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Feedback pathway compositions for hopping - influence of changes in body morphology and ground compliance

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1 Introduction

Legged animals manage to maneuver over a huge variety of soft (e.g. grass, sand, mud etc.) and hard grounds (e.g. urban or stony environments). Neural networks in the spinal cord significantly contribute to control these motions in order to generate efficient and stable locomotion [1–4]. For hopping on changing ground properties (e.g. ground stiffness or damping) an adaptive behavior of the system (animal or robot) enables robust and safe locomotion. Previous studies on human hopping suggest that an important strategy for the motor control system is to maintain similar center of mass (CoM) dynamics [5,6]. This is achieve by changes of the muscle activation pattern (due to feed-forward and feedback contribution) [2–4] and intrinsic muscle-mechanical adaptations which account for an instantaneous leg stiffness adjustment [1,7]. Still, it remains unclear how different sensory reflex pathways (of different proprioceptive signals) are used - in parallel or in isolation - to control the adaptive behavior of leg extensor muscles.

In this simulation study we aim at better understanding the reflex mechanisms in hopping on changing body morphology (tendon elasticity) and environmental conditions (ground stiffness). We want to explore the capabilities of a monosynaptic feedback loops to cope with these changes. We consider different combinations of sensoric pathways (length, force and velocity feedback) in a fused model which controls one leg extensor muscle in a simple hopping model. By evaluating the generated motion with respect to stability, performance (hopping height) and efficiency (metabolic cost) we investigate the influence of elastic structures regarding the proper composition of the reflex pathways.

A deeper understanding of the contribution of different reflex pathways and their combinations under different body morphologies (e.g. tendon compliance, prostheses) and environmental changes (e.g. ground properties) may help to improve control policies for robotic and assistive systems.

2 Methods

To alter (1) the serial elasticity and (2) the ground stiffness we use to models (Figure 1A and B). Considering [8], both hopping models are comprised of a point mass (m), two massless leg segments (length l_s) and a leg extensor muscle-tendon-complex (MTC), consisting of a contractile element (CE) and a serial elastic element (SE). For alterations of the SE elasticity (Model A), three configurations of the SE reference strain are used: (1) 'stiff configuration' (0.01), (2) 'moderate configuration' (0.03) and (3) 'compliant configuration' (0.05). Ground stiffness manipulations (Model B) are modeled by changing the linear spring constant (k_{ground}): (1) 'compliant ground' (100 kN/m), (2) 'stiff ground' (500 kN/m), (3) 'reference ground' (9999 kN/m).

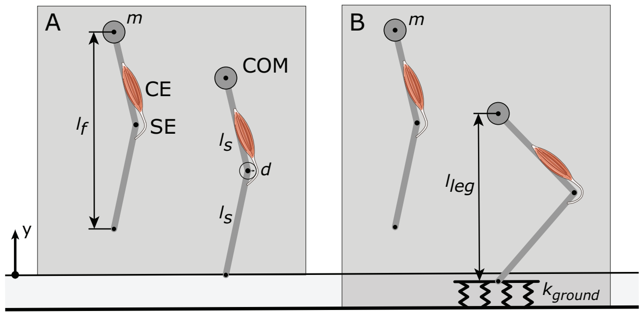

Figure 1: Hopping models in flight and stance: **(A)** SE elasticity and **(B)** ground stiffness (k_{ground}) alterations.

In order to investigate the individual and fused contribution of multiple feedback pathways on the hopping performance, we extend the neuromuscular feedback model of [8]. To generate an activation signal of the CE, all three feedback signals (FFB: muscle force F_{ce}, LFB: fibre length l_{ce}, VFB: fibre velocity v_{ce}) are multiplied by a blending factor ($\lambda_{F,L,V}$) to weight the individual pathways: $S(t) = \lambda_F * G_F * F_{ce}/F_{max} + \lambda_L * G_L * (l_{ce} - L_{off}) + \lambda_V * G_V * (v_{ce} - V_{off})$. The dimensionality of the spanned parameter space is reduced by restricting the sum of all three blending factors [9]: $\lambda_F + \lambda_L + \lambda_V = 1$, $0 \leq \lambda_{F,L,V} < 1$. We use the hopping height (h_{max}) at apex ($v_y = 0$) to evaluate the motion performance.

3 Results

Figure 2 shows the predicted (Model A) hopping height of all possible feedback combinations which resulted in stable hopping for three different serial elasticities. Increasing compliance generates higher hopping heights. For all serial elasticities, highest hops are found close to single FFB. Increasing contribution of VFB reduces the hopping height. When changing the ground stiffness Model B produced stable hops over a range of ground stiffness ($100 - 9.999$ kN/m). Figure 3 reveals similar results compared to SE elasticity changes.

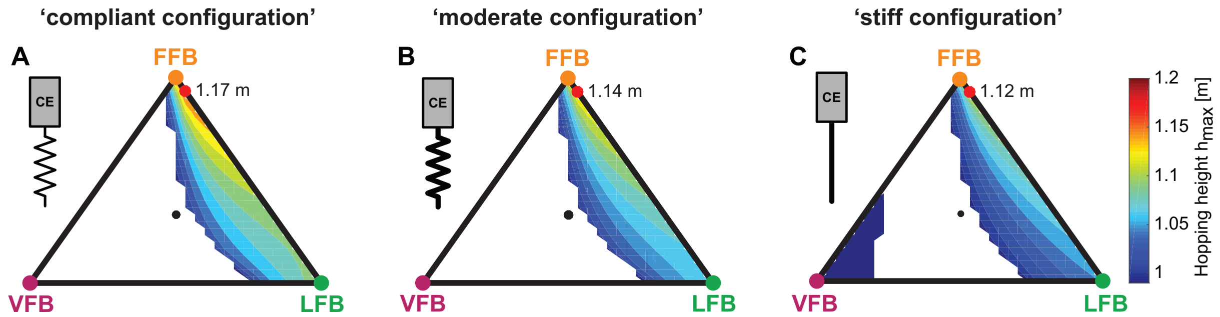

Figure 2: Maximum steady-state hopping height of blended feedback signals for **three different SE elasticities**: **(A)** 'compliant', **(B)** 'moderate' and **(C)** 'stiff configuration'. Every point within the triangle represents a unique combination of the three feedback pathways: corners of the triangle represent a full contribution of one single feedback (e.g. 100% FFB, 0% VFB, 0% LFB), while the middle point describes an equal composition of all feedback pathways (33.3% FFB, 33.3% VFB, 33.3% LFB). Unstable predictions and maxima are visualized by white areas and red points respectively.

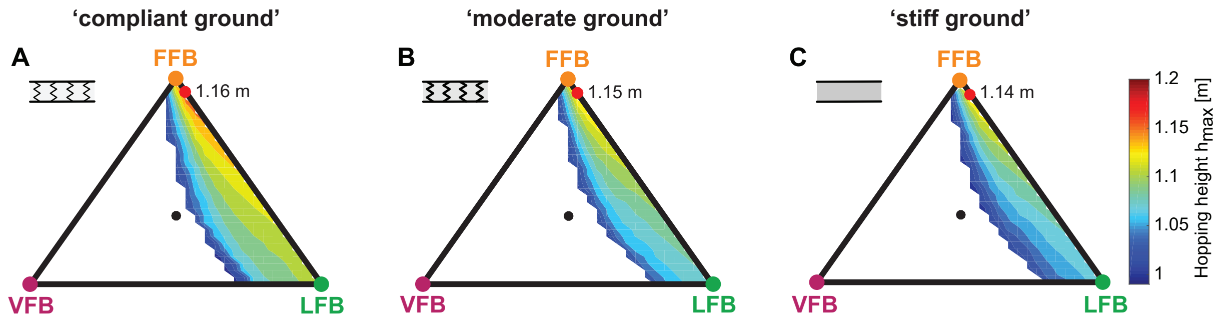

Figure 3: Maximum steady-state hopping height of blended feedback signals for **three different ground stiffness**: **(A)** 'compliant', **(B)** 'moderate' and **(C)** 'stiff ground'.

4 Discussion

Increasing compliance of the system and its environment resulted in an enhanced motion performance. Changes in the body morphology (serial elasticity) or the environment (ground stiffness) showed no influence on the distribution of stable feedback compositions. Also, the predicted hopping performance and the location of the global maxima seem to be consistent for both modifications. Thus, the neuromuscular feedback system seems to be independent to stiffness alterations of the interacting mechanical structures. This consistency might be beneficial for the motor control system as changes of the (stable) solution space would require effort to control the recruitment of feedback pathways.

As we used a highly simplified hopping and feedback model its adaptive behavior does not reflect complex response behaviors. Still, previous simulations with similar simple feedback models were able to generate robust and adaptable behavior for hopping and walking motions [4, 8, 10].

For proof-of-concept we aim at implementing this approach for fusing multi-sensoric feedback pathways on a robotic hopping leg, called *MARCO Hopper II* [11]. Preliminary results may be available until the conference (AMAM 2017).

References

[1] Moritz, Chet T., and Claire T. Farley. "Passive dynamics change leg mechanics for an unexpected surface during human hopping." *Journal of Applied Physiology* (2004)

[2] Zuur, Abraham T., et al. "Contribution of afferent feedback and descending drive to human hopping." *The Journal of Physiology* (2010)

[3] Taube, Wolfgang, Christian Leukel, and Albert Gollhofer. "How neurons make us jump: the neural control of stretch-shortening cycle movements." *Exercise and Sport Sciences Reviews* (2012)

[4] Haeufle, D. F. B., et al. "Integration of intrinsic muscle properties, feed-forward and feedback signals for generating and stabilizing hopping." *Journal of The Royal Society Interface*(2012)

[5] Ferris, Daniel P., and Claire T. Farley. "Interaction of leg stiffness and surface stiffness during human hopping." *Journal of Applied Physiology* (1997)

[6] Farley, Claire T., et al. "Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses." *Journal of Applied Physiology* (1998)

[7] Van Der Krogt, Marjolein M., et al. "Robust passive dynamics of the musculoskeletal system compensate for unexpected surface changes during human hopping." *Journal of Applied Physiology* (2009)

[8] Geyer, Hartmut, Andre Seyfarth, and Reinhard Blickhan. "Positive force feedback in bouncing gaits?." *Proceedings of the Royal Society of London B: Biological Sciences* (2003)

[9] Seyfarth, Andre, Michael Günther, and Reinhard Blickhan. "Stable operation of an elastic three-segment leg." *Biological Cybernetics* (2001)

[10] Geyer, Hartmut, Andre Seyfarth, and Reinhard Blickhan. "Compliant leg behaviour explains basic dynamics of walking and running." *Proceedings of the Royal Society of London B: Biological Sciences* (2006)

[11] Oehlke, Jonathan, et al. "Template-based hopping control of a bio-inspired segmented robotic leg." *Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on. IEEE* (2016)