Toward general capture point-based analysis on standing, walk and slip:

the connection between robotic motions to human behaviors

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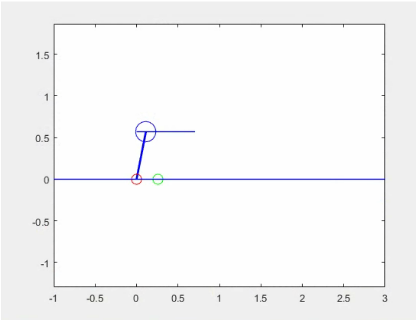
Motivation

1) Objective: to study the human stepping strategy during slip recovery → bipedal robot controller design
2) Capture Point is the stepping location which can make a complete stop for a legged system.



Blue: Center of Mass (COM)

Green: Instantaneous Capture Point (ICP)

Red: Capture Point

Capture Point is also called Extrapolated COM (XcoM), Divergent Component of motion (DCM) in the literature.

Motivation

How well the capture point-based method can estimate the foot placement for different walkers with different tasks?

Cases for Comparisons*

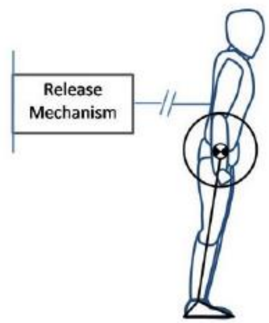
1) Stationary tasks (standing, one-step recovery from perturbation)
   a) Task 1: Subject is released at a specific angle.
   b) Task 2: Subject resists a gradually increased pushing force until step initiation.

2) Walking (Robots and Human) and Walking with Slip (Human)

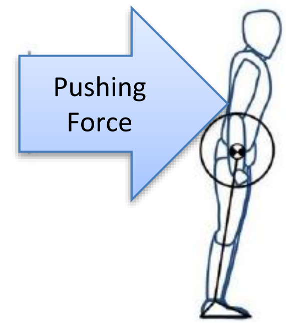
*Except for stationary task 2, we use the capture point method for linear inverted pendulum model with point feet

Comparison 1: Stationary Tasks

Task 1†



Task 2†



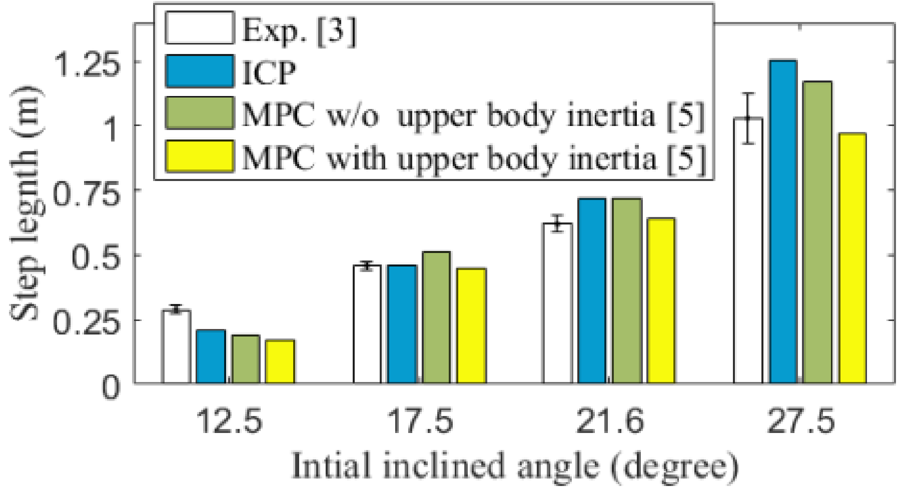
Methods

1) Experimental results from human subjects
2) Estimated by instantaneous capture point (ICP)
3) Estimated by simulation with model predictive control (MPC)†
   a) Without upper body inertial
   b) With upper body inertial

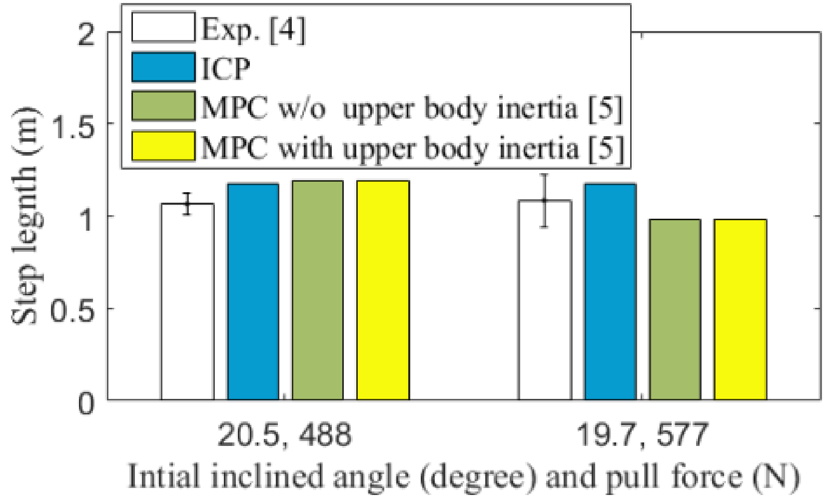
† Z. Aftab, T. Robert, and P. B. Wieber. (2016) Balance Recovery Prediction with Multiple Strategies for Standing Humans, *PLoS One.* (Vol. 11)

Comparison 1: Stationary Tasks

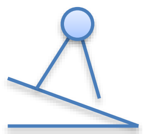
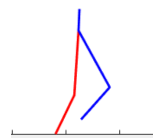
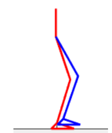
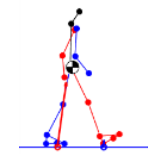
Task 1



Task 2



Comparison 2: Walking Tasks

	Compass Gait 	Kneed-Gait Robot 		ZMP-based Walking 	Human Gait 		
Task Name	CG	KGUA	KGFA	ZMP	Walking	Mild Slip	Severe Slip
# of links	2	5	5	7			
# of actuators	0	4	6	6	As many as human uses		
Actuation Type	Passive, unactauted	Under-actuated	Full-actuated	Full-actuated			
Contact Type	Point foot	Point foot	Point foot	Flat-foot	No Slip	PHV<1.44 (m/s)	PHV>1.44 (m/s)

Using Human-inspired Control

Foot Placement Estimation for Walking Tasks

1-step CP $x_{ic} = x_c + \frac{\dot{x}_c}{\omega}$

∞-step CP $x_{\infty cp} = x_{ic} - d_{\infty}$

$d_{\infty} = l_{max} \frac{e^{-\Delta t_s}}{1 - e^{-\Delta t_s}}$

E-ICP (estimated) $x_{ic} = x_c + \frac{\dot{\bar{x}}_c}{\omega}$

x_c : COM position

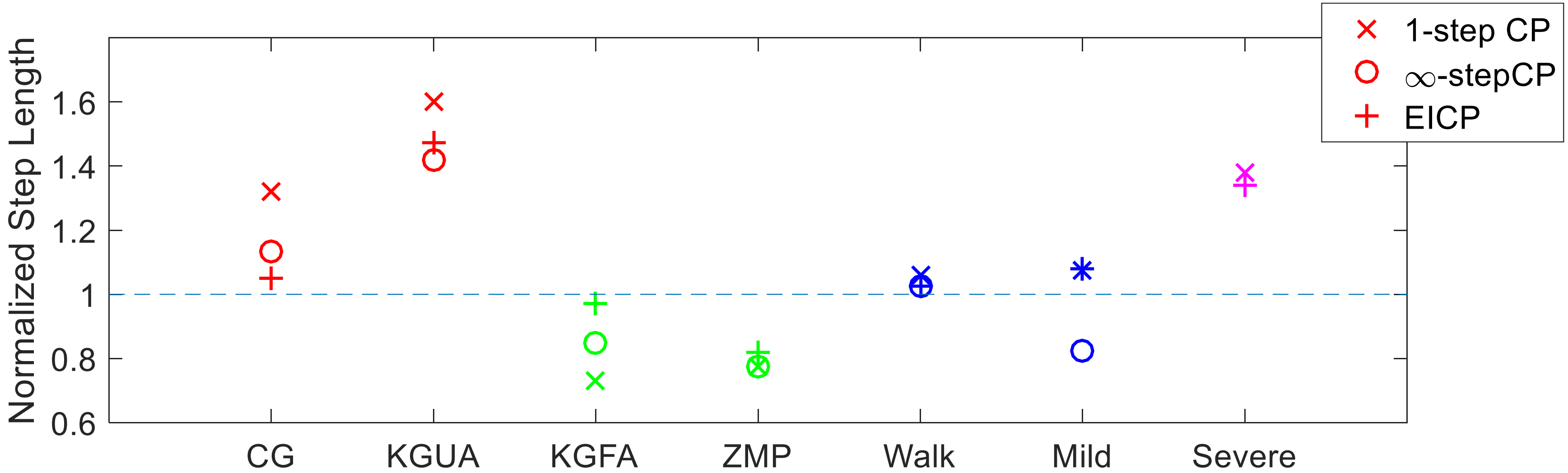
x_{ic} : ICP

l_{max} : Max reachable range

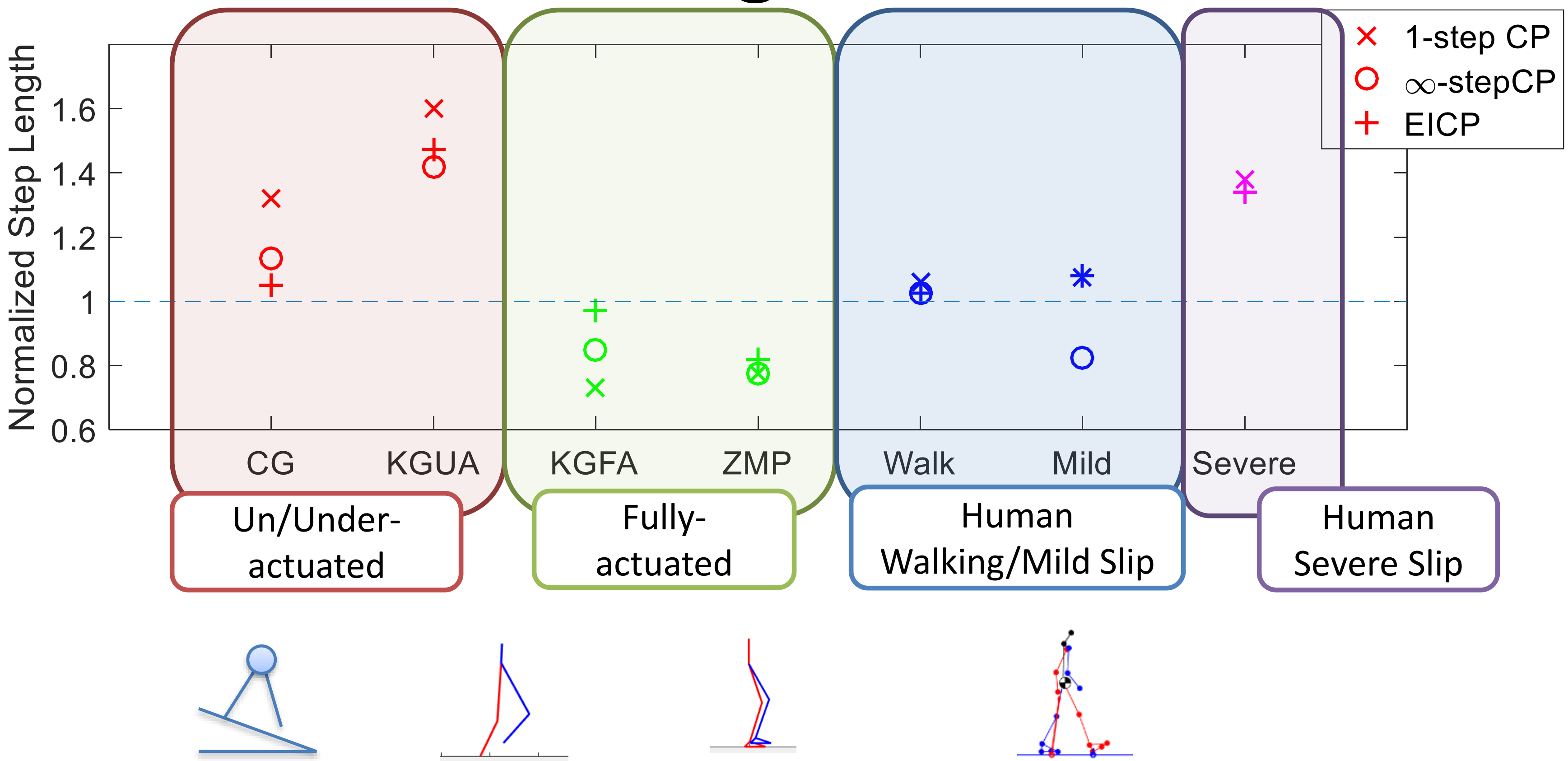
t_s : Stepping time

(Replace the $\dot{x}_c$ to the mean COM velocity)

Foot Placement Estimation for Walking Tasks



Foot Placement Estimation for Walking Tasks



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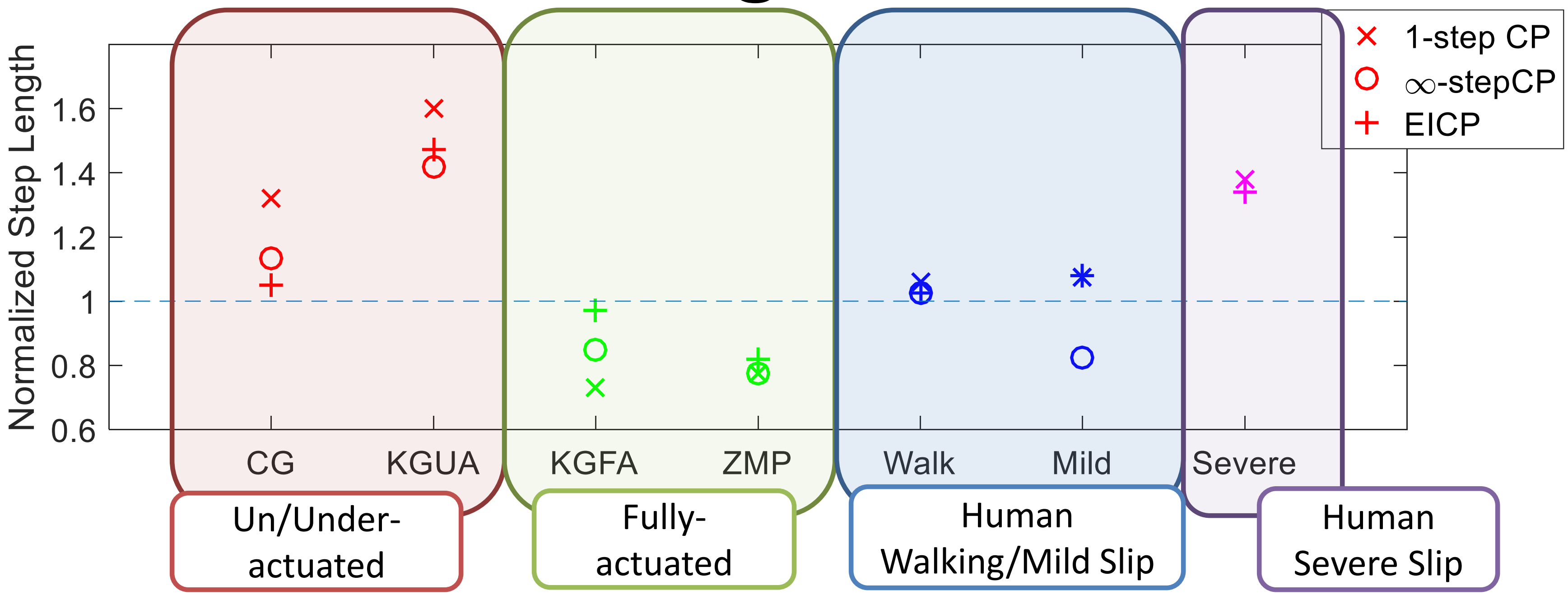


Under-actuated:
Free-swaying support foot, w/o considering the power dissipation of ***impact***

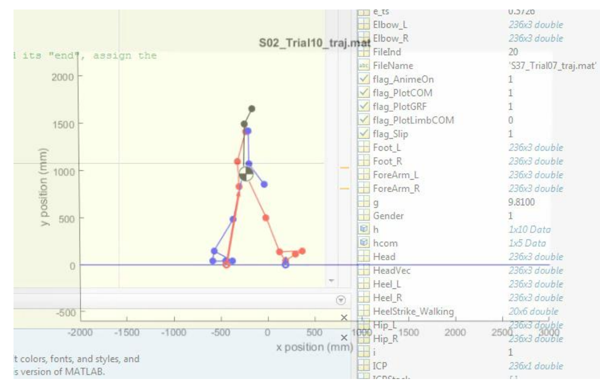
Human walking and mild slip:
Foot rolling motion, mixed actuation

Fully-actuated:
Ankle joints dominate the COM velocity regulation, ***not really free-swaying***.

Severe Slip:
∞-step CP failed (value diverged)
Both 1-step CP and EICP cannot explain the stepping for backing to the double support well

Summary

- The upper body motion, the effects of impact and the COM motion in double support phase need to be considered for further development of the foot placement estimation.
- Stepping location estimations using CP-based method can provide reasonable predictions for one-step recovery, human walking and human walking with mild slip.
- For severe slips, CP-based method needs to be improved for better stepping location estimation.



Walking with severe slip examples

- Thanks

Dr. Pilwon Hur, Human Rehabilitation Group

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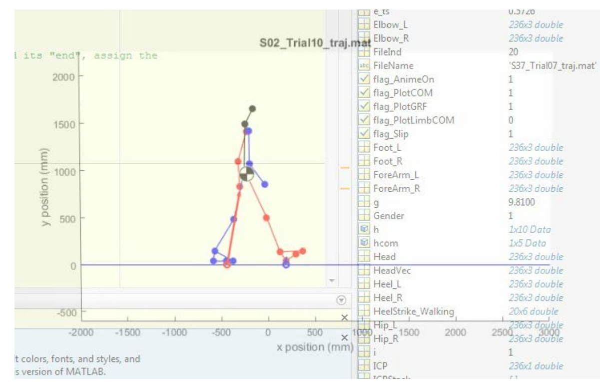


Walking with severe slip examples

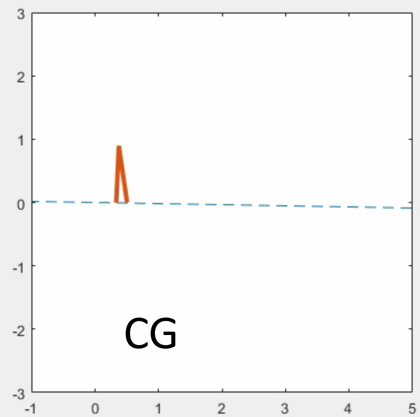
- Thanks

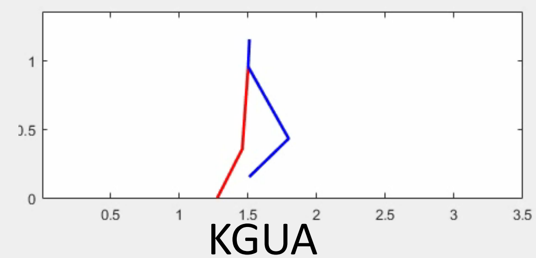
Dr. Pilwon Hur, Human Rehabilitation Group

Thank you! Any Questions?

Discussions for different categories

	CG	KGUA	KGFA	ZMP	Human (walk)	Human (mild slip)	Human (severe slip)
1-step CP	0.327 (0)	0.603 (0)					
∞-step CP	0.133 (0)	0.417 (0)					
EICP	0.048 (0)	0.473 (0)					

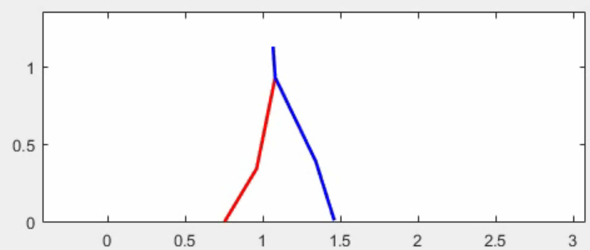




Under-actuated robotic walking: The estimated step length is (much) larger than the simulation one

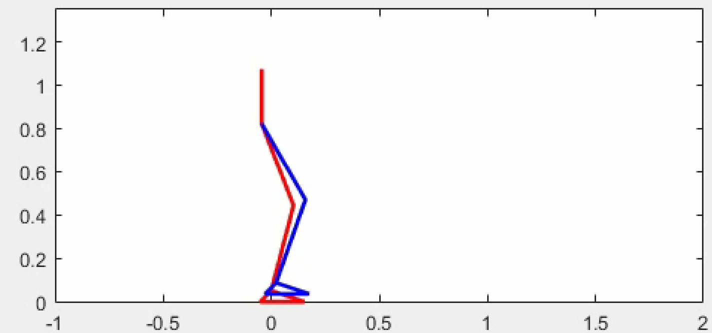
1) The current method did not consider the power dissipation due to impact

Discussions for different categories



KGFA

KGFA	ZMP
-0.269 (0)	-0.225 (0)
-0.154 (0)	-0.225 (0)
-0.031 (0)	-0.182 (0)

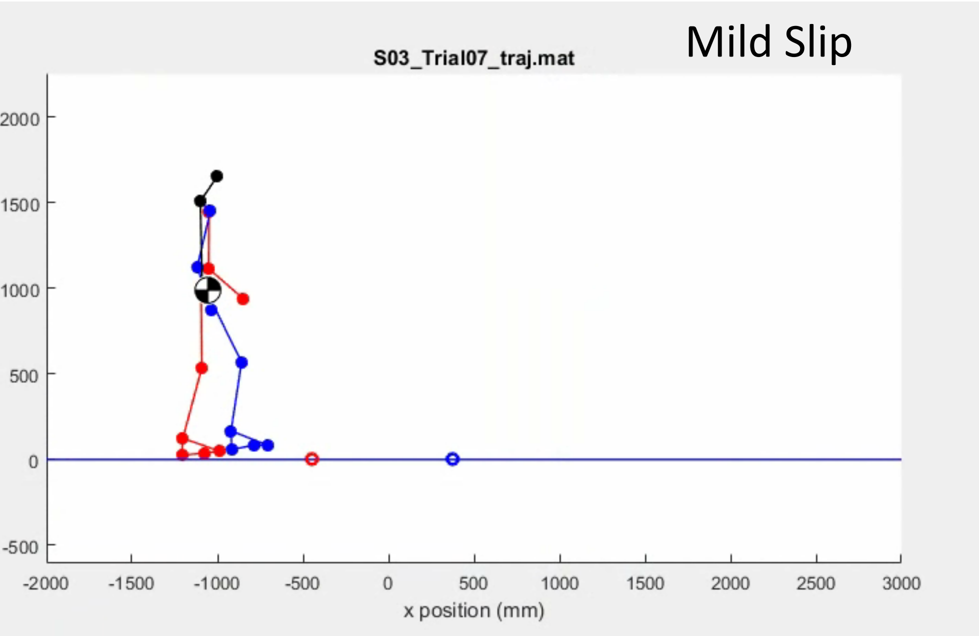


ZMP

For full-actuated robots: The required step length is (much) less than the simulation one

1) The activated ankle joints regulated the COM velocity dominantly, which makes walkers not really behave like a free-swaying IVP.
2) A certain portion of COM moving is achieved in double support rather than in single support (for the ZMP-based walker)

Discussions for different categories

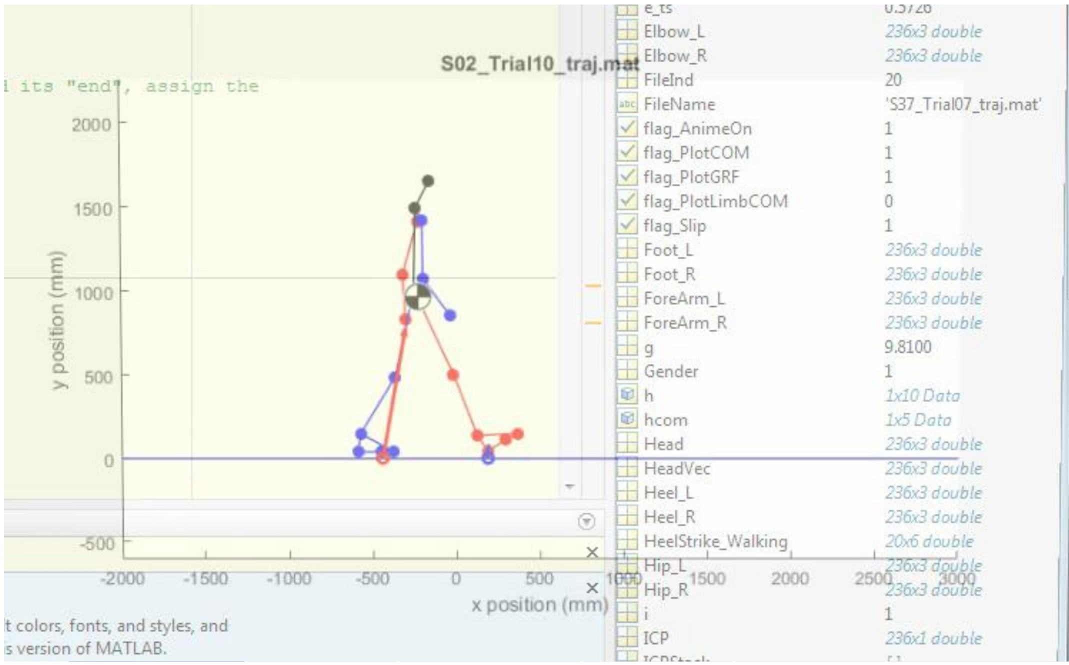


Human (walk)	Human (mild slip)	Human (severe slip)
0.06 (0.033)	0.074 (0.038)	0.379 (0.102)
0.024 (0.028)	-0.174 (0.066)	>1.00
0.023 (0.029)	0.078 (0.041)	0.341 (0.057)

Surprisingly, ICP or EICP gives a relatively better estimation for both walk and walking with mild slip

1) May imply the human actually behave neither pure-underactuated or pure-full-actuated.
2) Human will try to reduce the impact for landing, they will also try to utilize the free-sway dynamics during walking in a safe region.
3) Human use similar control strategy as walking for mild slip

Discussions for different categories



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N-step ICP failed…

1) The swing leg tends to make a step as soon as possible. (Usually still behind the front support foot)
2) EICP and ICP maynot provide good enough estimation because there is less clear of how ICP works for the double support phase.

Foot Placement Estimation Error for Walking Tasks

	CG	KGUA	KGFA	ZMP	Human (walk)	Human (mild slip)	Human (severe slip)
1-step CP	0.327 (0)	0.603 (0)	-0.269 (0)	-0.225 (0)	0.06 (0.033)	0.074 (0.038)	0.379 (0.102)
∞-step CP	0.133 (0)	0.417 (0)	-0.154 (0)	-0.225 (0)	0.024 (0.028)	-0.174 (0.066)	>1.00
EICP	0.048 (0)	0.473 (0)	-0.031 (0)	-0.182 (0)	0.023 (0.029)	0.078 (0.041)	0.341 (0.057)

Estimation Error = (CP – Real Step Location)/avg(real Step Length)
= (estimated Step Length – Real Step Length)/avg(real Step Length)

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∞-step CP $$d_\infty = l_{max} \frac{e^{-\Delta t_s}}{1 - e^{-\Delta t_s}}$$

l_{max} : Max reachable range

t_s : Stepping time

E-ICP (estimated) $$x_{ic} = x_c + \frac{\dot{x}_c}{\omega}$$

Replace the com v to the average one