On the role of angular momentum damping for foot contact stabilization during dynamic movements

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1. Foot contact stabilization

Our interest: motor control for postural stability during **highly dynamic** motion tasks, such as kicking, swinging a tennis racket, a golf club etc...

Known fact: variations in the angular momentum (AM) around the CoM (i.e. the system AM or SAM) lead to variations in the ground reaction moments (GRMs) [1].

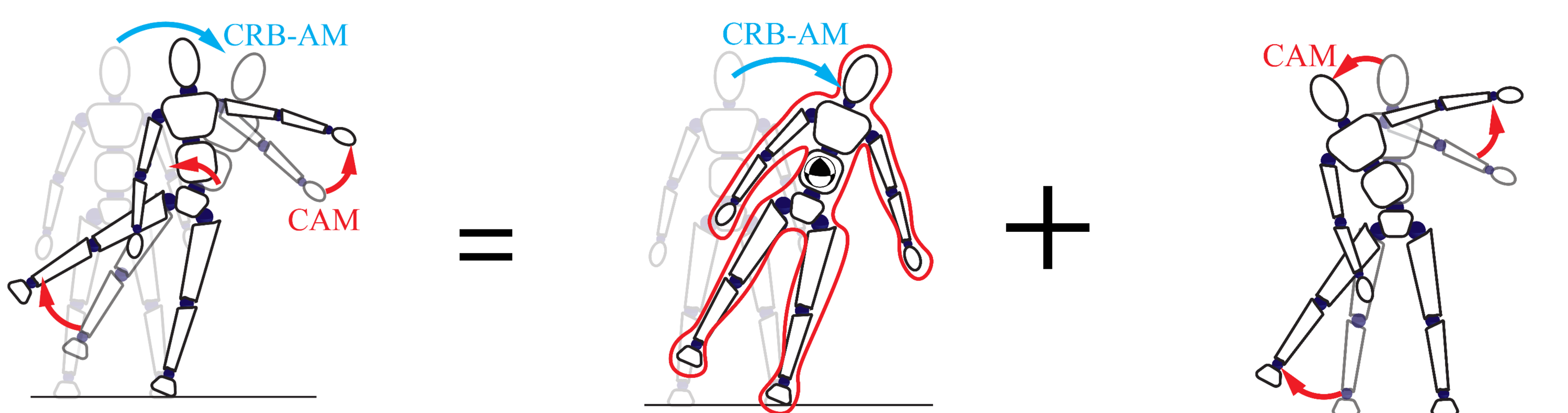
▶ Then:
- The posture may become destabilized
- The risk of falling increases

Hypothesis
To avoid the destabilization, the CNS generates motor control commands that damp the AM.

Purpose of this work
- Revealing the AM damping mechanism
- Analyzing the role of AM damping in foot contact and posture stabilization

2. Angular momentum/velocity analysis

■ **Momentum equilibrium principle [2]**
For any movement, the SAM is in dynamic equilibrium, as:



SAM

CRB-AM
Due to the CRB rotational motion.

Coupling AM (CAM)
Due to the joint motion.

Composite Rigid Body (CRB): A system state with locked joints.

$$\boldsymbol{l}_C(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) = \boldsymbol{I}_C(\boldsymbol{\theta})\boldsymbol{\omega}_P + \boldsymbol{H}_C(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}$$

n : The total DoF in the joints
$\boldsymbol{\theta} \in \Re^n$: Joint angle vector
$\boldsymbol{I}_C(\boldsymbol{\theta}) \in \Re^{3\times 3}$: Inertia tensor of the CRB
$\boldsymbol{H}_C(\boldsymbol{\theta}) \in \Re^{3\times n}$: Coupling inertia tensor
$\boldsymbol{\omega}_P \in \Re^3$: Angular velocity of the pelvis

$\times \boldsymbol{I}_C^{-1}$

■ **Angular velocity (AV) based analysis**

$$\underbrace{\boldsymbol{\omega}_C}_{\text{SAV}} = \underbrace{\boldsymbol{\omega}_P}_{\text{CRB-AV}} + \underbrace{\boldsymbol{J}_\omega(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}}_{\text{coupling AV}}$$

System Angular Velocity (SAV)
(called also average AV [3]) :

$$\boldsymbol{\omega}_C = \boldsymbol{I}_C^{-1}\boldsymbol{l}_C$$

$\boldsymbol{J}_\omega = \boldsymbol{I}_C^{-1}\boldsymbol{H}_C$
AV Jacobian

Relative Angular Velocity (RAV)

$$\Delta\boldsymbol{\omega} \equiv \boldsymbol{J}_\omega\dot{\boldsymbol{\theta}} = \boldsymbol{\omega}_C - \boldsymbol{\omega}_P$$

3. Joint velocity components

■ The joint velocity has two components [4]:

$$\dot{\boldsymbol{\theta}} = \dot{\boldsymbol{\theta}}_{rl} + \dot{\boldsymbol{\theta}}_{SAM}$$

Reactionless motion synergies: $\boxed{\dot{\boldsymbol{\theta}}_{rl} \in \mathcal{N}(\boldsymbol{H}_C)}$

$\mathcal{N}(\boldsymbol{H}_C)$: Called the Reaction Null-space (RNS)

The segment movements that do not contribute to balance control.

▶ Do not alter the SAM : $\boldsymbol{H}_C\dot{\boldsymbol{\theta}}_{rl} = \boldsymbol{0}$, $\dot{\boldsymbol{\theta}}_{rl} \neq \boldsymbol{0}$

Contributing motion synergies: $\boxed{\dot{\boldsymbol{\theta}}_{SAM} \in \mathcal{R}(\boldsymbol{H}_C^T)}$

The segment movements that contribute to balance control.

▶ Alter the SAM: $\boldsymbol{H}_C\dot{\boldsymbol{\theta}}_{SAM} \neq \boldsymbol{0}$

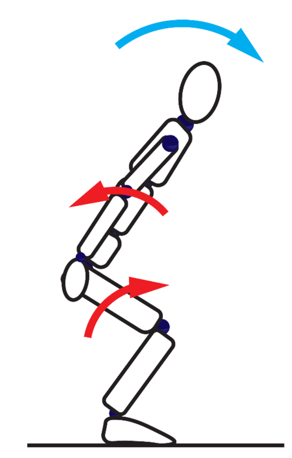
4. AM conservation strategies

■ **SAM conservation strategy**

Cancel the CRB-AM with the CAM $(\dot{\boldsymbol{\theta}}_{SAM})$

$(\boldsymbol{\omega}_C = \boldsymbol{0} \Rightarrow \Delta\boldsymbol{\omega}(\dot{\boldsymbol{\theta}}_{SAM}) = -\boldsymbol{\omega}_P)$

▶ Useful to avoid self-destabilization.



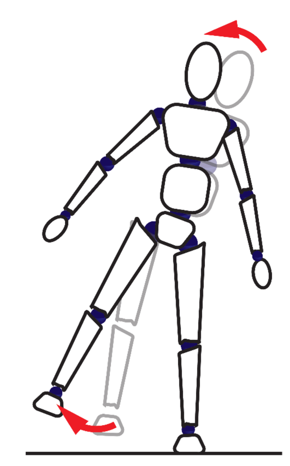
■ **CAM conservation strategy**

Generates reactionless synergies.

▶ The segments move but the body behaves as a CRB.

$(\boldsymbol{\omega}_C = \boldsymbol{\omega}_P \Rightarrow \Delta\boldsymbol{\omega}(\dot{\boldsymbol{\theta}}_{rl}) = \boldsymbol{0})$

▶ Useful to generate a motion impulse (e.g. in kicking, hitting).



5. Contact stability and acceleration

■ Rate of change of SAM (R.C. of SAM)

$$\dot{\boldsymbol{l}}_C = \boldsymbol{I}_C\dot{\boldsymbol{\omega}}_B + \boldsymbol{H}_C\ddot{\boldsymbol{\theta}} + \underbrace{\boldsymbol{c}_m}_{\text{nonlinear term}}$$

■ The relative angular acceleration (RAA)

$$\Delta\dot{\boldsymbol{\omega}} = \dot{\boldsymbol{\omega}}_C - \dot{\boldsymbol{\omega}}_P$$

■ Past work: the RNS filter [4]
Extract reactionless synergies from motion capture data.

$$\underbrace{\ddot{\boldsymbol{\theta}}_{moc}}_{\text{joint acceleration from motion capture}} = \ddot{\boldsymbol{\theta}}_{rl} + \ddot{\boldsymbol{\theta}}_{SAM}$$

■ The AM damping mechanism

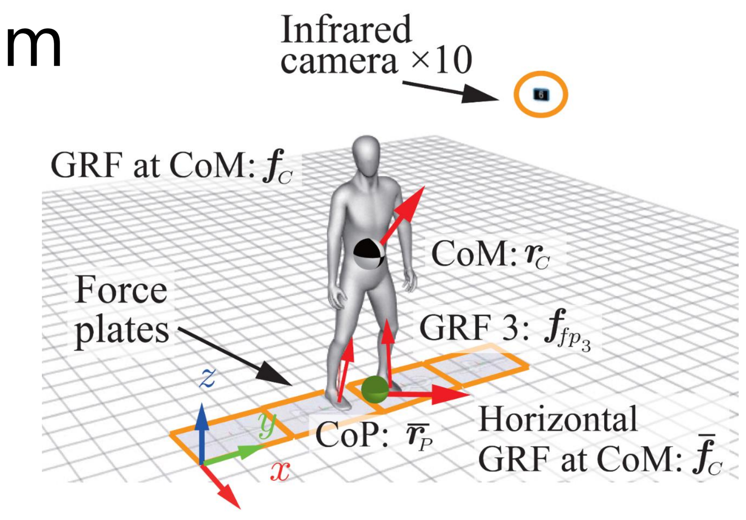
SAM damping : $\boldsymbol{\omega}_C^{ref} = \boldsymbol{0} \Rightarrow \dot{\boldsymbol{\omega}}_C^{ref} = -\boldsymbol{D}_\omega\boldsymbol{\omega}_C$

CAM damping : $\Delta\boldsymbol{\omega}^{ref} = \boldsymbol{0} \Rightarrow \Delta\dot{\boldsymbol{\omega}}^{ref} = -\underbrace{\boldsymbol{D}_\omega}_{\text{nonnegative damping gain}}\Delta\boldsymbol{\omega}$

6. Experimental system

■ Motion capture (moCap) system

- Infrared camera
  - Joint motion : $\ddot{\boldsymbol{\theta}}_{moc}$
  - Pelvis motion : $\boldsymbol{\omega}_P$
- Force plate
  - GRFs : $\boldsymbol{f}_{fp_i}$



■ CoP variation due to the R.C. of SAM and the GRF [1]

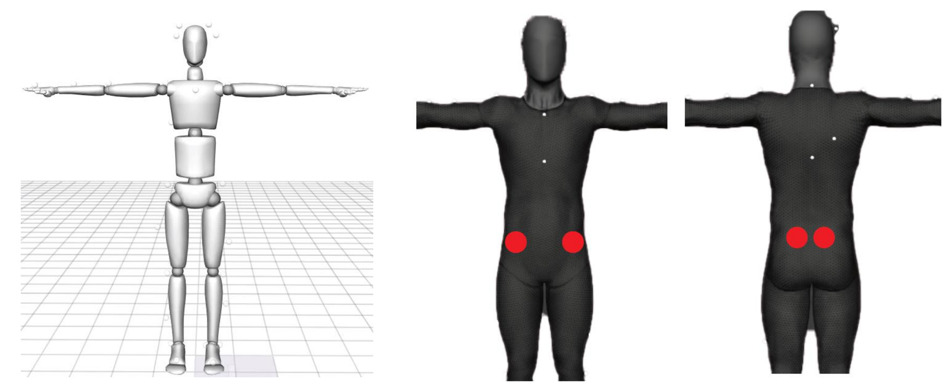
$$\Delta\bar{\boldsymbol{r}}_p = -\frac{1}{f_{C_z}}(r_{c_z}\bar{\boldsymbol{f}}_C + \boldsymbol{S}^{\times}\dot{\boldsymbol{l}}_C) \quad \boldsymbol{f}_C = \sum_{i=1}^{4}\boldsymbol{f}_{fp_i} \quad \boldsymbol{S}^{\times} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

■ The moCap human model

- Segments: 17, Joint DoF: 43
- Mass : 60 kg , Height: 174 cm
- Inertia parameters from statistical data
- CRB attitude = pelvis attitude

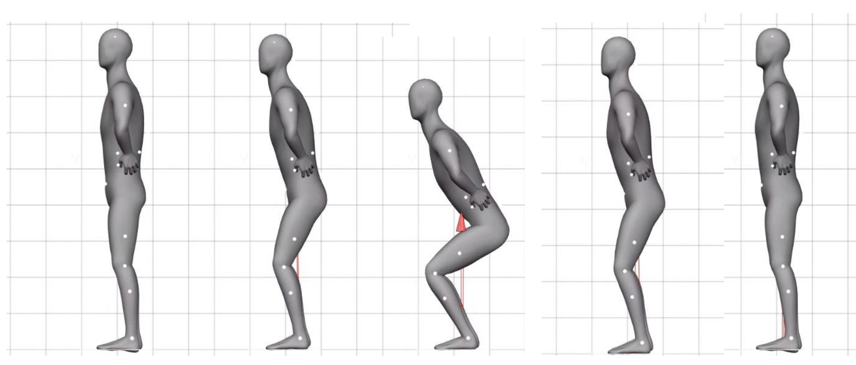
■ The simulation model

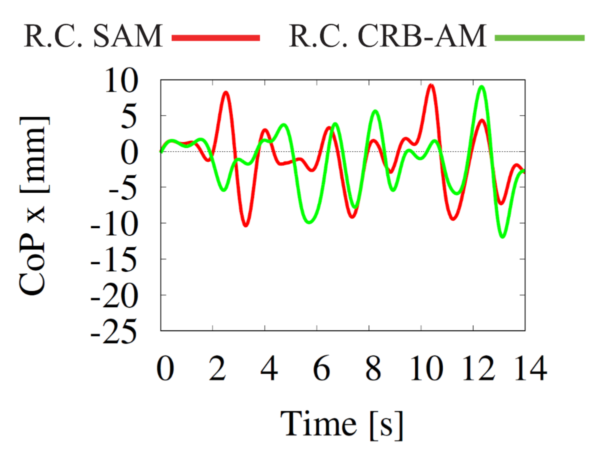
- Joint DoF: 31
- Mass: 65 kg
- Height: 170 cm

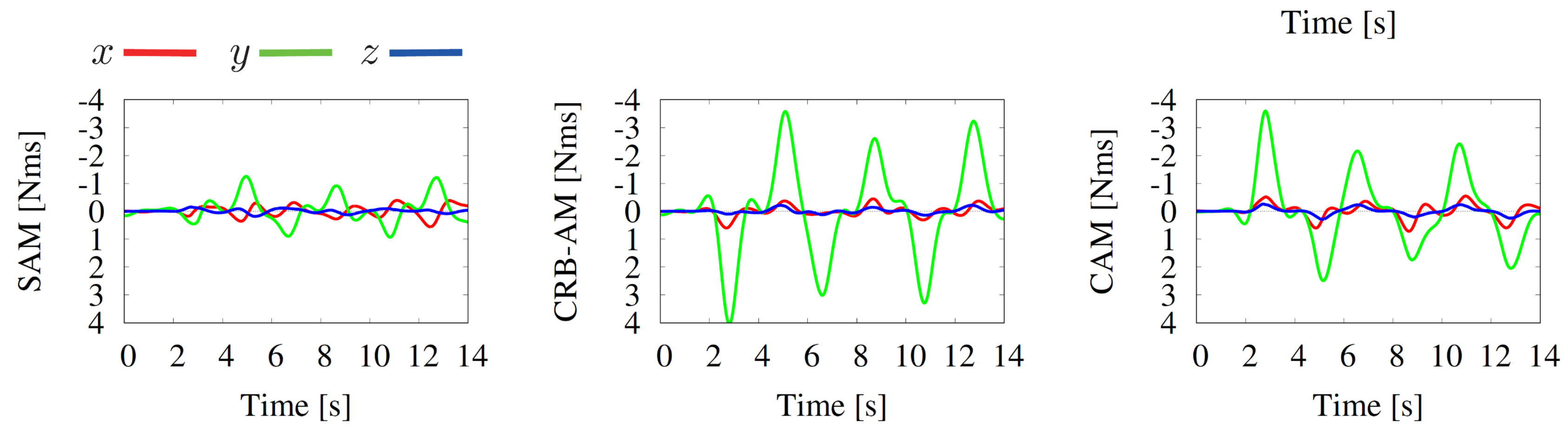


7. Simple moCap experiment and simulation

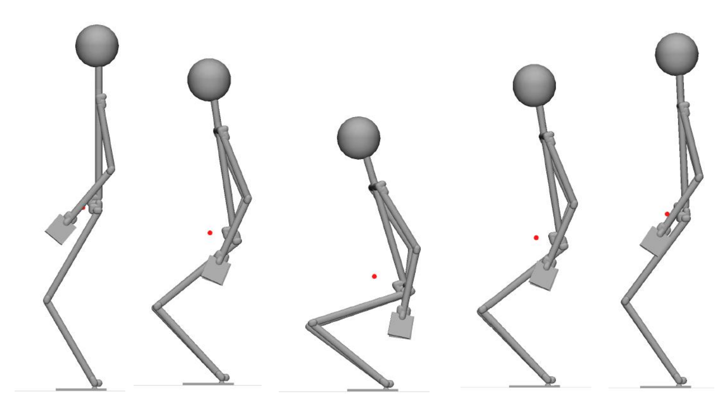
■ Squat (SAM conservation strategy)

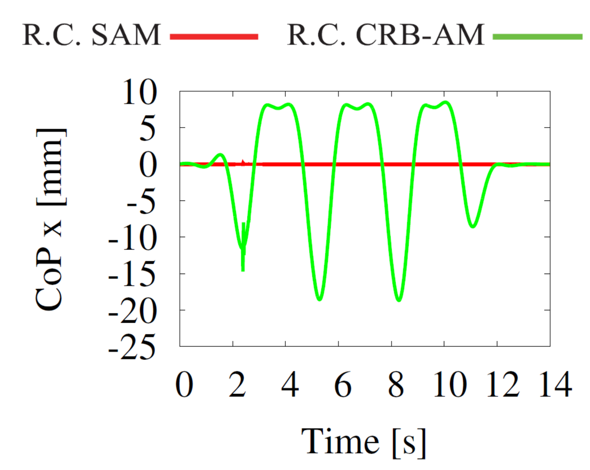


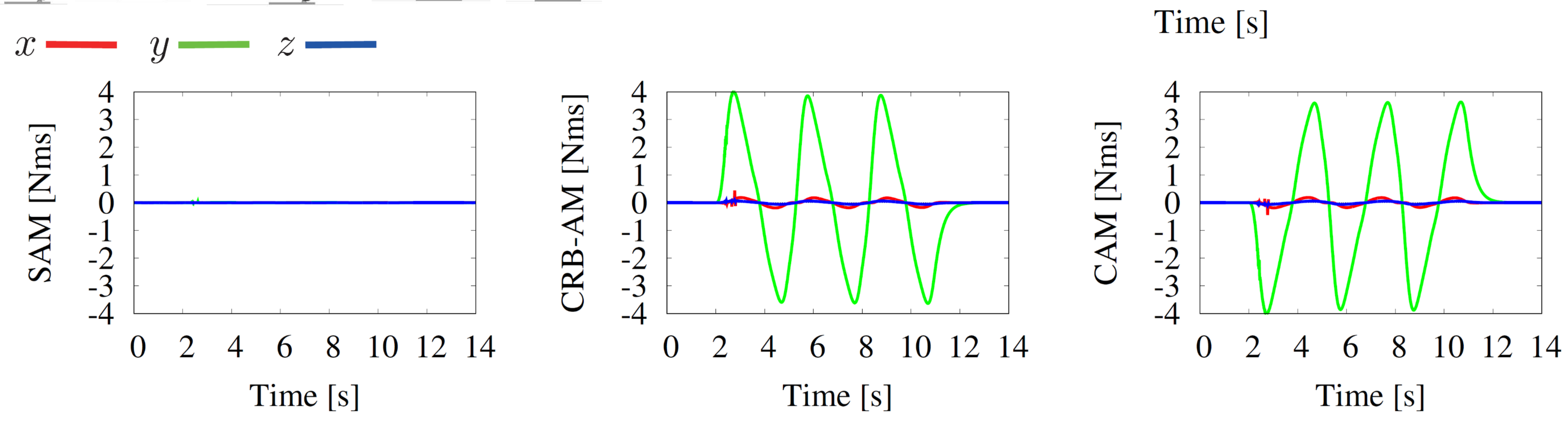




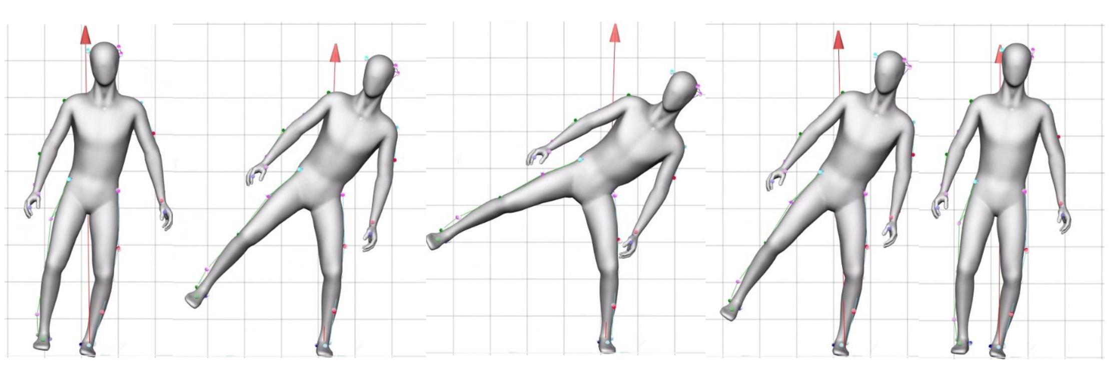
■ Squat with SAM damping control

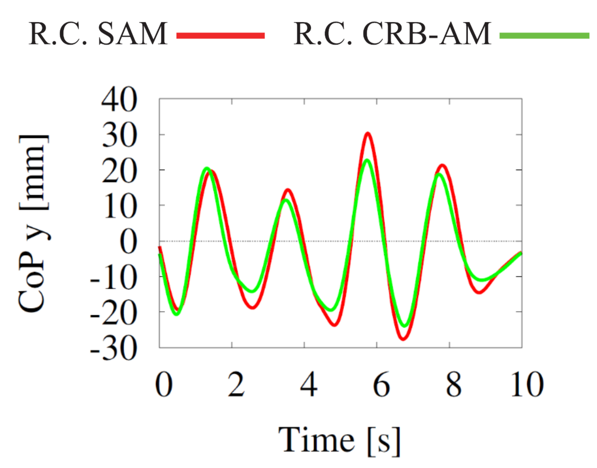


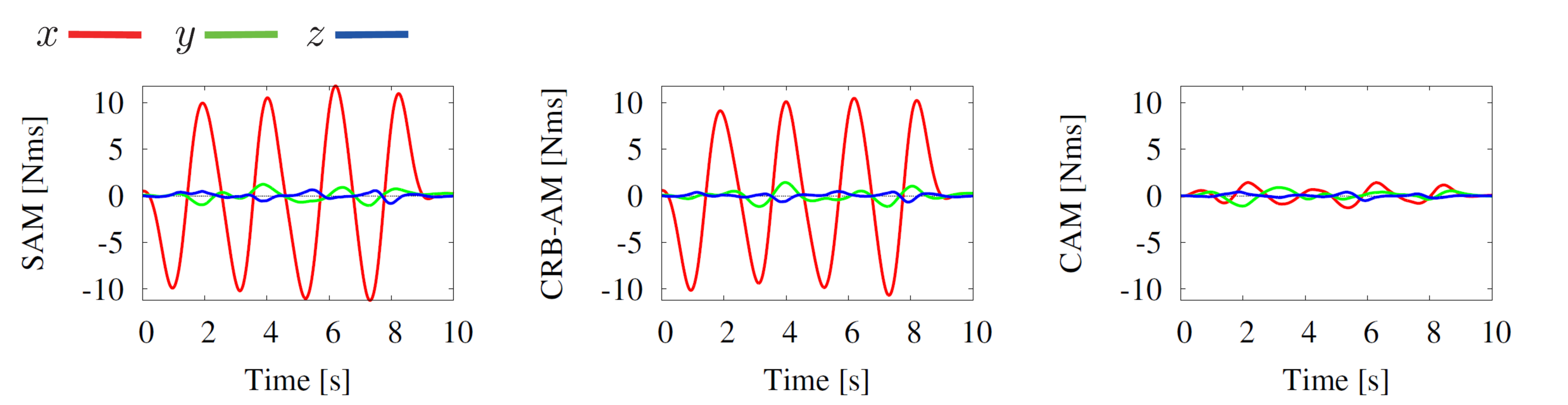




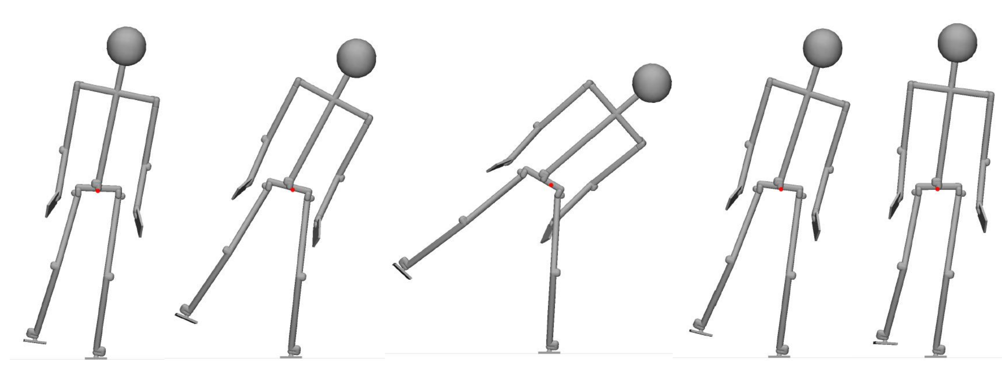
■ Frontal-plane lift-leg (CAM conservation) strategy

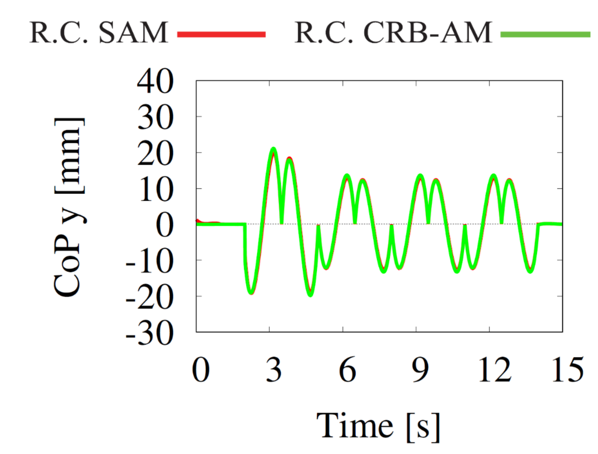


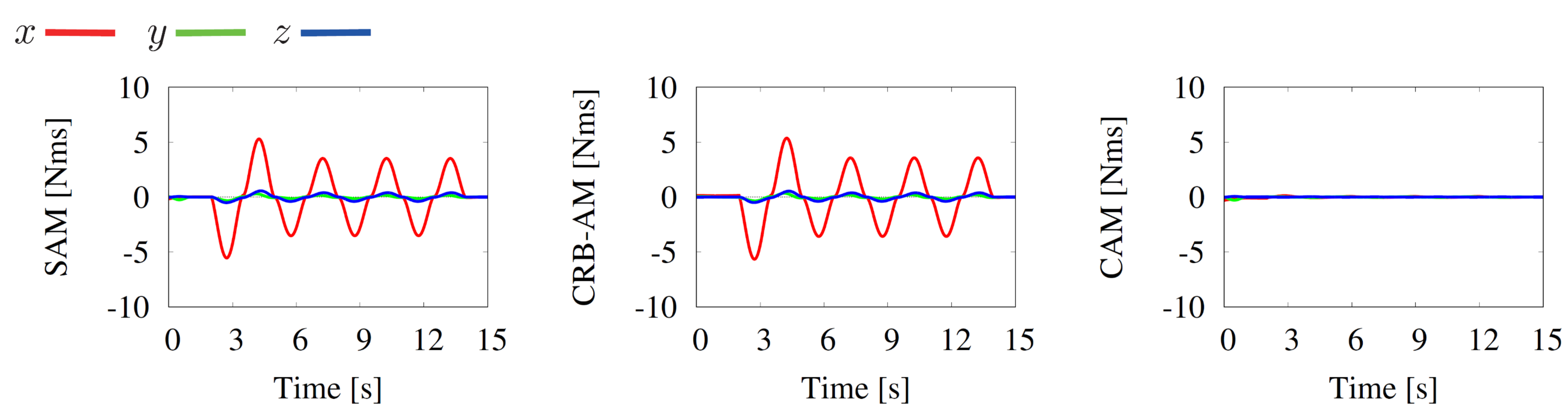




■ Frontal-plane lift-leg with CAM damping control





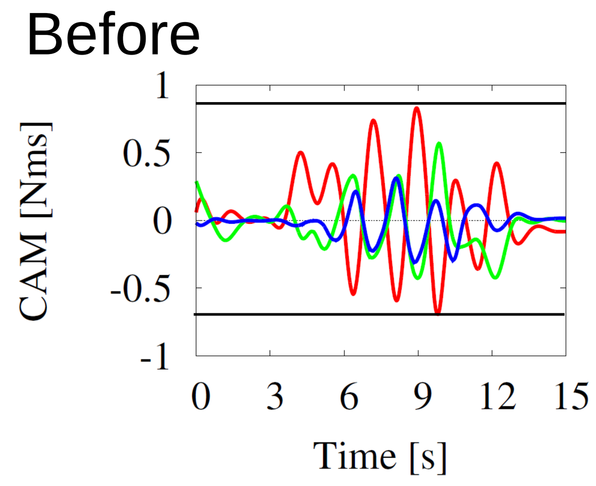


8. Preliminary result - Training outcome assessment -

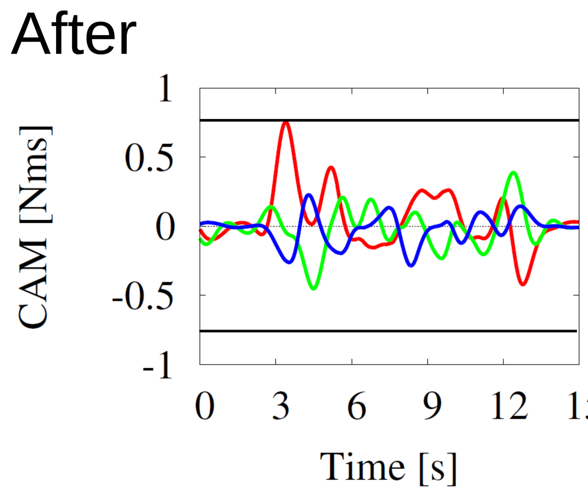
■ Training method

- Single stance on an unstable board
- Practice lift-leg for 5 minutes

Before



After



■ The CAM decreased as a result of the training.

■ The SAM and CRB-AM components were unchanged.

10. Conclusions

- Proposed a new method of AM assessment via AV.
- Revealed the role of the momentum equilibrium principle and the CRB and CAM components in balance control.
- Revealed the role of SAM and CAM conservation in highly dynamic movements.
- Revealed the mechanism of AM damping control.

References

[1] Popovic M., Goswami A., and Herr H. Ground reference points in legged locomotion: definitions, biological trajectories and control implications. *Internal Journal of Robotics Research* 24, 1013–1032, 2005.

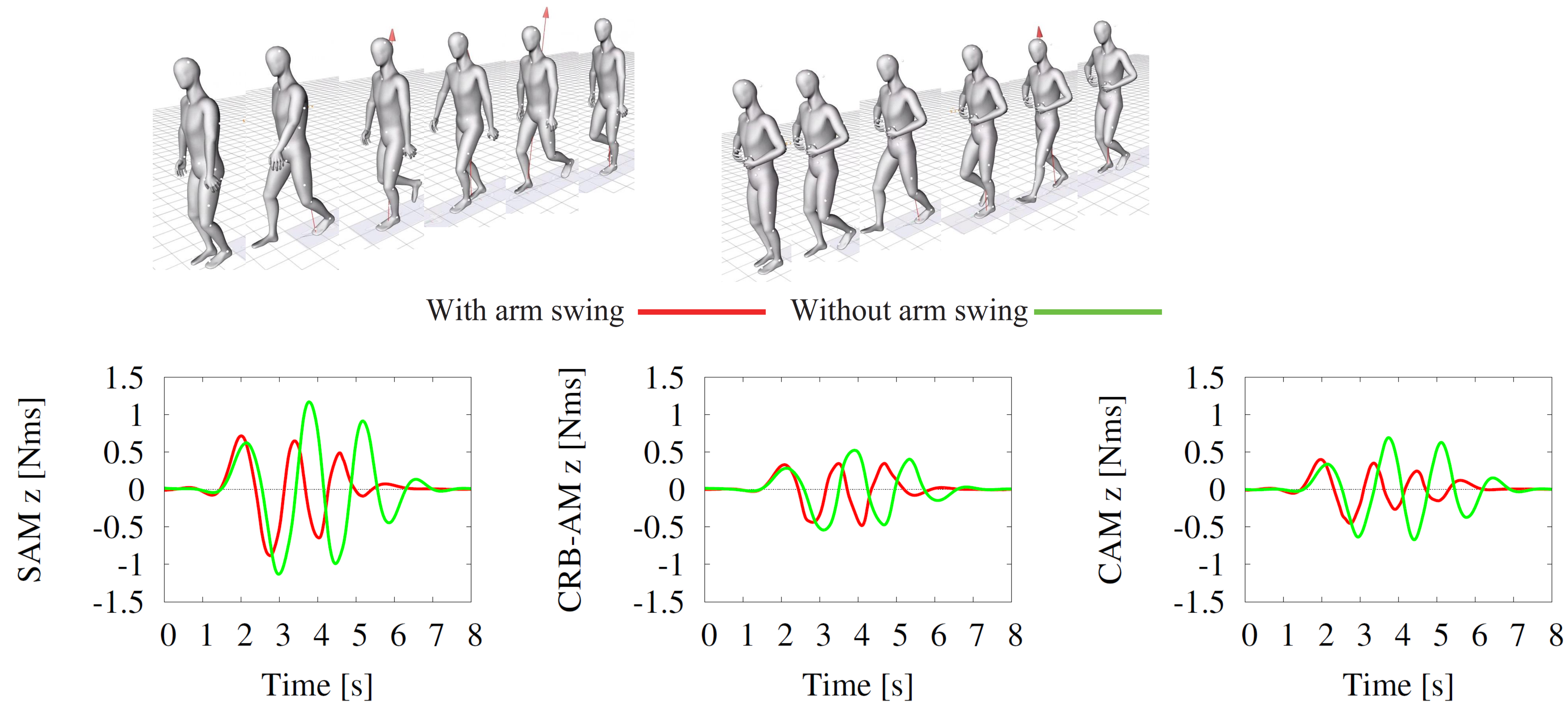
[2] D. N. Nenchev. The Momentum Equilibrium Principle: Foot Contact Stabilization With Relative Angular Momentum/Velocity. In *IEEE-RAS 18th International Conference On Humanoid Robot*, 17–24, Beijing, PR China, 2018.

[3] Essén, H. Average angular velocity. *European Journal of Physics*, 14, 201–205, 1993.

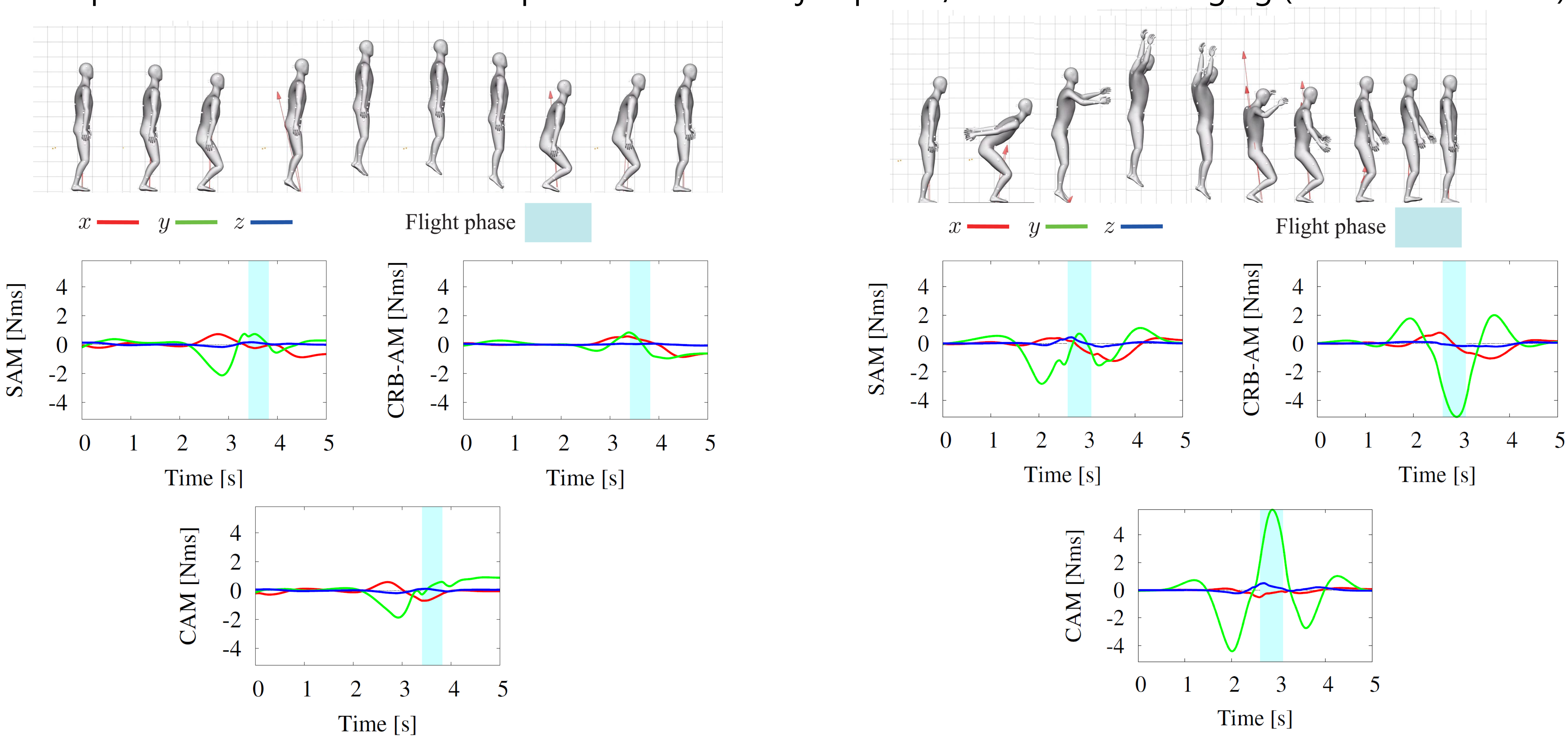
[4] D. N. Nenchev, Miyamoto, Y., Iribe, H., Takeuchi, K., and Sato, D. Reaction null-space filter: extracting reactionless synergies for optimal postural balance from motion capture data. *Computer Methods in Biomechanics and Biomedical Engineering*, 19(8), 864–874, 2015.

Appendix - Various motions

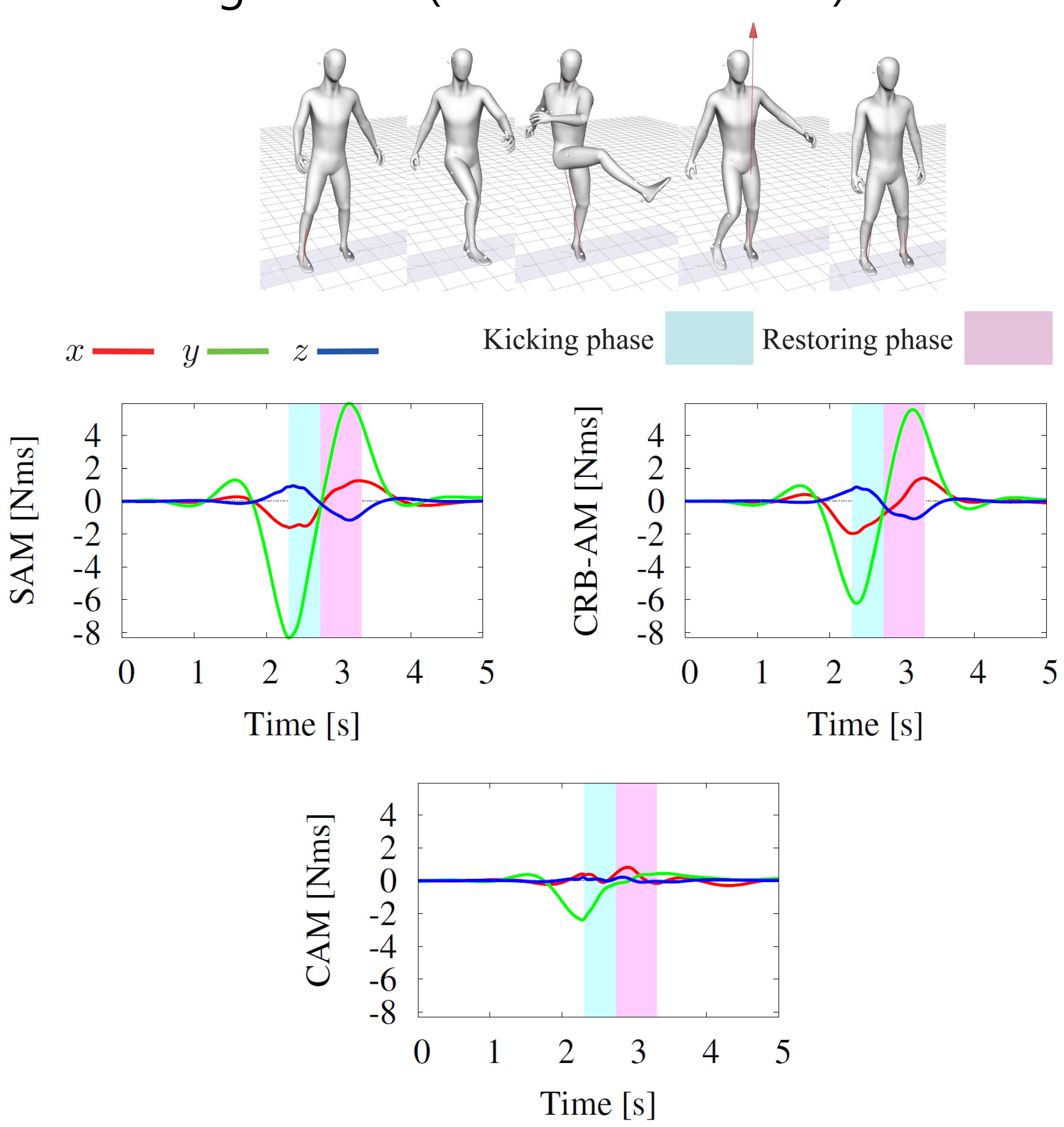
■ Comparison between the AM components around the yaw (z) axis while walking with/without arm swinging



■ Comparison between the AM components in vertical jump with/without arm swinging (SAM conservation)



■ Kicking motion (CAM conservation)



■ Step-kick-step motion (CAM conservation)