Modular control of locomotion in simulated hypogravity

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Summary

Skipping, an asymmetric gait rarely used on Earth, is often observed in hypogravity, as seen during the Apollo missions to the Moon. What drives astronauts to adopt this gait? To address this question, we analysed muscle synergies during walking, running, and skipping at Earth and simulated Mars and lunar gravity levels. We found that skipping emerges from pre-existing neuromuscular patterns associated with running. This adaptation, likely largely facilitated by central pattern generators in the spinal cord, may explain why astronauts are intuitively drawn to skipping in hypogravity.

Introduction

On Earth, the main forms of human locomotion are walking and running. Unilateral skipping, an asymmetric gait often adopted by children, is rarely used by adults. However, during the Apollo missions to the Moon, astronauts frequently skipped unilaterally, reportedly for a "sense of security" [1]. Indeed, *in vivo* and *in silico* experiments have shown that skipping has mechanical and metabolic advantages over walking and running in low gravity environments [2, 3]. Studying the motor control strategies that underlie locomotion at different levels of gravity may shed new light on why astronauts intuitively choose skipping to move in hypogravity: a question that is critical for defining future lunar suited surface operations and unsuited lunar habitats [4].

Methods

Twelve participants (5 female, 31 ± 6 years) walked, skipped and ran at 1.1, 1.4, and 3.1 m/s, respectively, on a treadmill (Bertec) at three gravity levels: Earth (1.00 g), Mars (0.38 g) and Moon (0.17 g), yielding nine locomotion conditions. Hypogravity was simulated using an elastic body weight support system [3]. Bilateral electromyographic (EMG) activity was recorded (Delsys, 2 kHz) from the *vastus lateralis*, *semitendinosus*, *biceps femoris*, *tibialis anterior*, *gastrocnemius lateralis*, and *soleus*. Gait cycles were segmented to the touchdown of the leading leg (LL) for walking and running, and the trailing leg (TL) for skipping. Muscle synergies, composed of time independent muscle weights (i.e. the relative muscle contributions within each synergy) and time dependent activation patterns, were extracted via non-negative matrix factorisation using the R package *musclesyneRgies* v1.2.5 [5]. We fitted mixed effects statistical models including fixed (gait mode, gravity level) and random (intercept varying by subject) effects.

Results and Discussion

Five synergies sufficiently reconstructed the EMG activities, with no effect of gait mode ($p = 0.111$) or gravity level ($p = 0.575$). Four functional synergies were clustered by *k-means* for all locomotor conditions. In walking, these synergies described 1) the LL weight acceptance and early swing, 2) the LL propulsion and the TL late swing, 3) the TL weight acceptance and early swing, 4) the TL propulsion and the LL late swing. In running, synergies described 1) the LL weight acceptance and propulsion, 2) the TL swing, 3) the TL weight acceptance and propulsion, 4) the LL swing. Skipping shared similar activation patterns with running, but with a reordering of muscle weights: the weights of synergy 1 and 2 in running were those of synergy 3 and 4 in skipping. When running EMG activities were reconstructed with the skipping weights without reordering, the reconstruction quality was lower than that obtained with the reordered weights ($p < 0.001$), independent of the gravity level ($p = 0.028$, all pairwise *post-hoc* comparisons $p < 0.001$).

Conclusions

Although skipping is an asymmetric gait mode, it is produced by muscle activation patterns derived from running with a reordering of muscle weights. This similarity may partly explain why astronauts choose skipping as an alternative gait mode when moving on the Moon.

References

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