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Dynamic operation of a human-like three-segmented leg during bouncing gaits

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I. Background

- Multimodal locomotion (standing, walking and running) is supported by **three-segmented leg** operation
- Previous work [1] investigated leg configuration stability in the static case
- Little is known about the **leg segment dynamics** during bouncing gaits

Our question:

How individual elastic structures at the joint level influence the kinematic and dynamic leg behavior?

II. Methods

Initial leg configuration
$\Delta\theta_0 = (\theta_{K,0} - \theta_{A,0})$

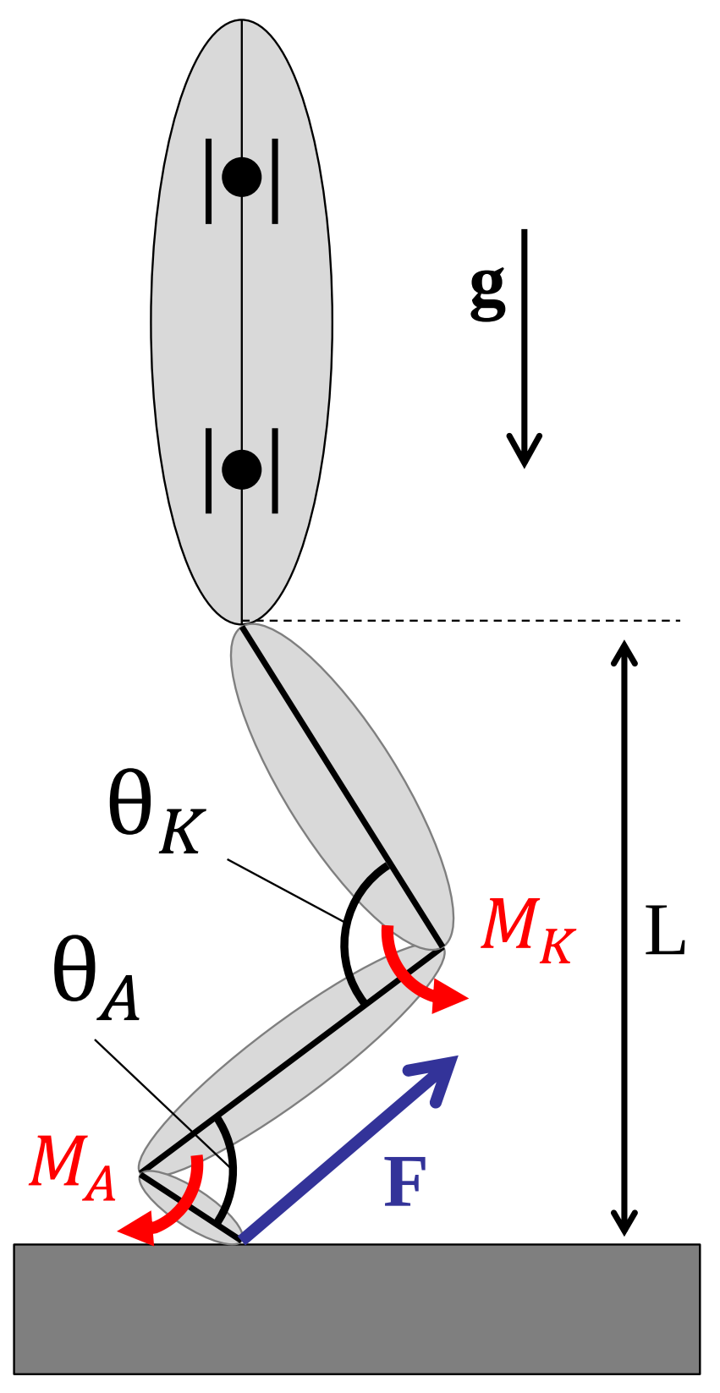


Figure 1: Simulation model. The motion of the trunk is constrained to 1D vertical motion. Segment properties are taken from [2]

Task: Passive rebound after free-fall drop

Monoarticular structures

$$M_A = c_A(\theta_{A,0} - \theta_A)$$

$$M_K = c_K(\theta_{K,0} - \theta_K)$$

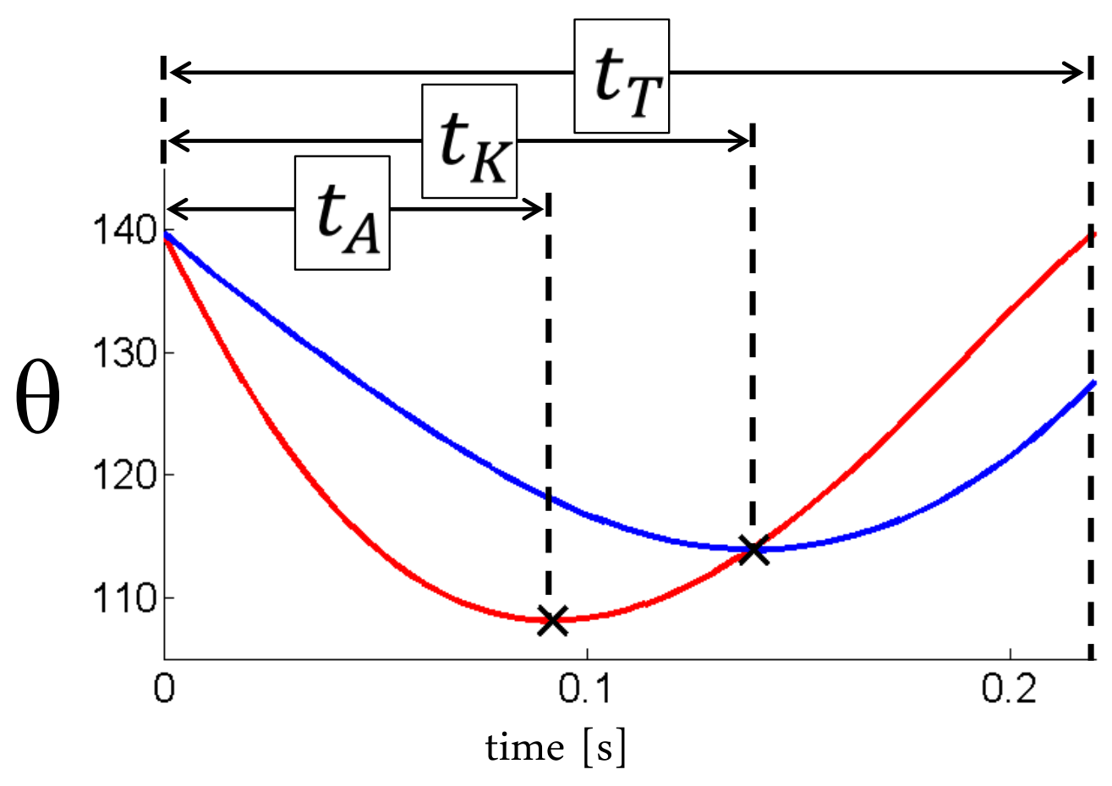


Figure 2: Example of the time series of the ankle (red) and knee (blue) joint angles. The indicator of the coordinated motion of both joints, the phase difference $\Delta\varphi$, is computed using the timing of the maximum flexion events, t_A and t_K for the ankle and knee respectively.

Bi-articular structure (Gastocnemius)

$$\theta_{Gas} = (\theta_{A,0} - \theta_A) - r_{Gas}\,(\theta_{K,0} - \theta_K)$$

$$M_{Gas} = c_{Gas}\theta_{Gas} + d_{Gas}\dot{\theta}_{Gas}$$

$$M_{A,Gas} = \max(0, M_{Gas})$$

$$M_{K,Gas} = \max(0, -r_{Gas}\,M_{Gas})$$

ratio of lever arms at knee and ankle joints (i.e. l_K/l_A)

Leg operation indexes:

Kinematics: **Synchronous flexion**

Phase difference: $\boxed{\Delta\varphi = |(t_K - t_A)/t_T|}$

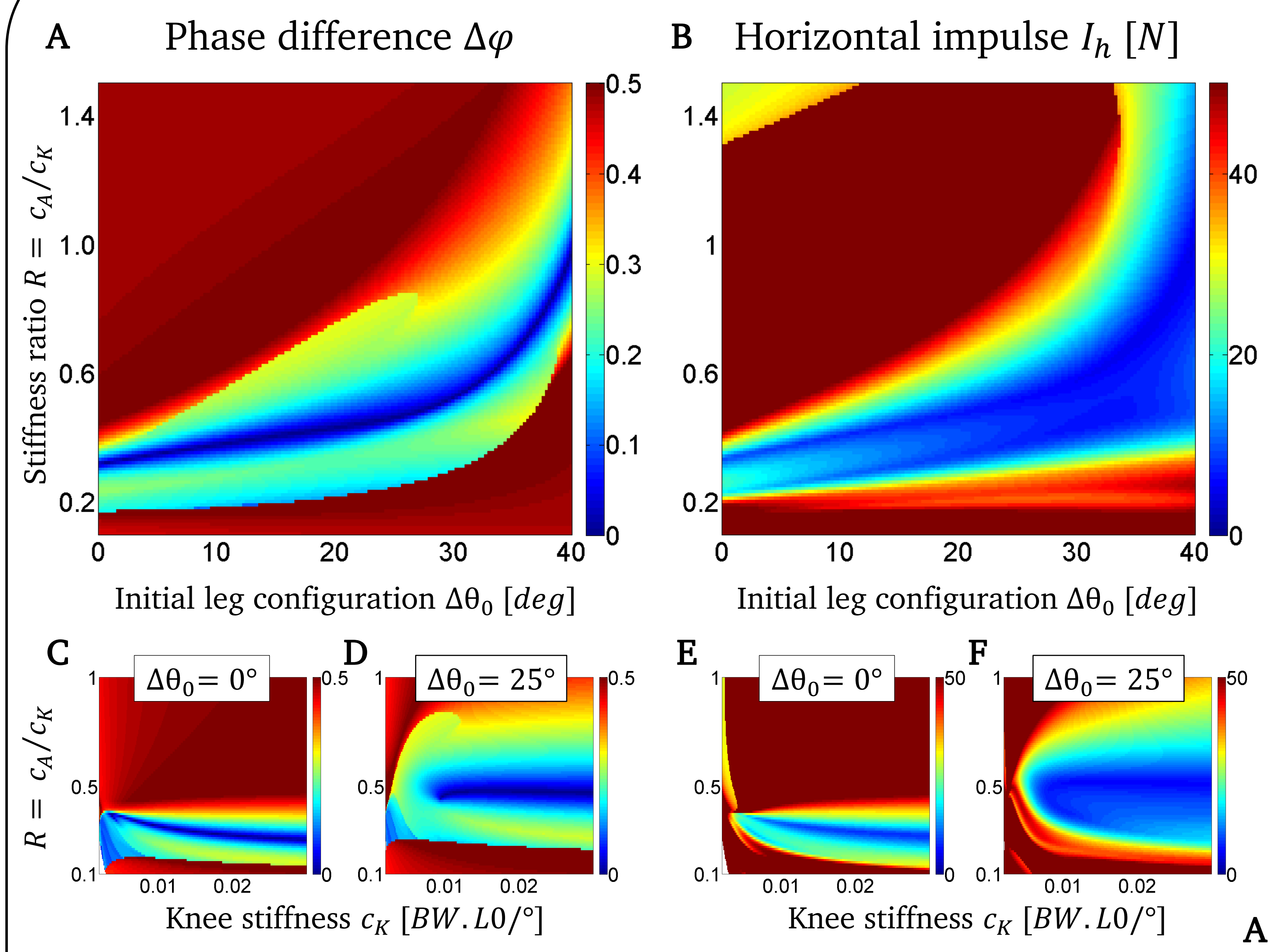
Dynamics: **GRF direction**

Horizontal impulse during the stance phase

$$\boxed{I_h = \int_0^T |F_h|\,dt}$$

F_h : horizontal force

III. Results

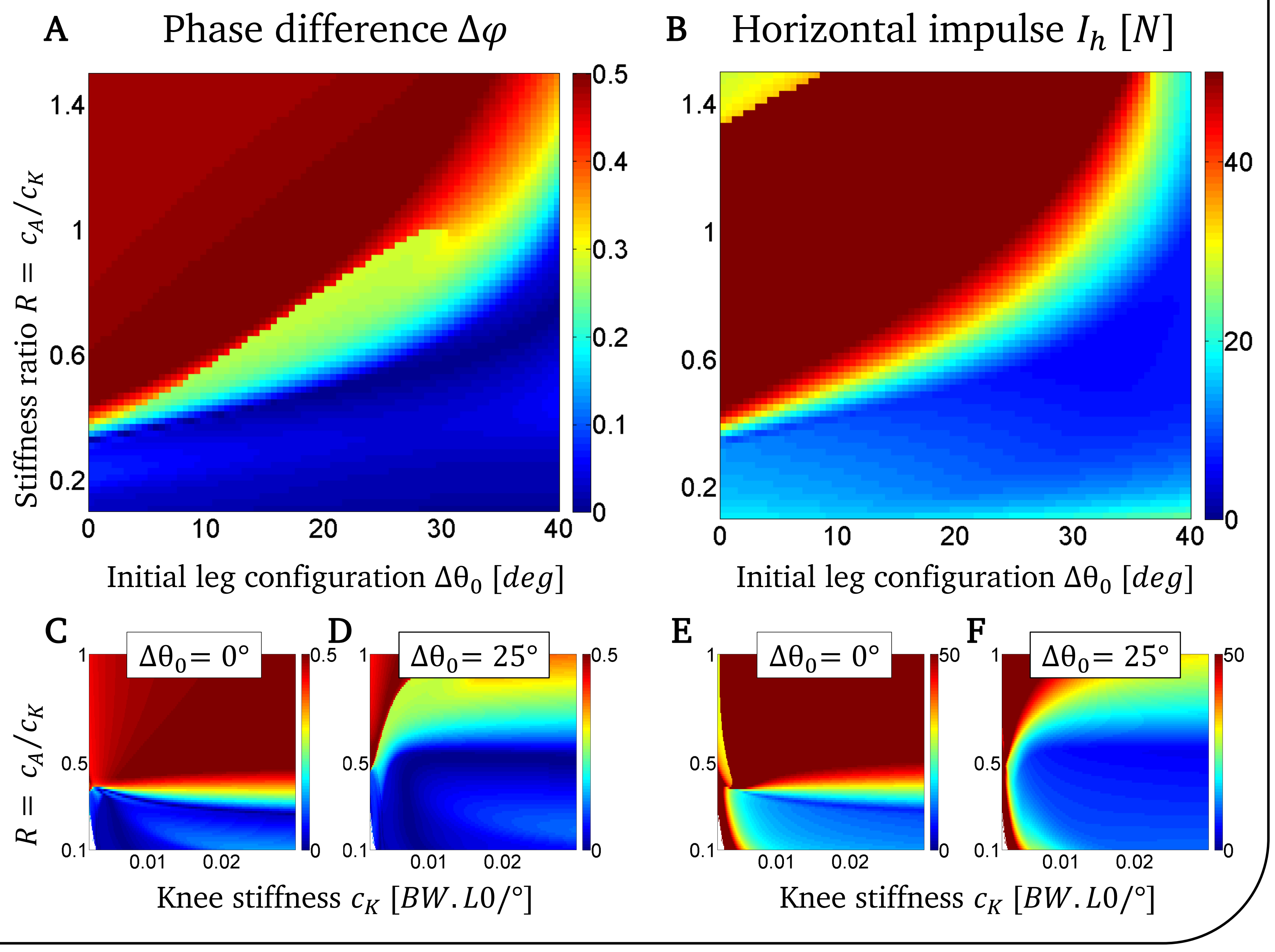


A. Monoarticular structures only

- Good performance with respect to both indexes (i.e. synchronous flexion of knee and ankle joints and low horizontal forces) can be achieved with the same joint stiffness adjustments (Fig.3-A,B)
- The stiffness ratio R must be adjusted depending on the initial leg configuration $\Delta\theta_0$ (Fig.3-A)
- Asymmetric leg configuration ($\Delta\theta_0 > 0$) reduces the sensibility of the behavior w.r.t. to stiffness changes (compare Fig.3-C,E to Fig.3-D,F)

← Figure 3: Simulation results with knee and ankle monoarticular structures
A & B: influence of the stiffness ratio R and the initial leg configuration $\Delta\theta_0$ on the performance indexes: phase difference $\Delta\varphi$ and horizontal impulse I_h - C to F: influence of the absolute stiffness values on the same indexes ($\Delta\varphi$ for C & D and I_h for E & F) for two initial leg configurations

Other parameter values: drop height $= 0.08\,L_{max}$; $L_0 = 0.94\,L_{max}$



B. Mono- and biarticular structures

- The biarticular structure (mimicking the Gastocnemius) compensates for insufficient ankle stiffness (Fig.4-A,B), even with small values of the stiffness c_{Gas}
- As a result, synchronous flexion of both joints is obtained in a much larger range of stiffness ratios R. This holds for different initial leg configurations $\Delta\theta_0$ (here shown for 0° and 25°, Fig.4-C,D)

Figure 4: Same graphs as Fig. 3 with the mono- and biarticular structures →

Other parameter values: drop height $= 0.08\,L_{max}$; $L_0 = 0.94\,L_{max}$
$r_{Gas} = 2$; $c_{Gas} = 0.1\,c_K$; $d_{Gas} = 0.5\sqrt{c_{Gas}}$

References: [1] A. Seyfarth, M. Guenther and R. Blickhan, Biol. Cybern., 84, 365-382, 2001
[2] H. Geyer, H.M. Herr, IEEE Trans Neural Syst Rehabil Eng 18(3): 263-273, 2010.

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