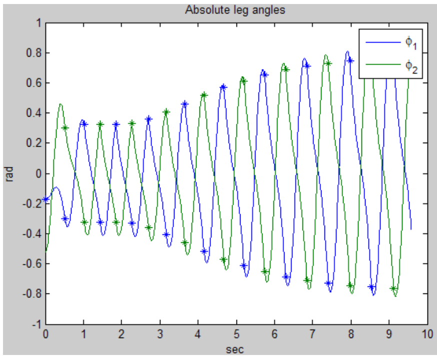
On the other hand, we have decided that the ease of assembly of the PDW is not of a main concern as it only takes about 10 – 15 minutes to assemble a particular PDW. But let's not forget that this only applies in this particular scenario as in some of the 3D PDW (in the world out there), the ease of assembly is taken with the highest weighting as its components is of a higher complexity to put together.

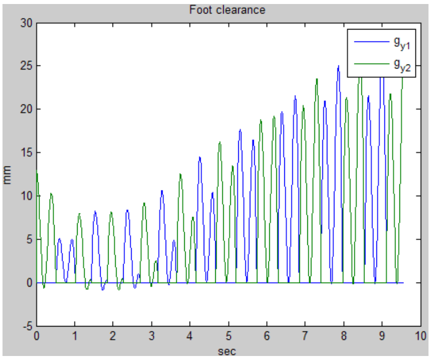
RESULTS (COMMUNICATING)

FINAL DESIGN

We have decided to go with 'Alternate Design 3' which gained the highest total based on the constructed weighting matrix. We have not decided to alter the parameter values as it exceeds the number of steps that the test course allows based on the simulation [see appendices]. The final PDW design can cope with a surface that has a slope of between 0.5^{O} to 2.155^{O}. It has the following parameters:

Initial Values		**Parameters**	
initial angle leg1	- 10*pi/180;	leg length - m	300/1000
initial angle leg2	- 30*pi/180;	foot radius - m	190/1000
initial speed of rotation leg1	0	vertical distance hip -CoM -m	110/1000
initial speed of rotation leg2	0	horizontal distance hip -CoM -m	0
NOTE: The slope angle was reduced to 2.155^{O} instead of 5^{O}		leg mass – kg	0.4





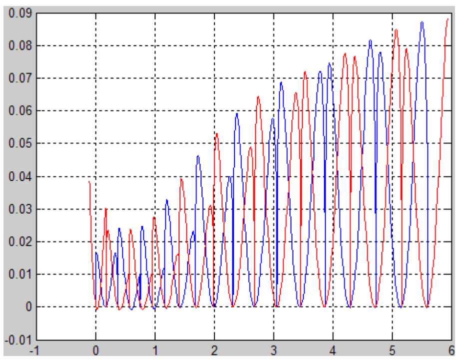


Fig.9 above left – leg angles (phi1 and phi2) as functions of time
Fig.10 above centre – feet clearances [mm] as functions of time
Fig.11 above right – PDW heel trajectories (to assist in determining heel impact points)

- Horizontal axes: heel x-coordinate[m]
- Vertical axis: heel y-coordinates[m]

In the simulation, the final design was able to do 18 steps. It had an almost identical human-like gait and was pretty stable as well.

TESTING

We tested the final design in the testing course 10 iterations [see appendices] and achieved an average (sample mean) of the final PDW walking in 3.9 steps with a sample standard deviation of 1.66 steps resulting in a 95% confidence interval (CI) of 2.24 steps to 5.56 steps based on a ten-point test sample [see Fig.10 for evidence of normal distribution].

Fig.12 below – probability of achieving a certain number of steps based on the collected test sample

Number of Steps	Probability	Within the CI
2	0.3	No
3	0.1	Yes
4	0.3	Yes
6	0.3	No

Fig.13 below – probability distribution graph of collected test sample

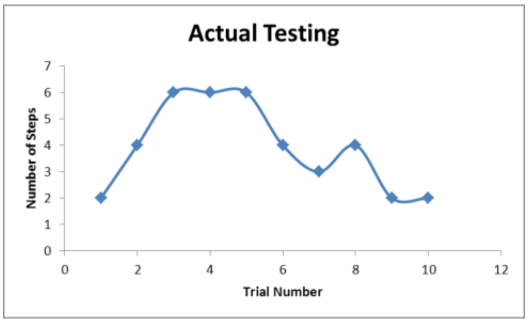
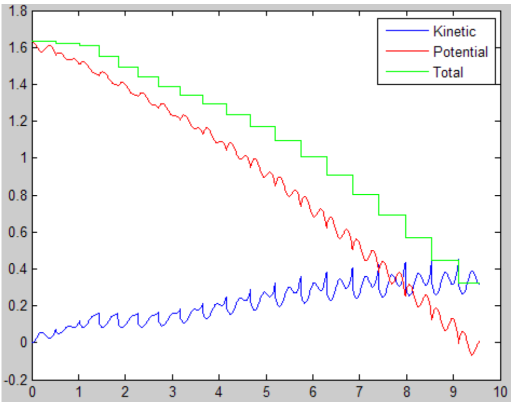


Fig.14 below – energy content of system



Analysis: The probabilities of the PDW executing 2 steps, 4 steps or 6 steps during a test run are the same (3 out of 10 = 0.3). In saying this, the PDW is guaranteed to walk as least 2 steps and at most 6 steps.

In comparison to the simulation, the actual test run of the PDW yielded a CI of 2.24 steps to 5.56 steps which is a third of the expected 18 steps from the simulation. This is in part, due to the assumptions made in the simulation model. It is worthy to note that during the test run [see appendices], there is/are:

- damping/friction in the hip joint per step
- a bounce effect during the heel strike impact
- 2 floor tiles that were not tightly screwed/fixed (and this was only noticed in the middle of the test run).

Furthermore, the sum of kinetic and potential energy should be constant for a consistent passive walker and as shown in Fig. 14, it is as it should be.

DISCUSSION

HOW MANY (TESTS) IS ENOUGH?

STEIN'S 2-STAGE SAMPLING

$\bar{x} - \frac{ts}{\sqrt{n}}$ to $\bar{x} + \frac{ts}{\sqrt{n}}$.

The formula on the left is the definition of the confidence interval under standard statistical assumptions. The Stein's two-stage sampling approach uses this relationship to determine the required sample size (n).

The half-width (d) of the confidence-interval is the distance from the mean to the edge of the confidence interval. Putting this in the formula for confidence interval, $d = \frac{ts}{\sqrt{n}}$. Rearranging this equation to put sample size on the left yields, $n = \left(\frac{ts}{d}\right)^2$. This equation gives a way to calculate n.

We estimate s, the expected variability, from the data collected from a pilot study – hence the name 'two-stage': The first stage is conducting a pilot study and the second stage is conducting the full study designed by using the pilot data.) The value of t is the tabulated value from a t-table. You need two numbers to look up t-values. The degree of freedom is that of the pilot study (Austin 1983). Calculating this, we get:$n = \left(\frac{ts}{d}\right)^2 = \left(\frac{10.215 \times 1.66}{3}\right)^2 = 31.94849529$.

This means that at least 32 sample points are needed to establish a sound measured value (mean) and its CI. This does not mean to say that the testing done in inconclusive. It just means that we cannot be at the highest 100% confidence with our results considering sampling variability (randomness of events).

ALTERNATIVE APPROACH

WALKER WITH KNEES (KNEE-JOINTED WALKER)

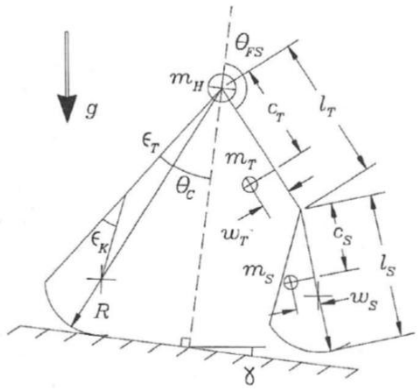


Fig. 12 see right – Model of four rigid, inanimate links. Links are connected by pin-joints, with mechanical stops at the knees to prevent hyperextension.

Add knees to the catalogue of design options. The motivation is twofold. First, knees make the gait more anthropomorphic, which is aesthetically pleasing and also useful for study of walking in nature. Second, knees solve the problem of toe stubbing in the so-called recovery phase, when the free leg is brought forward in preparation for the next step (McGeer 1991).

A straight-legged biped had to clear its feet actively during using small retraction motors in each leg; these substantially complicated an otherwise passive design, and moreover used a lot of energy. By comparison foot clearance by knee flexure offers a solution that is passive, efficient, and reliable.

CONCLUSION

The experiment found that modelling, building and configuring a PDW to walk consistently is not a trivial task. Even with careful modelling of the PDW, it only achieved a third of the expected steps as suggested during simulation. It would have been better if some of the assumptions in the simulation was accounted for (measured) and not just assumed and it would be of great help if the implementation of the model would be improved by displaying more information during the simulation. Nevertheless, the experiment, as a whole, provided a stepping stone to the theory behind the mechanics of passive dynamic walkers.

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Austin, Homer W. “Sample size: How much is enough?” *Quality and Quantity* (Kluwer Academic Publishers) 17, no. 3 (1983): 239-245.

Luksch, Tobias. *Human-like Control of Dynamically Walking Bipedal Robots.* PhD Thesis, Kaiserslautern: Technischen Universit¨at Kaiserslautern, 2010.

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Tucker, V. A. “The Energetic Cost of Moving About.” *Ameica! Scientist. Volume 63*, 1975: 413-419.

Wisse, Martijn, and Arend Schwab. “First steps in Passive Dynamic Walking.” In *Climbing and Walking Robots*, by Manuel Armada and Pablo de González Santos. 2004.

APPENDICES

SIMULATION RESULTS (MY PROVISIONAL DESIGN)

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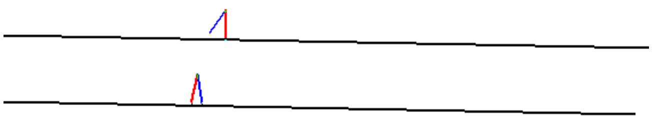
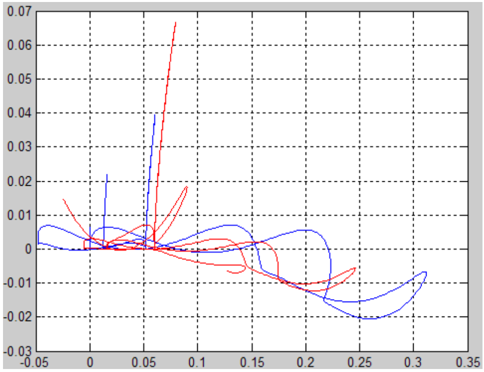
<tr><td>
PDW walked back and forth</td><td>
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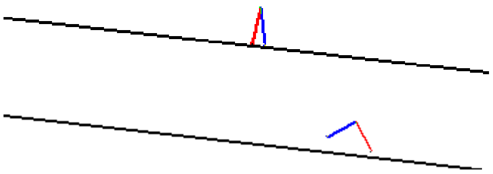
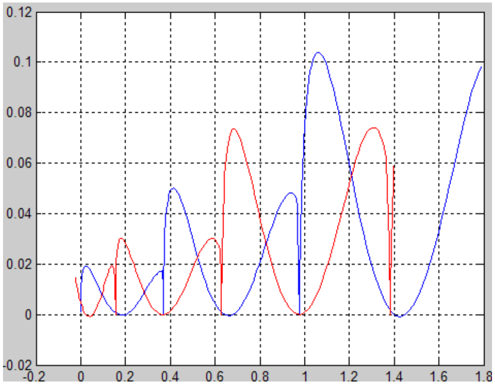
<tr><td>
PDW was able to walk 5 steps but is unstable</td><td>
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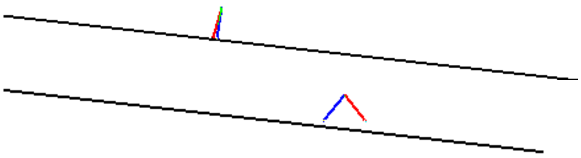
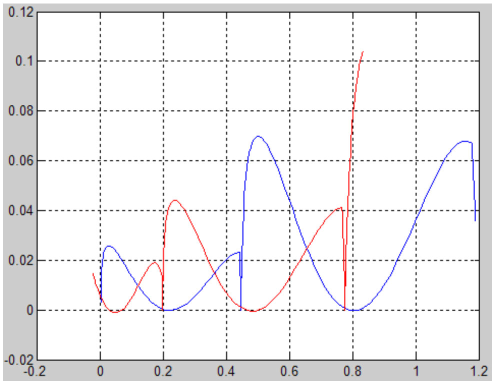
<tr><td>
PDW was able to walk 4 steps but is unstable and without having human like gait</td><td>
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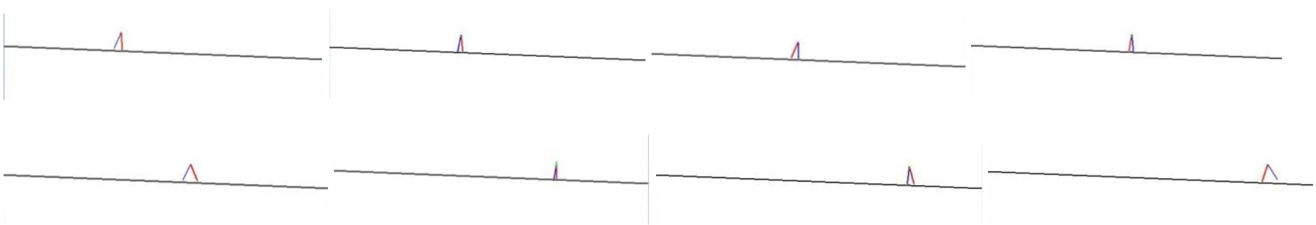
SIMULATION RESULTS (FINAL DESIGN)



EVIDENCE OF TESTING

TEST DATA FOR FINAL DESIGN

Trial	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**	**Median**	**Mode**	**Standard Deviation**
Number of Steps	2	4	6	6	6	4	3	4	2	2	3.9	4	2	1.66332999

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EXTENDING THE 'COMMUNICATING' STAGE IN THE DESIGN CYCLE (CHALLENGE COMPONENT)