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

Kei Kobayashi, Ryotaro Hinata and Dragomir N. Nenchev (Tokyo City University)

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].

- 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:

\[ l_C(\theta, \dot{\theta}) = I_C(\theta)\omega_P + H_C(\theta)\dot{\theta} \]

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

SAM

CRB-AM

Due to the CRB rotational motion.

Coupling AM (CAM)

Due to the joint motion.

3. Joint velocity components

The joint velocity has two components [4]:

\[ \dot{\theta} = \dot{\theta}_{rl} + \dot{\theta}_{SAM} \]

Reactionless motion synergies: \( \dot{\theta}_{rl} \in N(H_C) \)
N(H_C): Called the Reaction Null-space (RNS)
The segment movements that do not contribute to balance control.
- Do not alter the SAM: \( H_C\dot{\theta}_{rl} = 0, \dot{\theta}_{rl} \neq 0 \)

Contributing motion synergies: \( \dot{\theta}_{SAM} \in R(H_C^+) \)
The segment movements that contribute to balance control.
- Alter the SAM: \( H_C\dot{\theta}_{SAM} \neq 0 \)

4. AM conservation strategies

SAM conservation strategy
Cancel the CRB-AM with the CAM (\( \dot{\theta}_{SAM} \))
\( (\omega_C = 0 \Rightarrow \Delta\omega(\dot{\theta}_{SAM}) = -\omega_P) \)
Useful to avoid self-destabilization.

CAM conservation strategy
Generates reactionless synergies.
- The segments move but the body behaves as a CRB.
  \( (\omega_C = \omega_P \Rightarrow \Delta\omega(\dot{\theta}_{rl}) = 0) \)
- 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)
\[ \dot{\omega}_C = I_C\omega_B + H_C\theta + c_m \]
nonlinear term

The relative angular acceleration (RAA)
\[ \Delta\dot{\omega} = \dot{\omega}_C - \dot{\omega}_P \]

Past work: the RNS filter [4]
Extract reactionless synergies from motion capture data.
\[ \dot{\theta}_{moc} = \dot{\theta}_{rl} + \dot{\theta}_{SAM} \]
joint acceleration from motion capture

The AM damping mechanism
SAM damping: \( \omega_C^{ref} = 0 \Rightarrow \omega_C^{ref} = -D_\omega\omega_C \)
CAM damping: \( \Delta\omega^{ref} = 0 \Rightarrow \Delta\omega^{ref} = -D_\omega\Delta\omega \)
nonnegative damping gain
6. Experimental system

- Motion capture (moCap) system
  - Infrared camera
  - Joint motion: $\dot{\theta}_{\text{moc}}$
  - Pelvis motion: $\omega_P$
  - Force plate
  - GRFs: $f_{fp_i}$

- CoP variation due to the R.C. of SAM and the GRF [1]
  \[ \Delta \bar{r}_p = -\frac{1}{f_{C3}} (r_c \bar{f}_C + S^\top \hat{I}_C) \quad f_C = \sum_{i=1}^{4} f_{fp_i} \quad S^\top = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \]

- 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

- 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


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)