Effects of the rolling mechanism of the human foot on the inverted pendulum representation for normal walking gait

MESROB 2015

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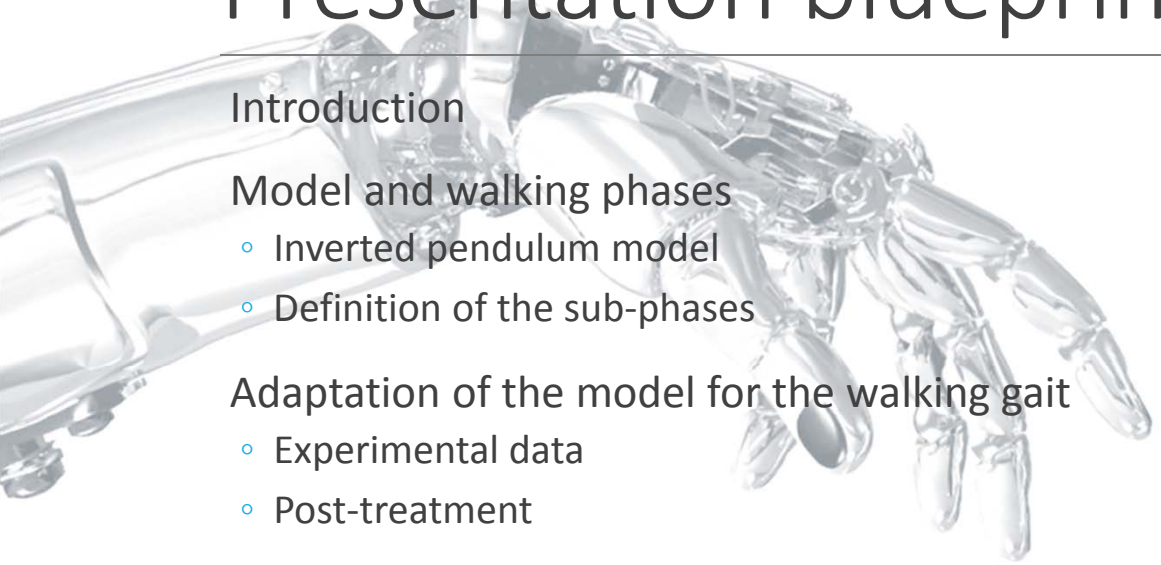
Presentation blueprint



Introduction

Model and walking phases

- Inverted pendulum model
- Definition of the sub-phases

Adaptation of the model for the walking gait

- Experimental data
- Post-treatment

Analysis and discussion

Conclusion

Introduction

Introduction

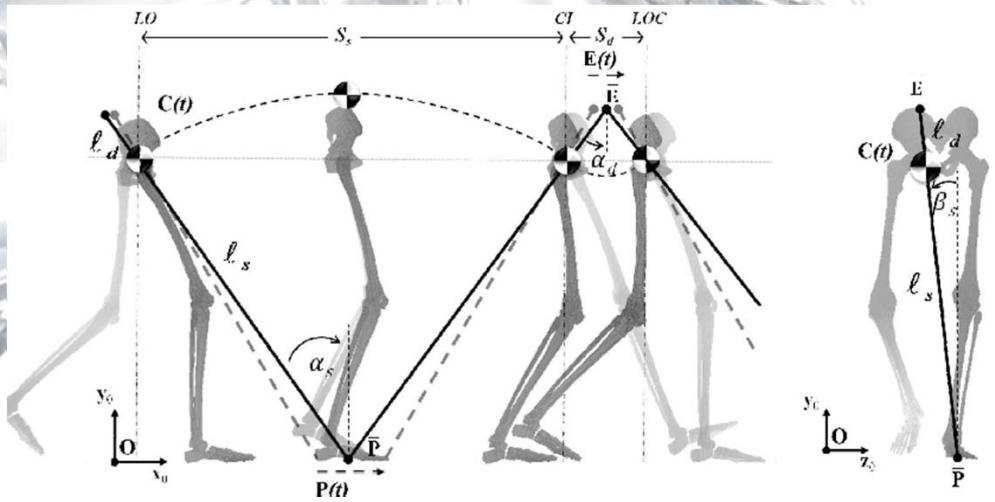
HUMAN BODY

- 206 bones
- More than 1 DoF between 2 bones
- Joint limitation
- Highly redundant

HUMANOID ROBOT

- Around 15 segments
- Up to 48 DoF
- Joint limitation
- Redundant

Introduction



An extended 3D inverted pendulum model to simulate the center of mass trajectory during normal gait
Hayot, C; Sakka, S; Lacouture, P

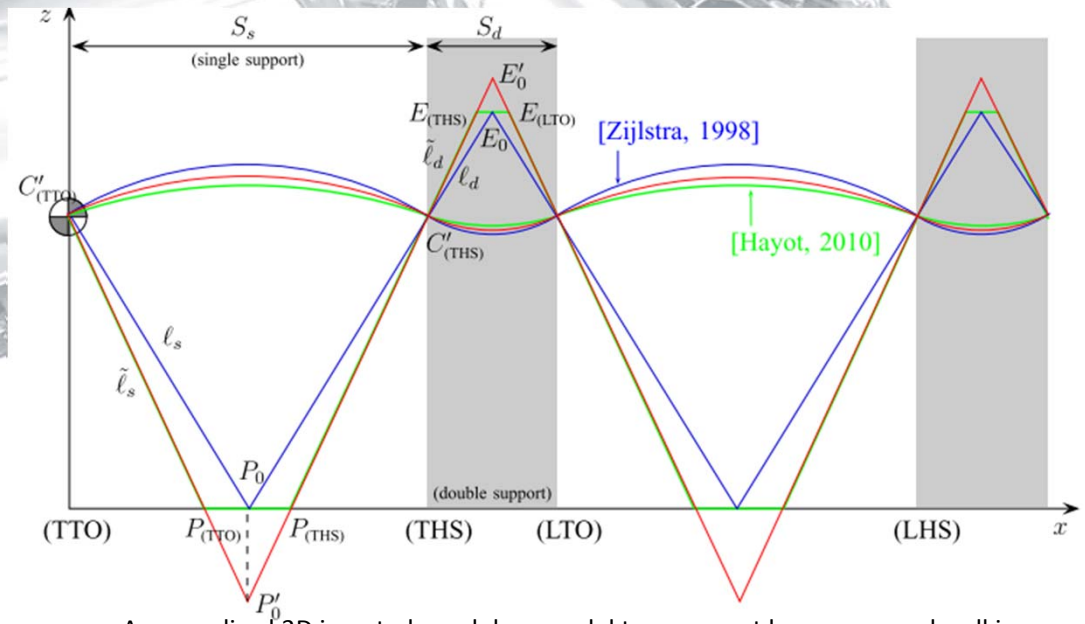
Human and humanoid don't match

Simplifications are needed

Models are defined

- Discontinuous
  - Compass gait
- Continuous
  - Inverted Pendulum

Introduction



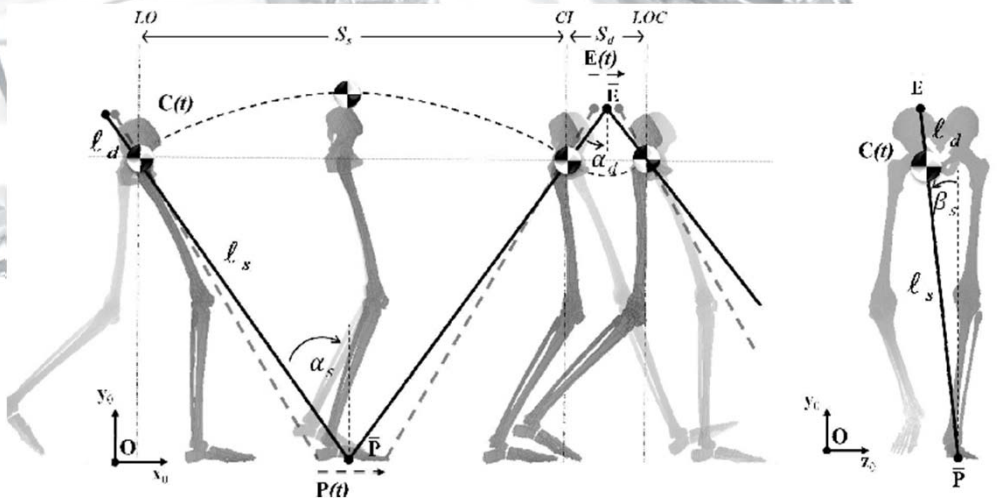
A generalized 3D inverted pendulum model to represent human normal walking
Sakka, Sophie; Hayot, Chris; Lacouture, Patrick

Different models are defined for the Pivot Point:

- The PP is in the middle of the trajectory of the CoP [Zijlstra1998] **Overestimated**
- The PP is equal to the CoP and move during the SSP [Hayot2010] **Underestimated**
- The PP is localized in the convergence of the lines connecting the CoM to the CoP during the SSP [Sakka2011] **Match to the calculated trajectory in the sagittal plane**

Model and walking phases

Inverted pendulum model

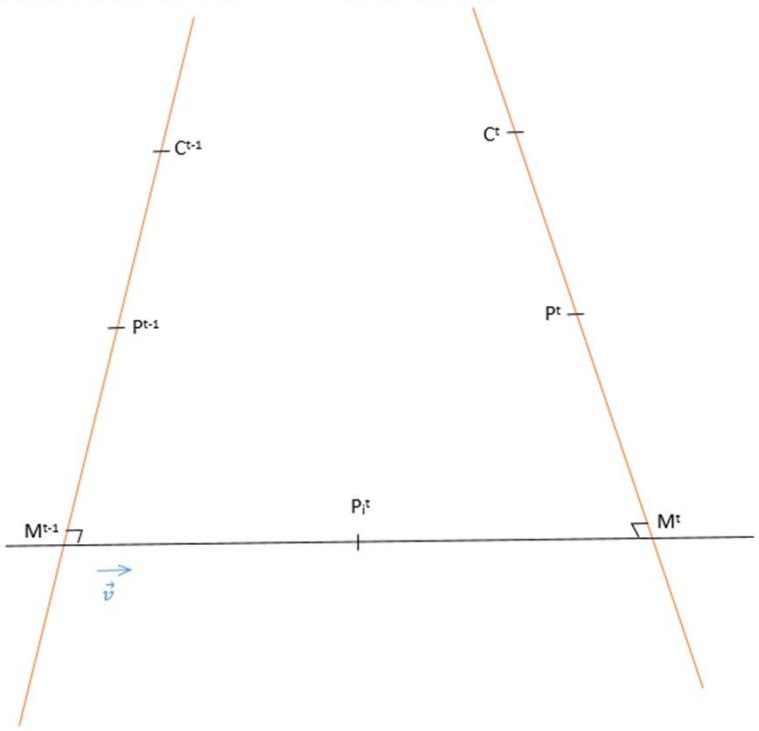


An extended 3D inverted pendulum model to simulate the center of mass trajectory during normal gait
Hayot, C; Sakka, S; Lacouture, P

Several properties are defined

- The gait is in steady state: there is no variation of CoM walking speed or trajectory amplitude during observation
- The walking is symmetric: similar motion is performed by the left and the right leg
- The system is conservative: Painlevé first integral is valid

Inverted pendulum model



Definition of the instantaneous pivot point:

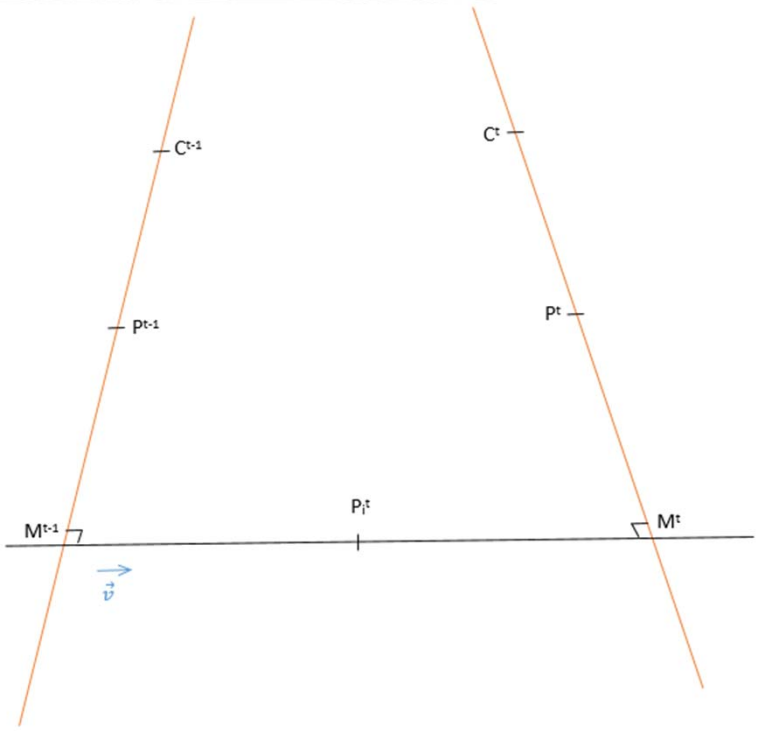
- Closer point between two consecutive support lines

$$\begin{cases} \boldsymbol{OP_i^t = OC^{t-1} + C^{t-1}M^{t-1} + M^{t-1}P_i^t} \\ \boldsymbol{OP_i^t = OC^t + C^tM^t + M^tP_i^t} \end{cases}$$

$$\begin{cases} \boldsymbol{OP_i^t = OC^{t-1} + \lambda_1 C^{t-1}P^{t-1} + \frac{l}{2}v} \\ \boldsymbol{OP_i^t = OC^t + \lambda_2 C^tP^t - \frac{l}{2}v} \end{cases}$$

- With $\boldsymbol{v = \frac{C^{t-1}P^{t-1} \times C^tP^t}{\|C^{t-1}P^{t-1} \times C^tP^t\|}}$
- l, λ_1, λ_2 three constants

Inverted pendulum model



$$\begin{cases} \boldsymbol{OP_i^t = OC^{t-1} + \lambda_1 C^{t-1}P^{t-1} + \frac{l}{2}v} \\ \boldsymbol{OP_i^t = OC^t + \lambda_2 C^t P^t - \frac{l}{2}v} \end{cases}$$

$$0 = \boldsymbol{OC^t - OC^{t-1} + \lambda_2 C^t P^t - \lambda_1 C^{t-1} P^{t-1} + v}$$

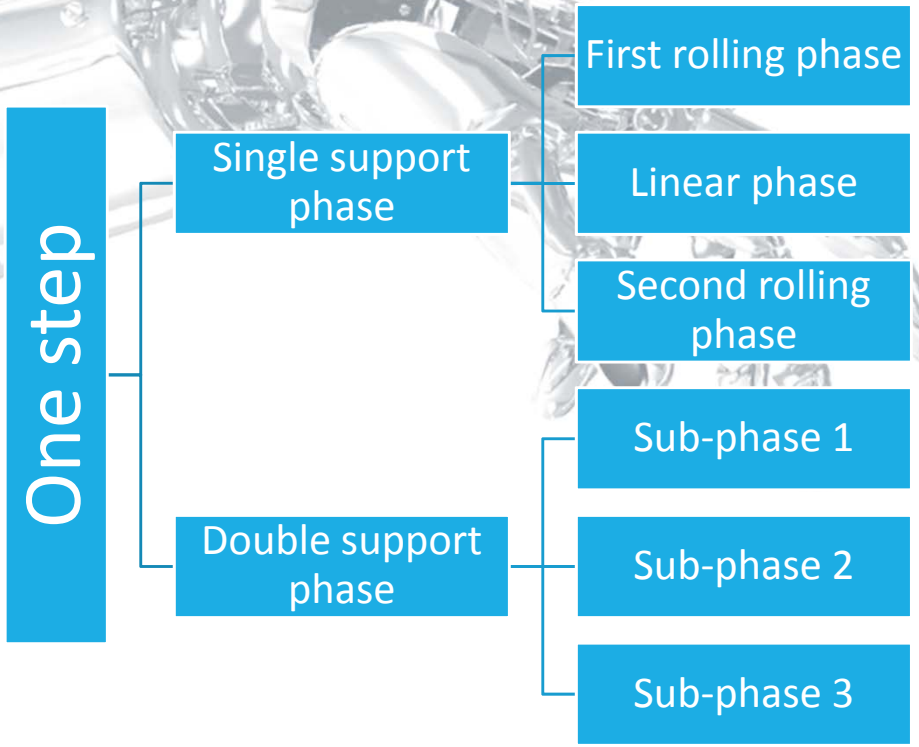
Can be solved using one linear equation:

- $\boldsymbol{b = AR}$
- With:
  - $\boldsymbol{b = OC^t\text{-}OC^{t-1}}$
  - $\boldsymbol{A = [C^{t-1}P^{t-1} \quad -C^tP^t \quad v]}$
  - $\boldsymbol{R} = [\lambda_1 \quad \lambda_2 \quad l]^t$

Solution:

- $\boldsymbol{R = A^{-1}b}$

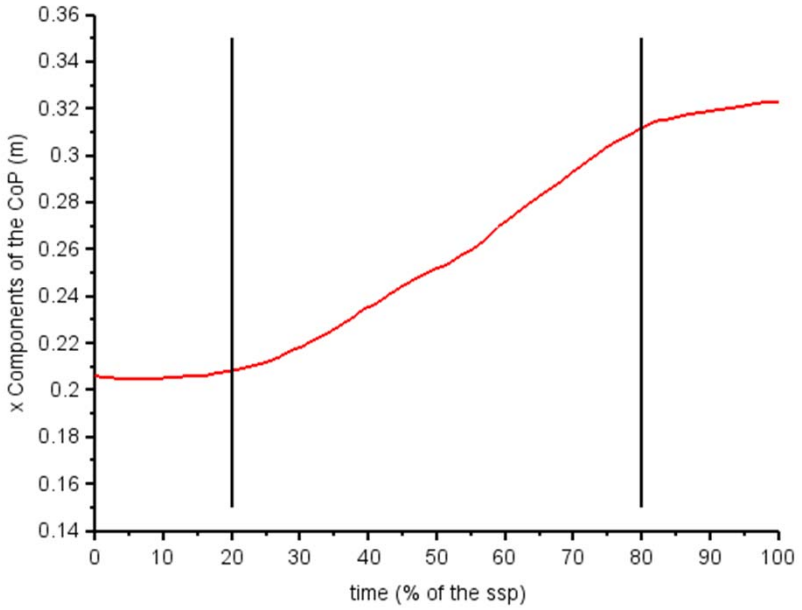
Definition of the sub-phases



The walking gait is a succession of
- single support phase (ssp)
- double support phase (dsp)

Each phase can be decomposed into three sub-phases, which can be:
- Rolling phases
  - CoP static in a boundary of the support pattern
- Linear phase
  - CoP moving linearly.

Definition of the sub-phases



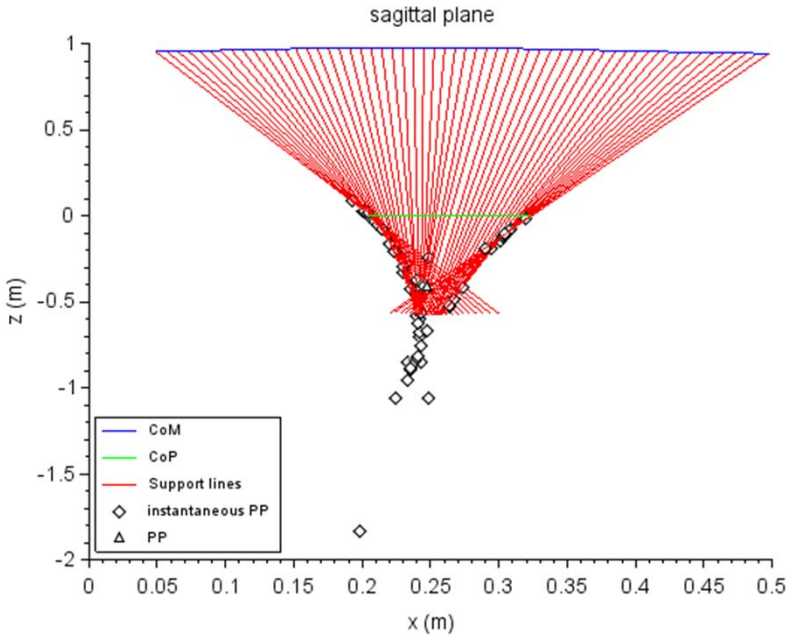
Can be observed

- With the x trajectory of the CoP
- With the GRF
- With the behaviour of the IPP

During the single support phase:

- One rolling phase $0 < t < 20\%$
  - CoP static
  - Rotation around the heel
- One linear phase $20 < t < 80\%$
  - Movement of the CoP
  - Flat foot
- One rolling phase $80 < t < 100\%$
  - CoP static
  - Rotation around the toes

Definition of the sub-phases



Evolution of the IPP during the ssp

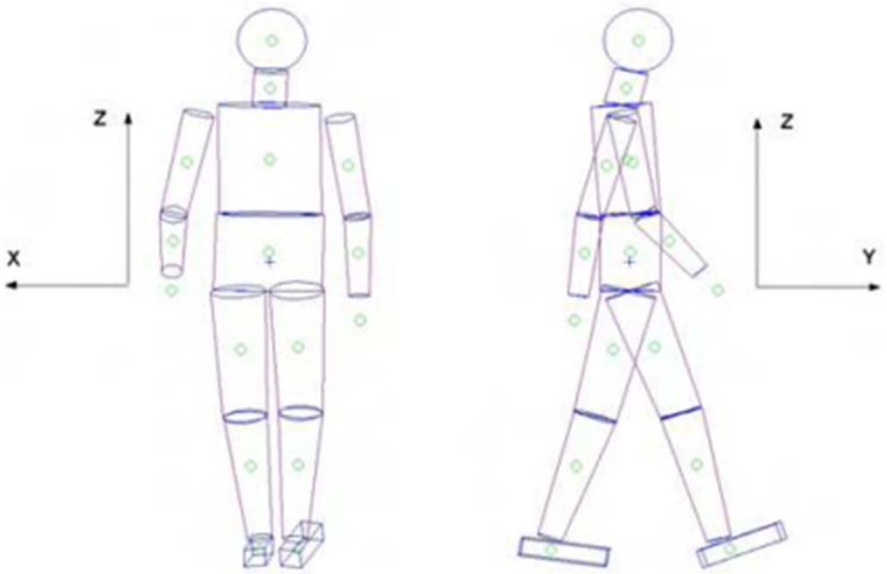
- First rolling phase:
  - Convergence under the heel
  - damping
- Linear phase
  - Shape of a V from the heel to the toes
  - stabilizing
- Second rolling phase
  - Convergence under the toes
  - propelling

Large convergence area

- Impossible to define one PP
- Model adapted to the study of human walking
- Model not adapted to the humanoid walking

Adaptation of the model for the walking gait

Experimental data



Ground Reference Points in Legged Locomotion : Definitions , Biological Trajectories and Control Implications
Popovic, Marko B; Herr, Hugh

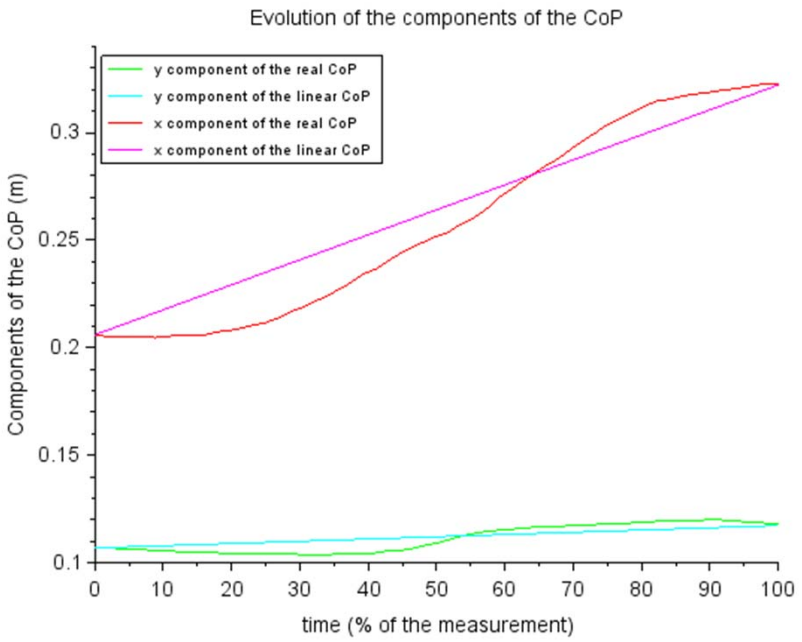
One database available

- Data from 6 actors
- Measurement of:
  - CoP
  - CoM for each segment
  - GRF

Calculation of the CoM of the full body

- $\begin{bmatrix} OC \\ 1 \end{bmatrix} = \frac{1}{M}\sum_{i=1}^{15} m_i T_i \begin{bmatrix} OC_i \\ 1 \end{bmatrix}$
  - With $T_i = T_0^i = \prod_{k=0}^{i-1} T_k^{k+1}$

Post-treatment



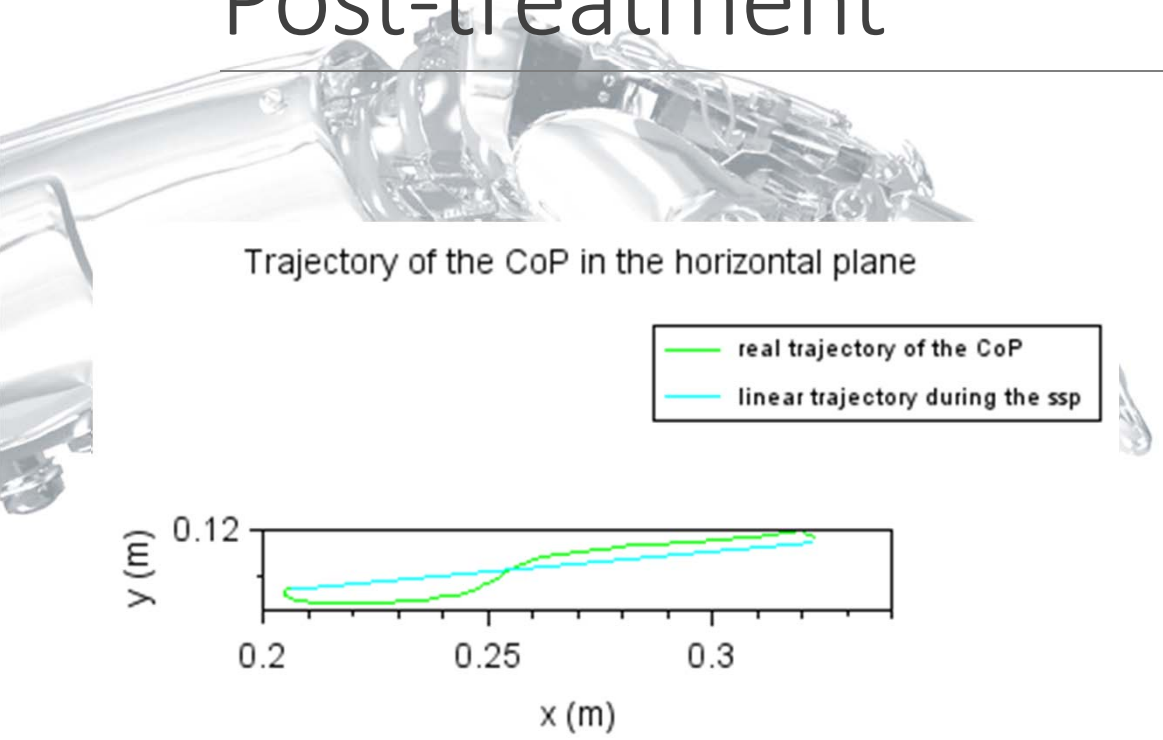
Linearization of the CoP trajectory

- Depend of initial and final configuration
- $\boldsymbol{OP}(t) = \frac{\boldsymbol{OP_f} - \boldsymbol{OP_i}}{t_f - t_i}(t - t_i) + \boldsymbol{OP_i}$

New trajectory without rolling phase:

- In advance at the beginning
- In retard at the end

Post-treatment



The new trajectory is similar to the other

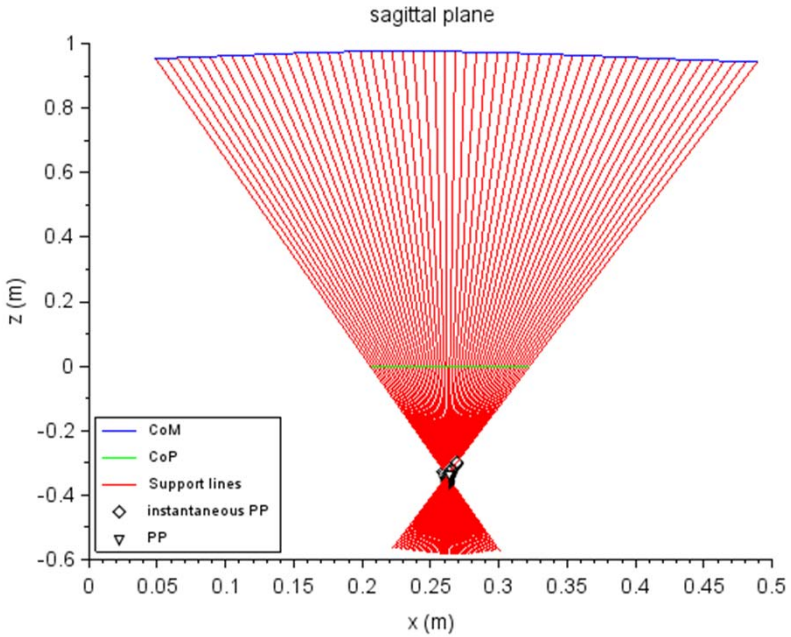
The extreme points are the same

The trajectory is simpler

- It is linear
- There is no rolling phase
- It permit to define a new GIP-3D model

Analysis and discussion

Analysis and discussion



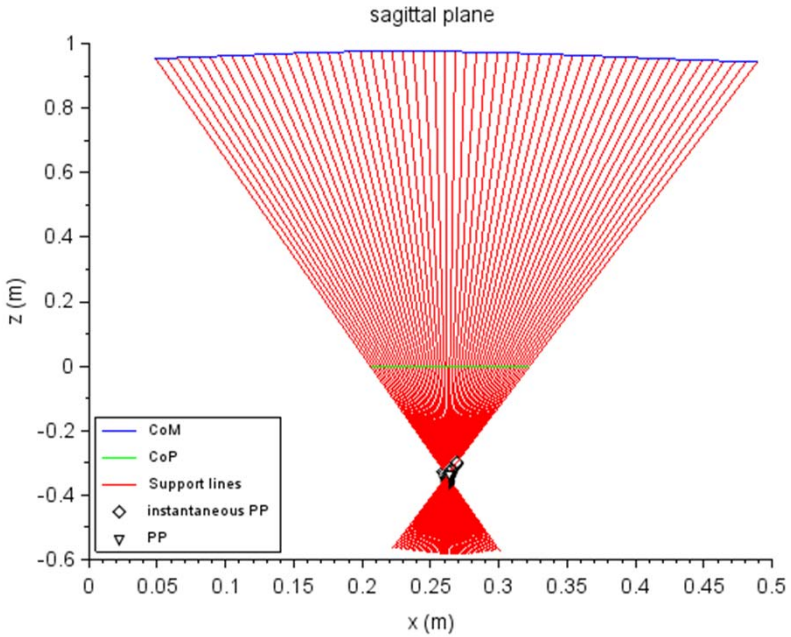
New GIP-3D model

- The IPP is the closer point between two consecutive support lines
- One support line connect the CoM to the corresponding linear CoP

In the sagittal plane

- All the IPP are included in a small area
- At 0.35m deep

Analysis and discussion

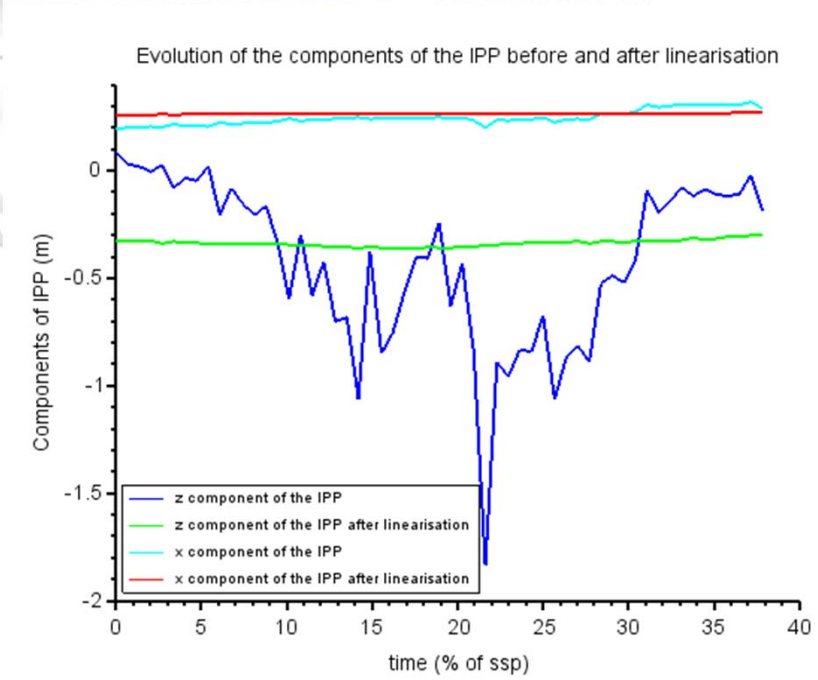


According to the new model
- X component of CoP evolve linearly

For all the human walking gait
- X component of CoM evolve linearly

Two linear evolutions
- Can explain the convergence

Analysis and discussion



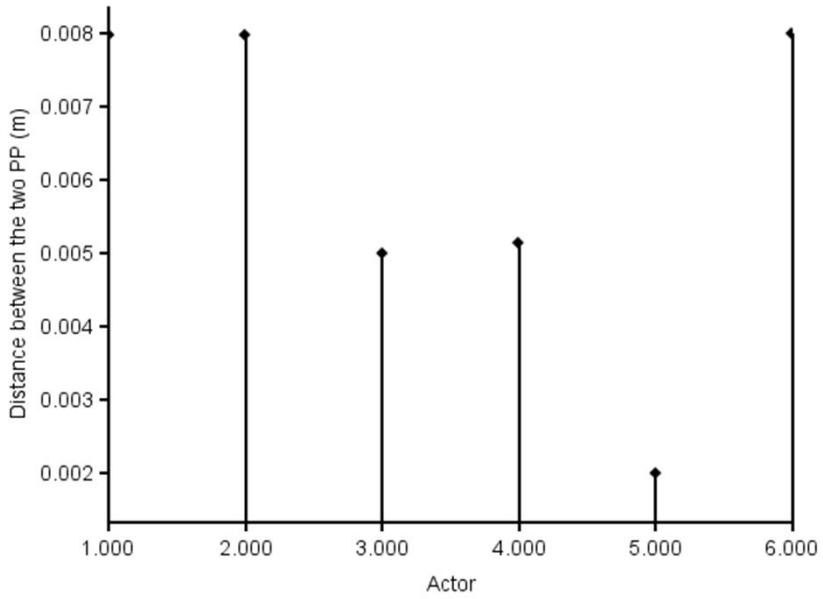
With the first GIP-3D

- Large convergence area
- Hard to define one PP

With the linear GIP-3D

- Small convergence area
- Possibility to defined one PP
- Can be model
  - At the convergence of all the supports lines
  - As the closer point of two particular support lines

Analysis and discussion



One PP can be model

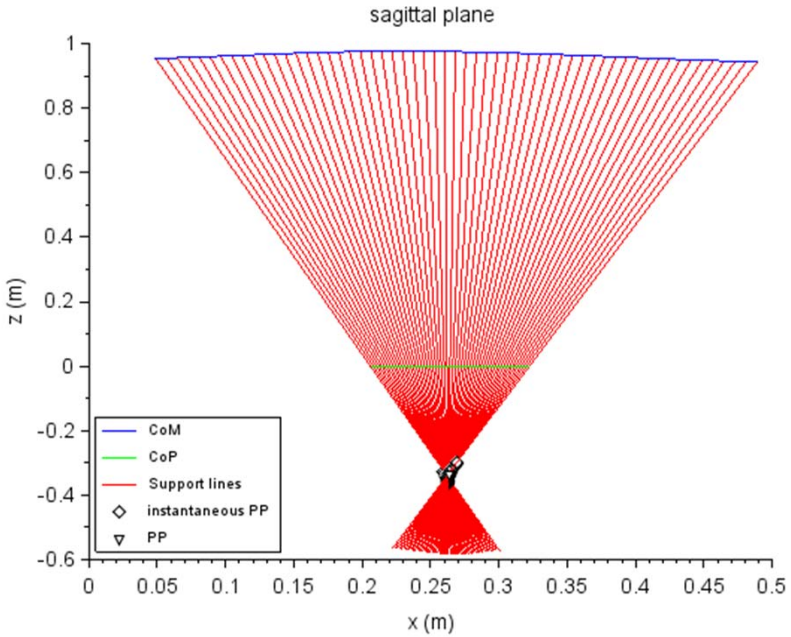
- At the convergence of all the supports lines
- As the closer point of two particular support lines: first and last

Difference between two definitions <8mm

There are equivalent

The PP can be calculated according to the initial and the final configuration

Analysis and discussion



Improvement of the model

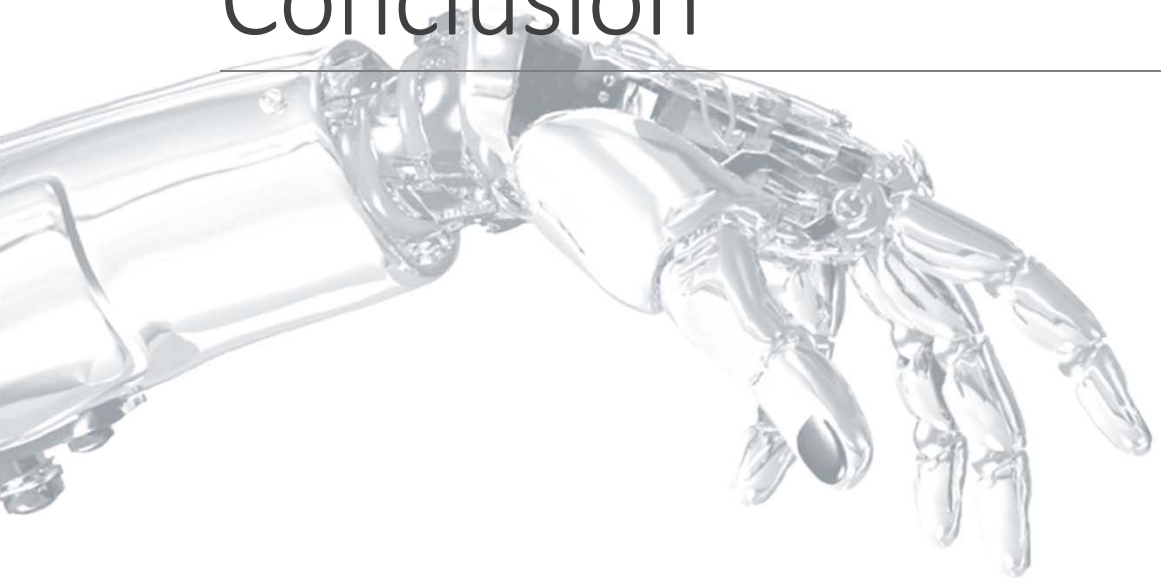
- IPP converge in a small area
  - Need extreme position of the CoP
  - Need real trajectory of the CoM
- PP easy to be calculated
  - Need extreme position of CoP
  - Need extreme position of CoM

The new model is adapted to humanoid robots

- Don’t need to solve a system at each iteration
- Permits to avoid some calculation

Conclusion

Conclusion



Optimisation of GIP-3D model

Definition of 3 sub-phases of ssp

- Definition of the IPP
- Adapted for the study of human walking

Linearization of the CoP trajectory

- New model
- Permits a smaller convergence of the IPP
- Permits to avoid some calculation
- Adapted for the development of humanoid walking

Thank you for your attention