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European robotic framework for bipedal locomotion benchmarking

DYSTURBANCE
Experiment Parameters definition

S. Monteleone, F. Negrello, G. Grioli, M.G. Catalano, F. Bonomo, M. Garabini

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Università di Pisa

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Impulsive test

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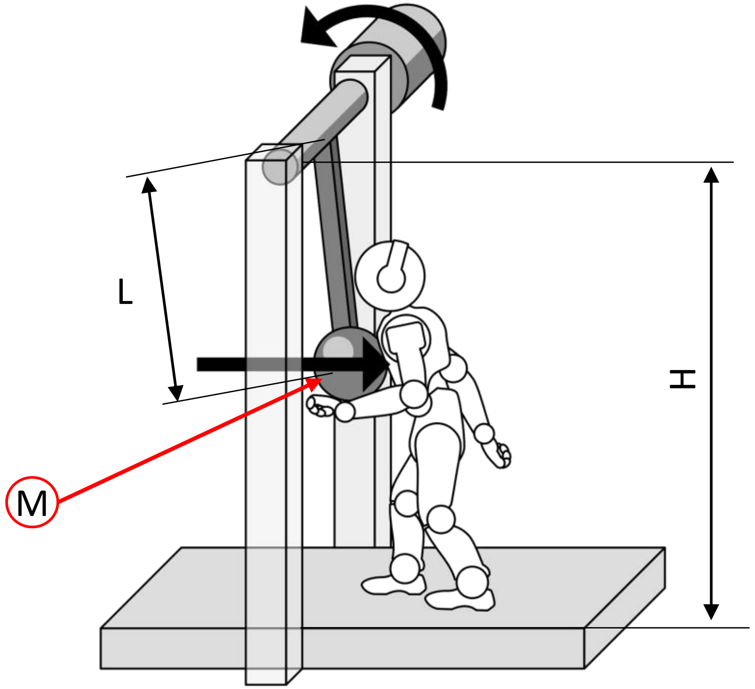
Parameters definition

Pendulum_height (h), Pendulum_length (L) and Pendulum_added_mass (M) have to be configured before starting test.



$$
\begin{cases}
E_i = \left(M + \frac{\delta L}{2}\right) g L_M (1 - \cos\theta) & \text{Initial Energy} \\
I = \sqrt{\left(M L_M^2 + \frac{\delta L^3}{3 L_M}\right) 2 \left(M + \frac{\delta L}{2}\right) g L_M (1 - cos\theta)} & \text{Maximum Impulse} \\
H = h - L_M & \text{Height of the impact point.} \\
L_M = L - f &
\end{cases}
$$

The height of the impact point depends on the robot (the test is done impacting the chest or the leg of the robot).
The parameters must be chosen to have a range of impacts ($\theta = 5° \div 90°$) that contains the destabilizing impulsive force

Impulsive force is computed considering

$$I = F_I \, \Delta t \qquad \text{Where } \Delta t = 0{,}01s$$

Human Force and Energy calculations

To have standardized couple of energy and force, we computed the minumum destabilizing force for a human subject.

$$F = \frac{I}{\Delta t}, with\ I = J\omega$$

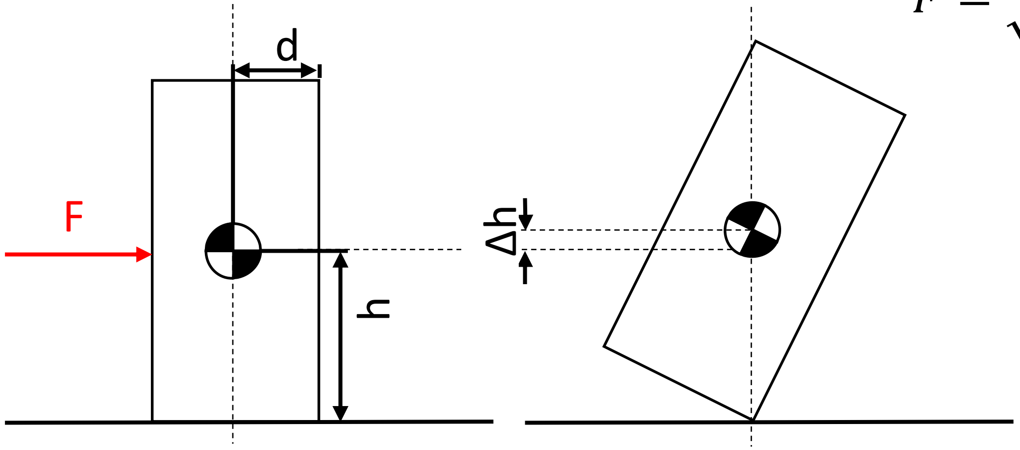
Using the energy conservation law:

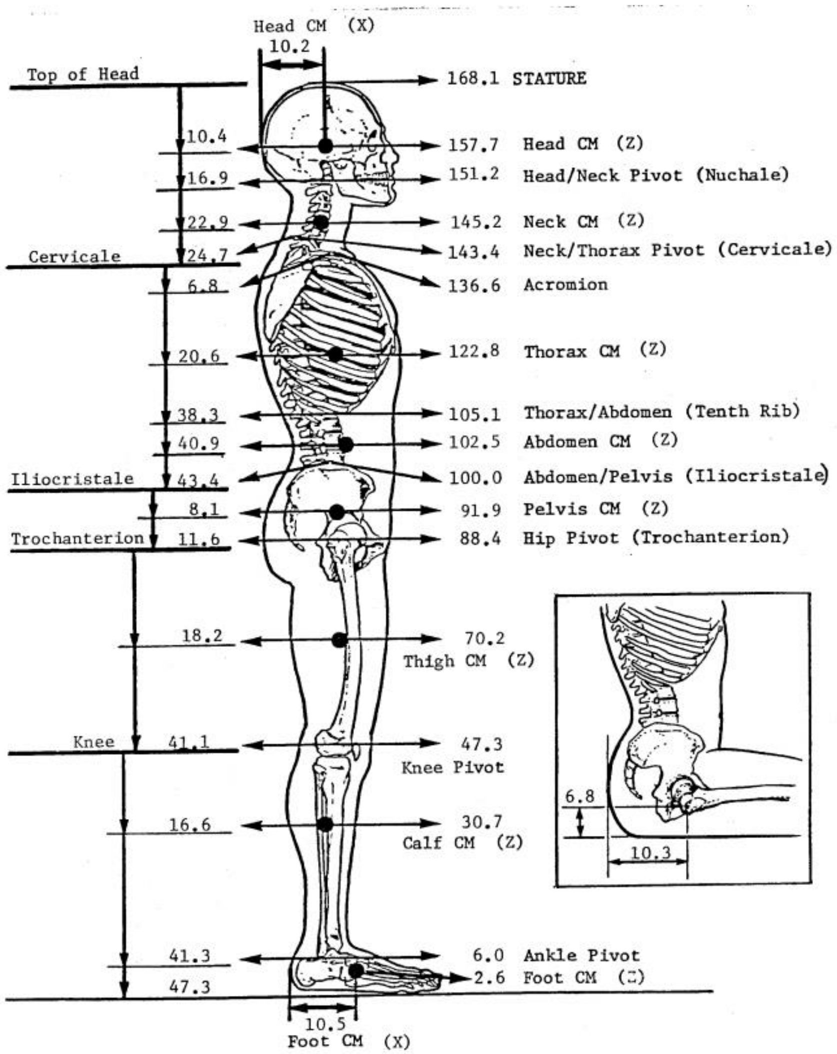
$$\frac{1}{2}J\omega^2 = mg\Delta h$$

From which:

$$F = \sqrt{\frac{\frac{3}{2}m^2 g}{\Delta t^2}\Delta h} \approx 1800N$$

$$E = mg\Delta h \approx 4\text{J}$$





Armstrong, Harry G. "Anthropometry and mass distribution for human analogues. volume 1. military male aviators." *Aerospace Medical Research Lab Wright-Patterson AFB Ohio USA, Tech. Rep* (1988).

Energy and impulsive force for tests

The initial energy and impulsive force that have to be used are summarized in the following table. Those value are the needed experiment for the robot, standardized for the human dimension factor.

Experiment	Initial Energy [J]	Impulsive Force [N]
1	5	400
2	5	700
3	8	700
4	8	1000
5	10	900
6	10	1300

To compute the E and F needed for the experiment, a normalization on robot dimension must be done. After that, the equivalent mass and initial pendulum angle can be extrapolated from the Tables or plots below.

Normalization factor

Normalization for different size of robots

Recalling Ki as the normalization factor, we can normalize Initial energy

And impulsive force to obtain an equivalent experiment on different size of robots.

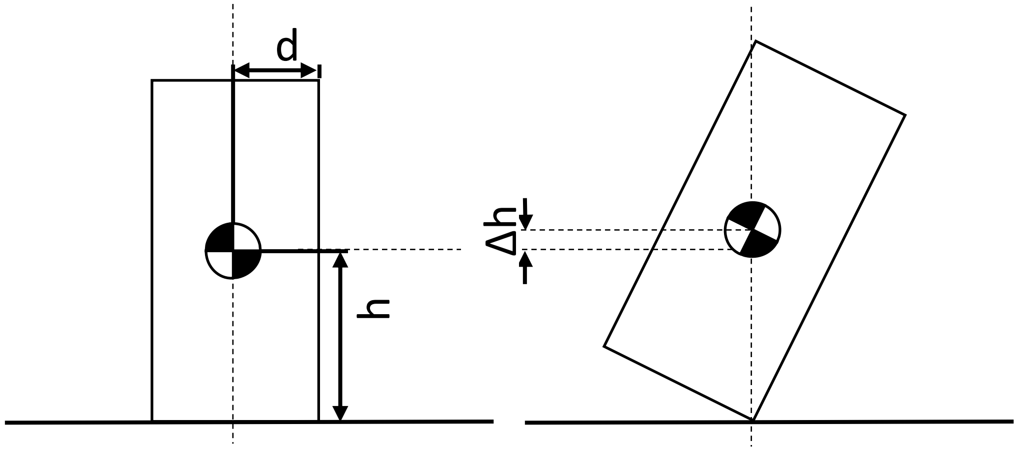
$$K_F = \frac{(m_{robot}\, d_{CoM_{robot}})}{(m_{human}\, d_{CoM_{human}})} \frac{h_{CoM_{human}}}{h_{CoM_{robot}}}$$

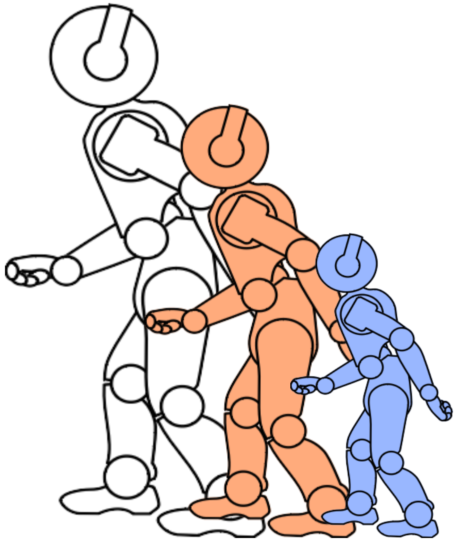
$$F_{R_1} = \frac{K_{F_{R_1}}}{K_{F_{R_2}}} F_{R_2}$$

Equivalently, for the energy it holds:

$$E_{R_1} = \frac{K_{E_{R_1}}}{K_{E_{R_2}}} E_{R_2}$$

$$K_{\boldsymbol{E}} = \frac{m_{robot}}{m_{human}} \frac{\left(\sqrt{h^2_{CoM_{robot}} - d^2_{CoM_{robot}}} - h_{CoM_{robot}}\right)}{\left(\sqrt{h^2_{CoM_{human}} - d^2_{CoM_{human}}} - h\_CoM_{human}\right)}$$





Experimental values

Defined the values of all the parameters for the experiment, tests must be done varying the value of K of:

$$K_{F_{experiment}} = [0.5: i: 2.0]K_F$$
$$K_{E_{experiment}} = [0.5: i: 2.0]K_E$$

With maximum step i = 0.3.
This way, since the chosen $E\ and\ F$ should be close to the unstabilizing point, it is possible to have a set of datas that vary from the stability to the unstability zone.

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Impulsive test parameter selection

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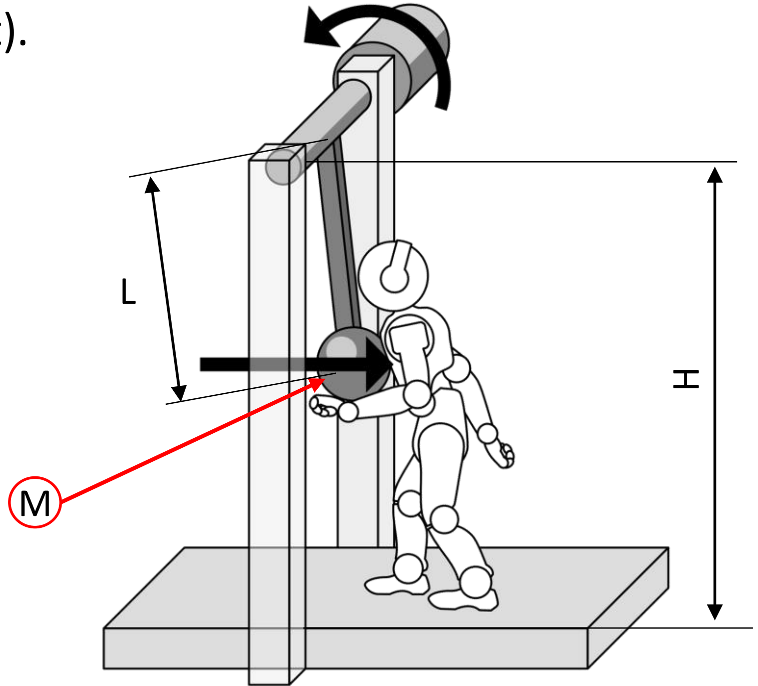
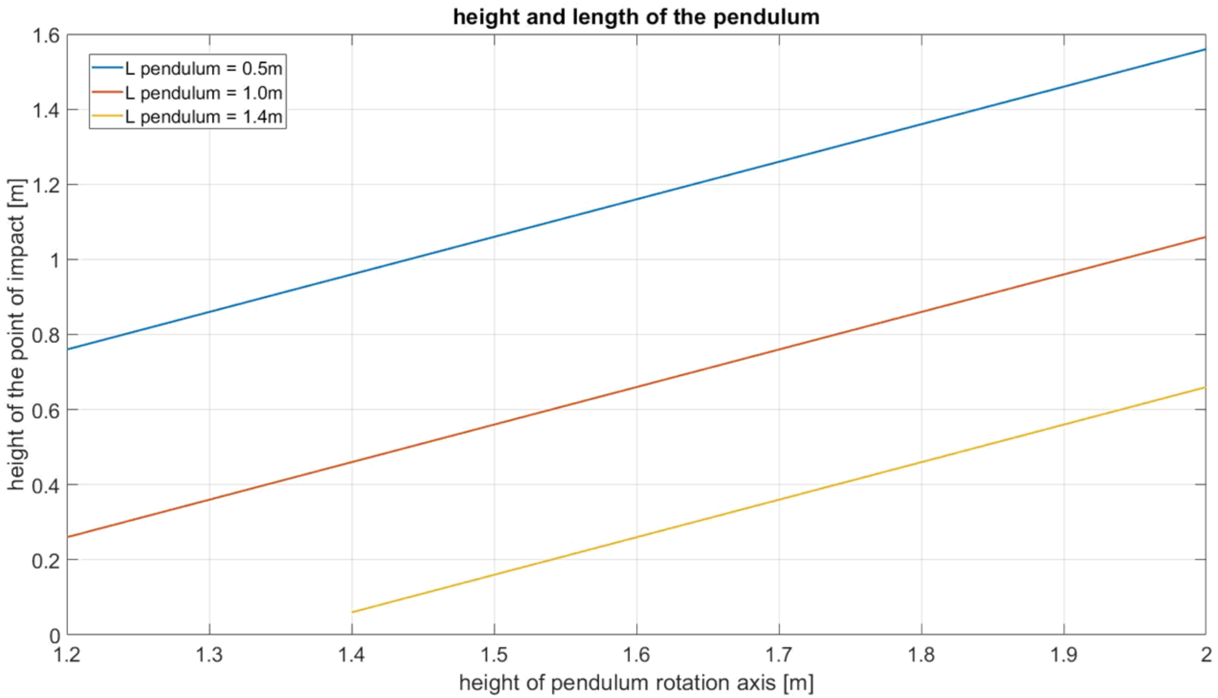
Pendulum length and pendulum height

To define the system parameters, we start with find the pendulum height and length. This equation holds:

$$h = H + L_M$$

h is the height of the impact point, H is the height of the axis of rotation of the pendulum and L_M is the length of the pendulum. h is a value deriving from the robot dimensions (i.e. measure the height of the center of the chest).





Defined h, H and L_M can be extrapolated from the plot.

In case of more than an L_M value is allowed, choose the largest one.

Two sets of h values will be given:
The first set will include absolute values of heights and the second one will be related to the robot height.

How to set M and θ

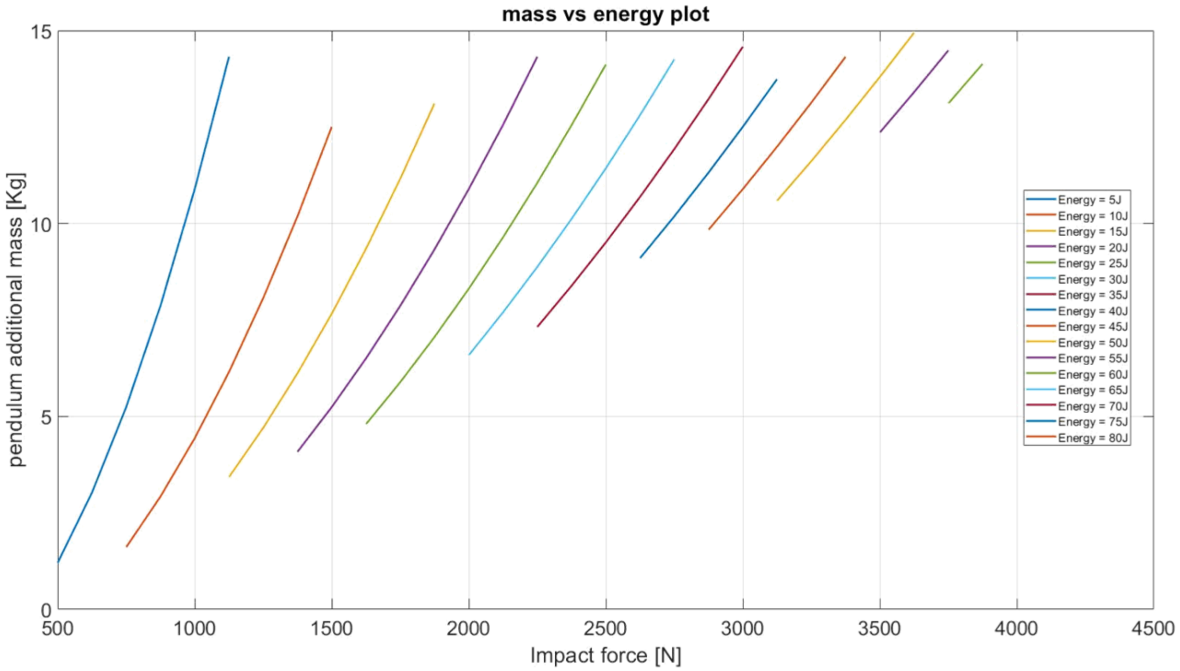
Values of Energies and Impulsive force must be translated in the corresponding values of pendulum mass, pendulum height and initial angle

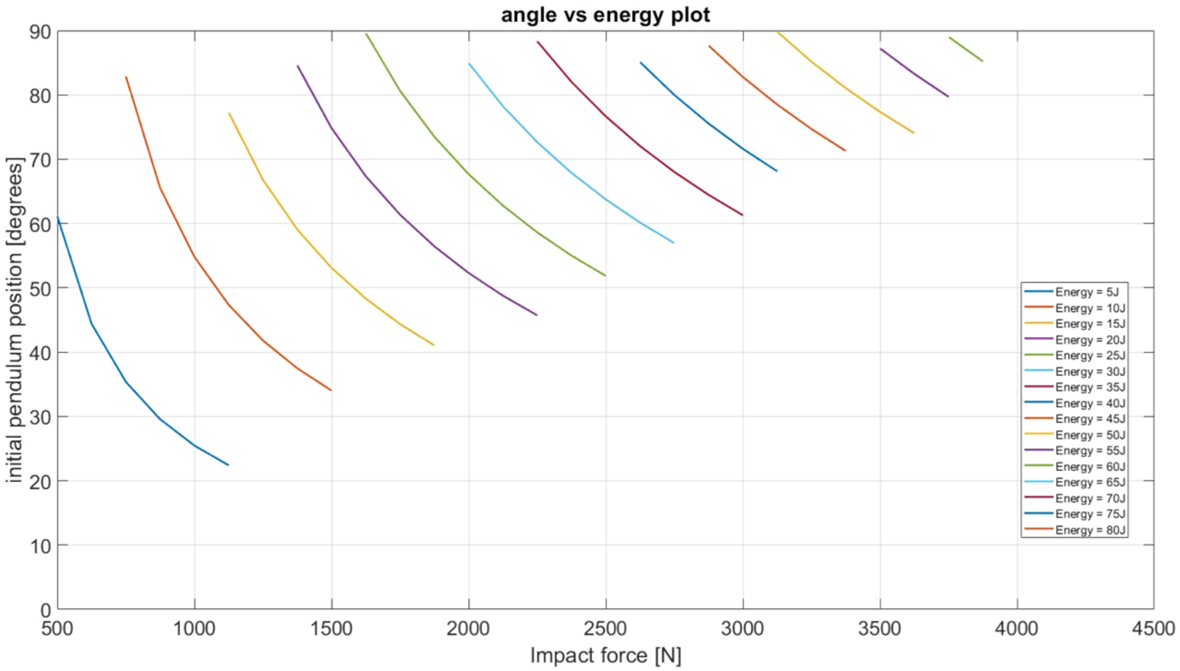
$$\begin{cases} M = \dfrac{1}{L_M^2}\left(\dfrac{F^2\Delta t^2}{2E_i} - \dfrac{\delta L^3}{3}\right) \\ \cos\theta = 1 - \dfrac{E_i}{\left(M + \dfrac{\delta L}{2}\right) g L_M} \\ L = L_M + f \\ h = H + L_M \end{cases}$$

- h and L_M depends on the height of impact. Since L_M can only assume 3 values (0,5m-1,0m-1,4m), and h can assume values between 1,2 and 2,0 m, the choice of those 2 may be not independent.
- f is a design value, so it is fixed and known.
- δ is the linear density, and it is fixed ($\delta = 4{,}13\ Kg/m$)
- Δt is the medium time of impact. We assume a reasonable value of 0.01 s

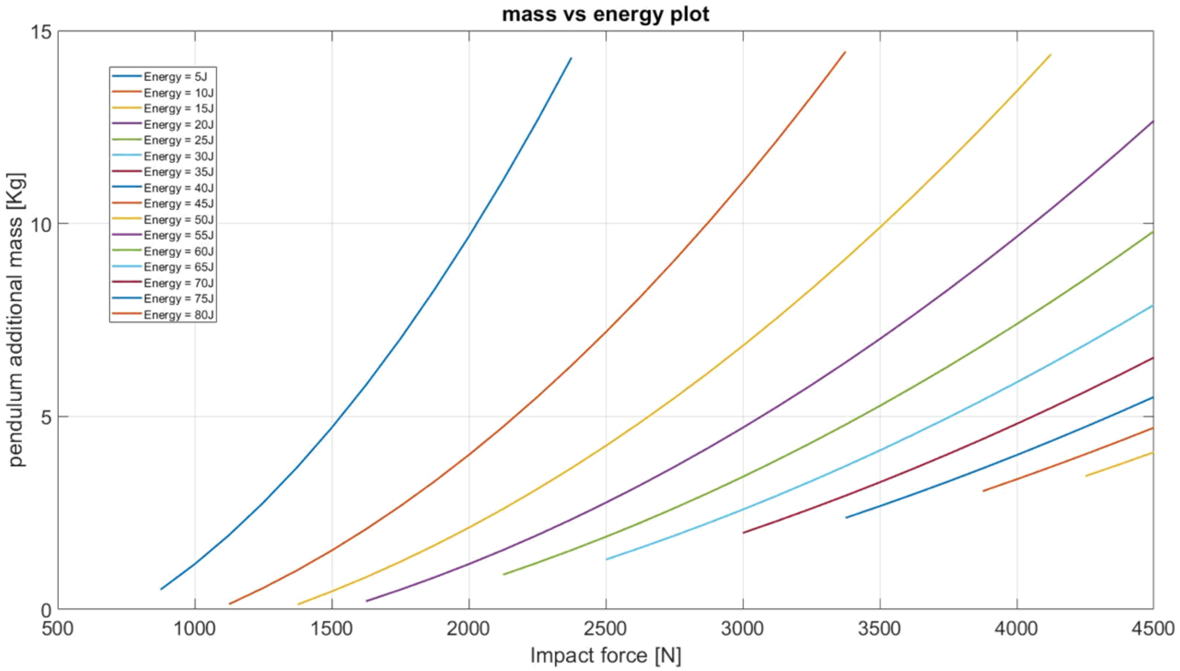
NOTE that $0 < \theta \leq 90°$

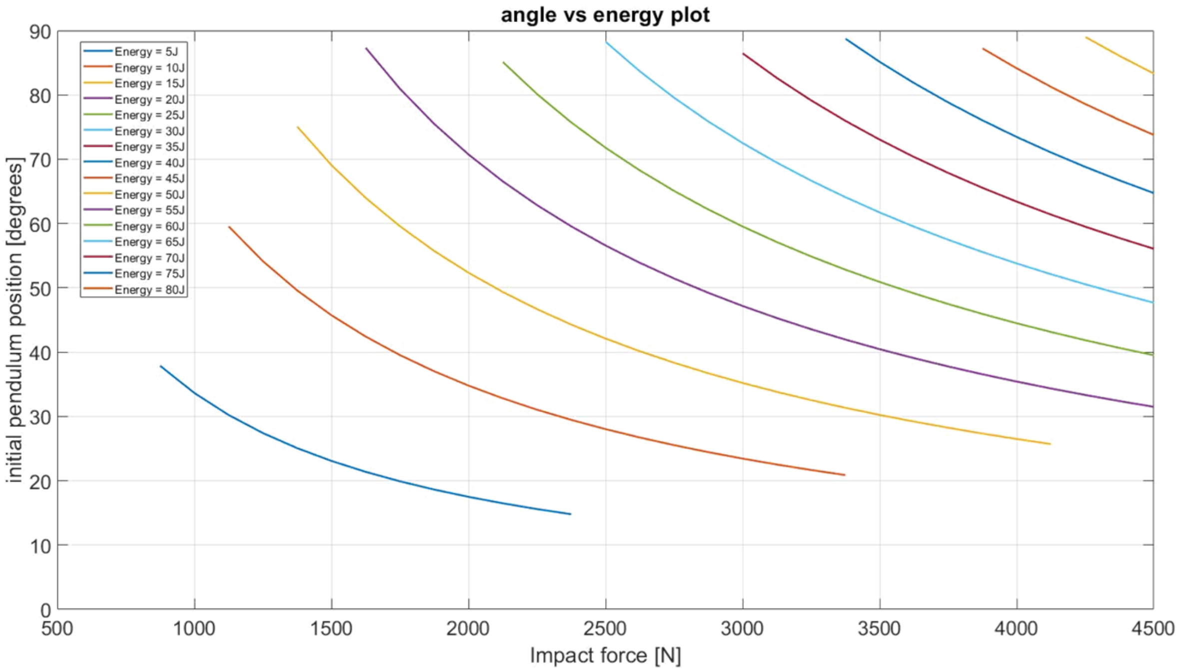
Mass/Angle plot for L = 0.5 m



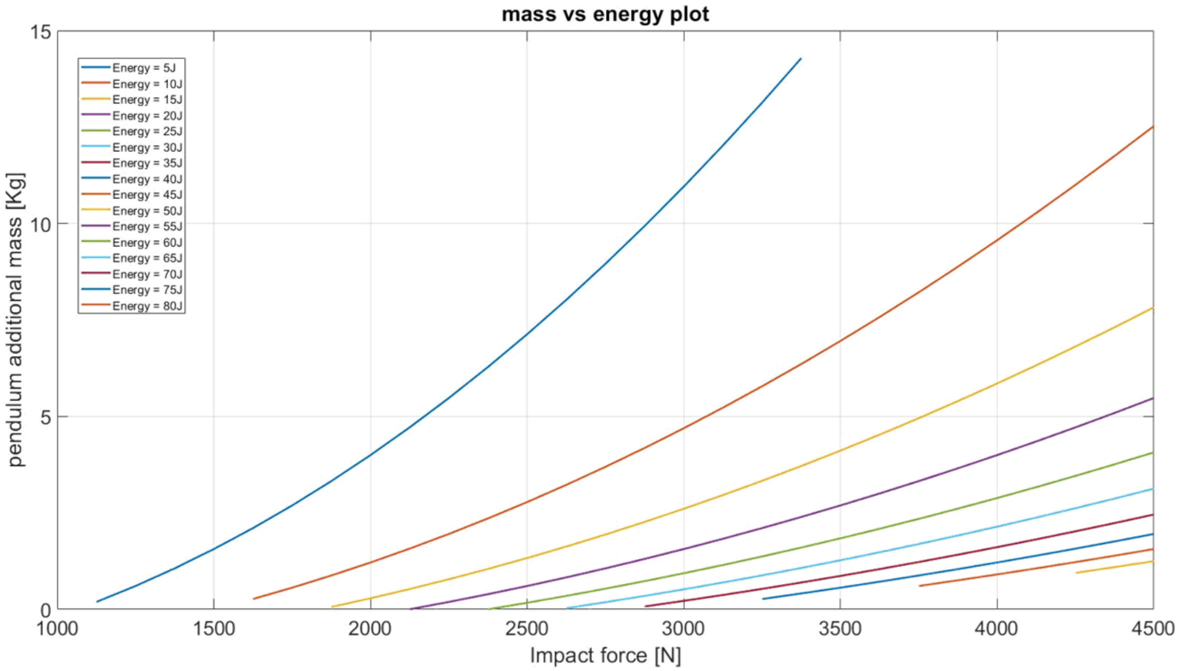


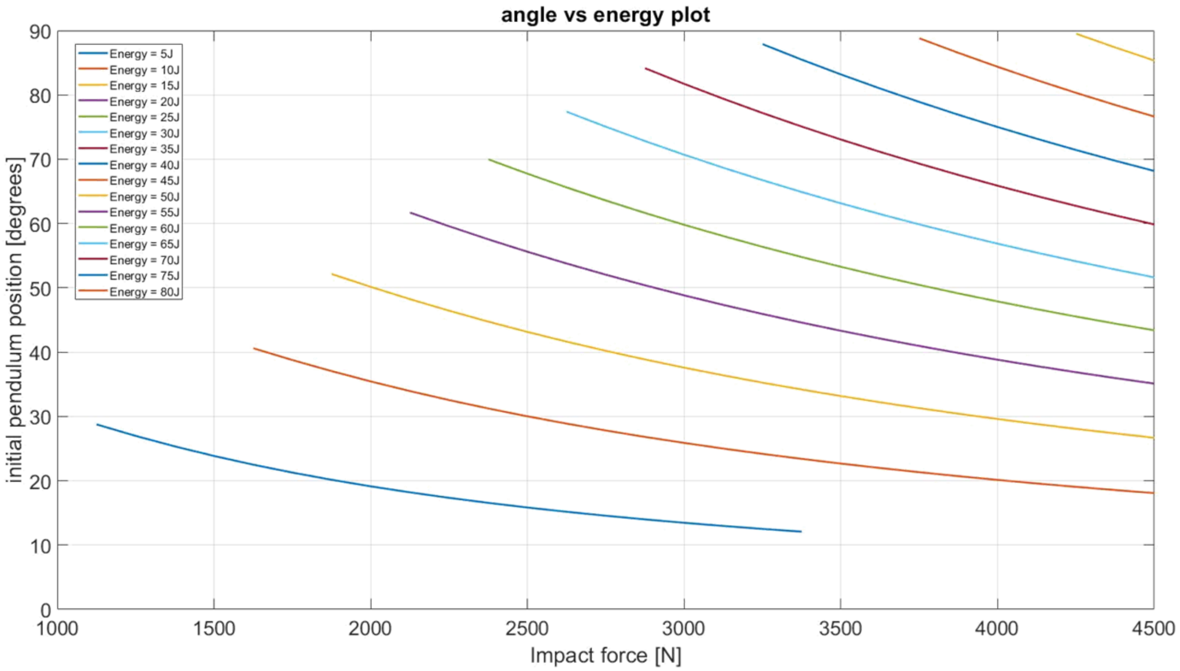
Mass/Angle plot for L = 1.0 m





Mass/Angle plot for L = 1.4 m





Mass/angle tables

Example of the mass/angle table, for L = 1.4m

	Energy = 10 J		Energy = 20 J		Energy = 30 J		Energy = 40 J		Energy = 50 J	
	Mass [Kg]	**Initial angle [degrees]**	**Mass [Kg]**	**Initial angle [degrees]**	**Mass [Kg]**	**Initial angle [degrees]**	**Mass [Kg]**	**Initial angle [degrees]**	**Mass [Kg]**	**Initial angle [degrees]**
Force = 2000N	1,2	35,4								
Force = 2500N	2,8	30	0,6	55,6						
Force = 3000N	4,7	25,9	1,6	48,9	0,5	70,7				
Force = 3500N	7,0	22,7	2,7	43,3	1,3	63,1	0,6	83,2		
Force = 4000N	9,6	20,1	4,0	38,8	2,1	56,9	1,2	75,0		
Force = 4500N	12,5	18,1	5,5	35,1	3,1	51,6	2,0	68,2	1,2	85,3

Mass/angle tables

L= 0.5 m	Energy = 1J		Energy = 2J		Energy = 3J		Energy = 4J		Energy = 5J		Energy = 6J		Energy = 7J		Energy = 8J		Energy = 9J		Energy = 10J	
	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]	Mass [Kg]	Angle [degree]
F = 100N																				
F = 200N	0,6	31,3																		
F = 300N	3,8	17,8	0,9	40,7																
F = 400N	8,3	12,8	3,1	27,2	1,4	44,2	0,6	65,2												
F = 500N	14,1	10,0	6,1	20,8	3,4	32,7	2,0	45,9	1,2	61,1	0,7	79,4								
F = 600N			9,6	17,0	5,7	26,2	3,8	36,1	2,6	46,9	1,9	58,8	1,3	72,3	0,9	88,0				
F = 700N			13,8	14,4	8,5	22,0	5,9	30,0	4,3	38,5	3,3	47,5	2,5	57,3	1,9	68,0	1,5	79,9		
F = 800N					11,8	19,0	8,3	25,7	6,2	32,8	4,9	40,1	3,9	47,9	3,1	56,2	2,6	65,1	2,1	74,7
F = 900N							11,1	22,6	8,4	28,6	6,7	34,9	5,5	41,4	4,5	48,2	3,8	55,4	3,2	63,0
F=1000N							14,1	20,1	10,9	25,5	8,7	30,9	7,2	36,6	6,1	42,4	5, 2	48,5	4,4	54,84

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Sinusoidal force test

Pendulum length and pendulum height

To define the system parameters, we start with find the pendulum height and length. This equation holds:

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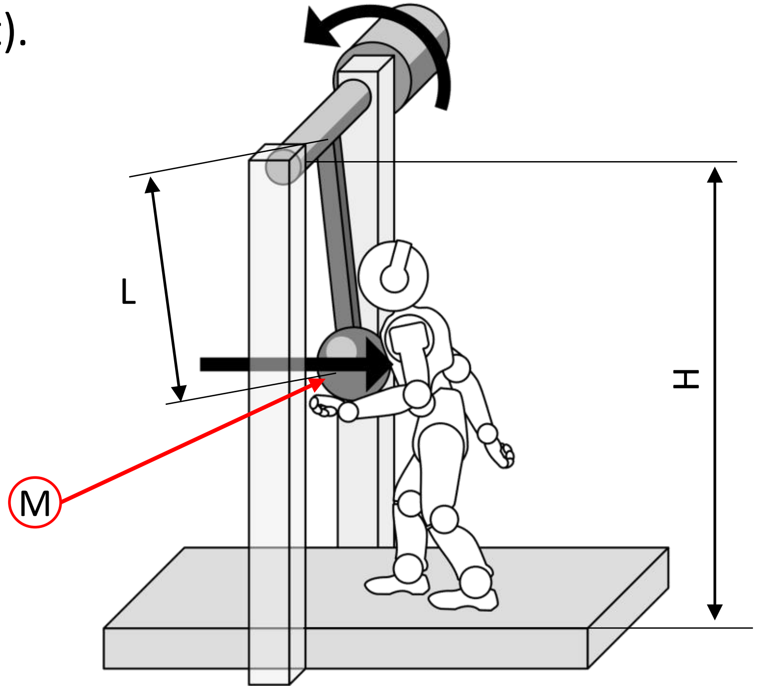

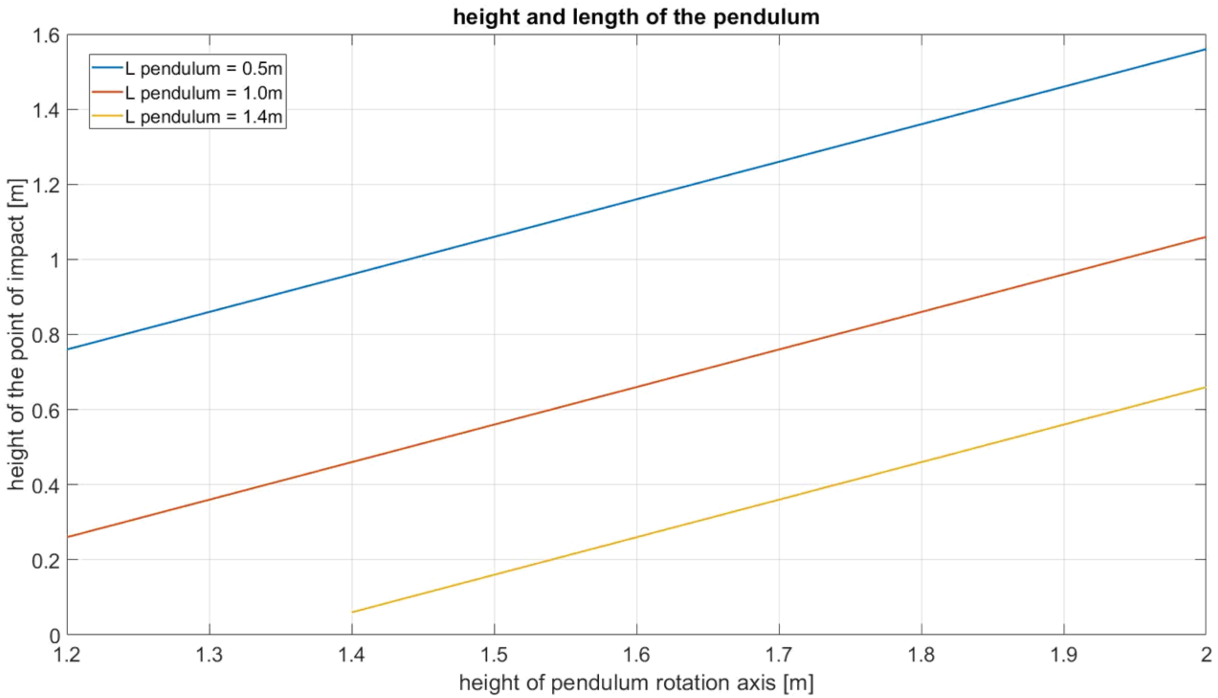

Defined h, H and L_M can be extrapolated from the plot.

In case of more than an L_M value is allowed, choose the largest one.

Two sets of h values will be given:
The first set will include absolute values of heights and the second one will be related to the robot height.

Force amplitude and frequency characterization

For protocol 2, we define a set of experiments for the standard robot that must be done to characterize the performances.

Experiment	Force Amplitude [N]	Frequency [Hz]
1	100	2
2	100	4
3	100	6
4	200	2
5	200	4
6	200	6
7	300	2
8	300	4
9	300	6

To perform the same experiment on the robot, still the normalization of the force amplitude must be done. The normalization factor is the same as the Impulsive case.

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Sinusoidal displacement test

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Pendulum length and pendulum height

To define the system parameters, we start with find the pendulum height and length. This equation holds:

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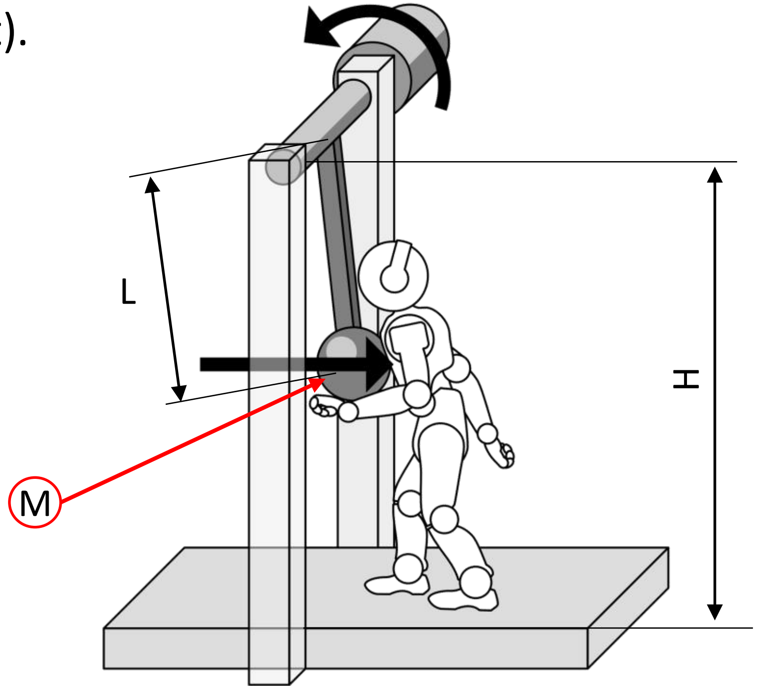
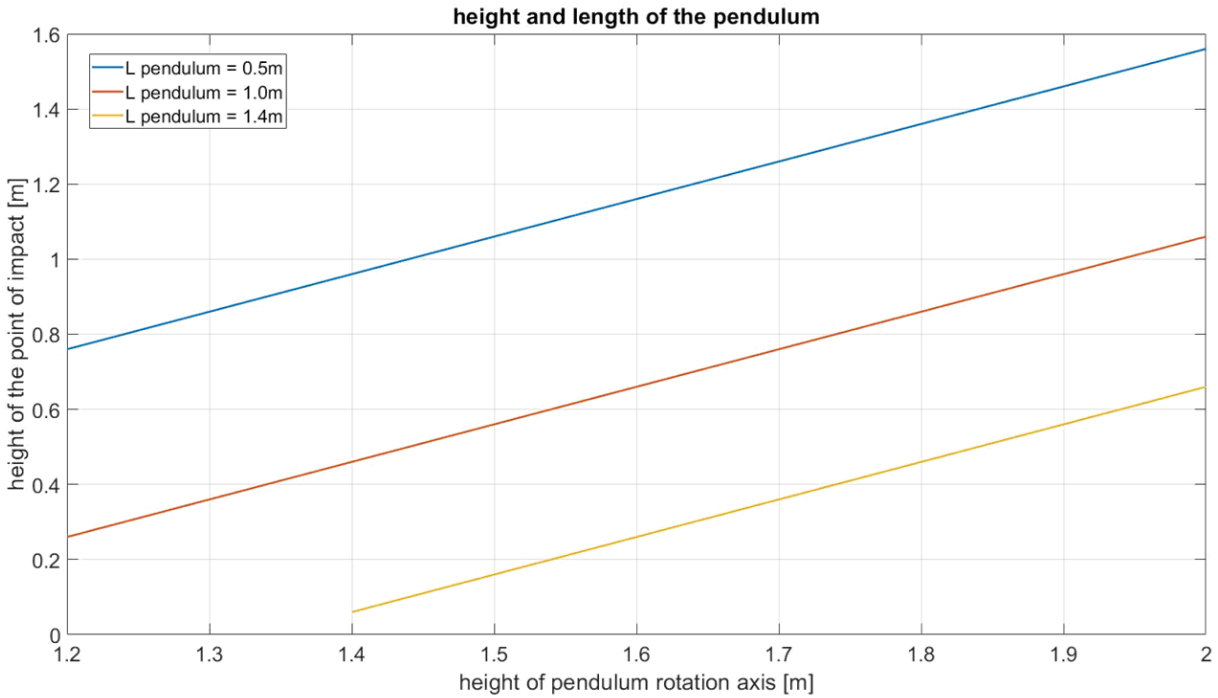
h is the height of the impact point, H is the height of the axis of rotation of the pendulum and L_M is the length of the pendulum. h is a value deriving from the robot dimensions (i.e. measure the height of the center of the chest).





Defined h, H and L_M can be extrapolated from the plot.

In case of more than an L_M value is allowed, choose the largest one.

Two sets of h values will be given:
The first set will include absolute values of heights and the second one will be related to the robot height.

Displacement amplitude and frequency characterization

For protocol 3, we define a set of experiments for the standard robot that must be done to characterize the performances.

Experiment	Displacement amplitude [meters]	Frequency [Hz]
1	0.10	2
2	0.10	4
3	0.10	6
4	0.20	2
5	0.20	4
6	0.20	6

To perform the same experiment on the robot, still the normalization of the displacement amplitude must be done. The normalization factor is explained in the following slide.

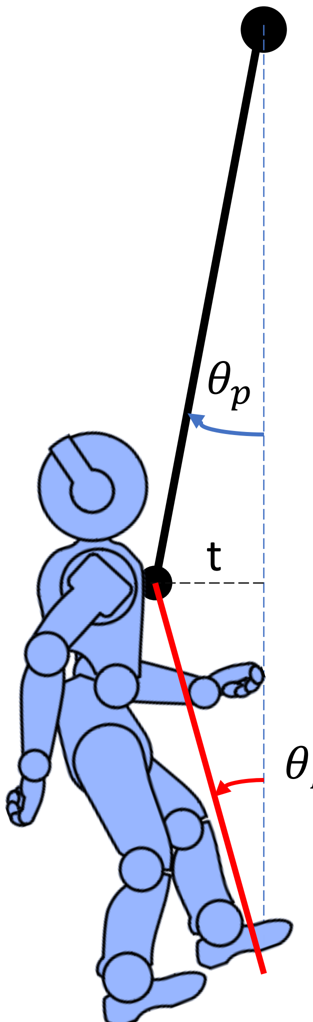
Displacement Normalization factor

Supposing we want to normalize the displacement on the robot dimensions, we have

$$\theta_{R_1} = \theta_{R_2} \rightarrow \frac{t_{R_1}}{H_{R_1}} \cong \frac{t_{R_2}}{H_{R_2}} \rightarrow K_{R_1} = \frac{H_{R_1}}{H_{human}}$$

$$t_{p_1} = \frac{K_{R_1}}{K_{R_2}} t_{p_2}$$

We provide the displacement in meters. Of course, the equivalent angle displacement depends on the pendulum length. L_M must be chosen as largest as possible, in accordance with the point of contact height.



$$t \approx L_m \theta_p$$

Parameters definition

There are additional parameters of the robot itself that have to be provided to compute the Normalization factor

- mass: The total mass of the robot
- height: The height of the robot
- center_of_mass_height: Indicatively, the robot center of mass
- base_depth: The length of the “foot” of the robot in the sagittal plane
- base_width: The dimension of the docking basis.