

PREDICTIVE SIMULATION OF GAIT AT LOW GRAVITY USING DIRECT COLLOCATION

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INTRODUCTION

Predictive simulations of gait have several applications that range from prostheses design to planning of surgical interventions. The conventional approach to solve the optimal neuromuscular control problem is represented by the work of Anderson and Pandy (2001). However, the overwhelming computational cost arising from the necessity of multiple numerical integrations of the system differential equations prevents its wider use.

Direct collocation (DC) is an alternative approach that reduces the computational burden by avoiding forward simulation. It also allows straightforward inclusion of task-related boundary conditions such as periodicity and forward movement. DC has been used in aeronautics and aerospace engineering (Betts, 1998) and was first employed to solve a neuromuscular optimization problem by Kaplan and Heegaard (2001). Here we use direct collocation to generate predictive simulations of gait in different gravitational environments.

METHODS AND PROCEDURES

The musculoskeletal model used is described elsewhere (Gerritsen et al., 1998) and is composed of seven segments actuated by eight Hill-type muscle models at each leg. The model has 50 state variables in x : 9 generalized coordinates, 9 generalized velocities, 16 muscle contractile element lengths, and 16 muscle activations. The interaction between ground and feet is

modeled by means of 10 spring-damper elements distributed along the foot sole. The dynamics of the model is described as

$$\dot{x} = f(x, u), \quad (1)$$

where u is the vector of neural excitations to the muscles. Assuming symmetry, the period of half a gait cycle is divided into n nodes, resulting in discretized time histories of the states and the neural excitations. The differential equations (1) are transformed into a set of algebraic constraints by a finite difference scheme, with additional periodic boundary conditions, as

$$x_k - x_{k-1} = f(x_k, u_k) \Delta t. \quad (2)$$

A cost function that quantifies muscle “effort” is adopted as

$$J = \frac{1}{(n-1) \sum V_i} \sum_{i=1}^{16} V_i \sum_{k=1}^{n-1} a_{i,k}^2, \quad (3)$$

where $a_{i,k}$ is the i^{th} muscle activation at node k , and V_i is volume of muscle i . The SNOPT optimization code (<http://www.tomlab.biz>) was used to minimize cost function (3), while requiring (2) to be satisfied.

RESULTS

Figure 1 shows predicted gait cycles for the four simulated scenarios: Earth ($g=9.8\text{m/s}^2$) at 1.1m/s; Mars ($g=3.72\text{ m/s}^2$) at 1.1m/s, Moon ($g=1.63\text{m/s}^2$) at 1.1 and 2.0 m/s, with $n=50$.

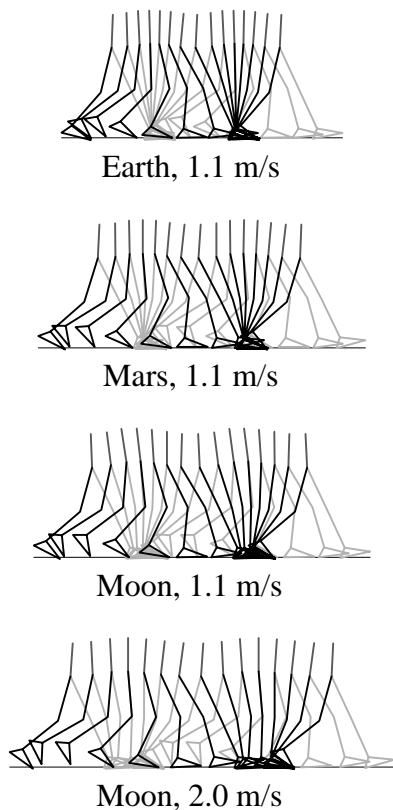


Figure 1. Predicted whole gait cycles for different speed and gravity conditions.

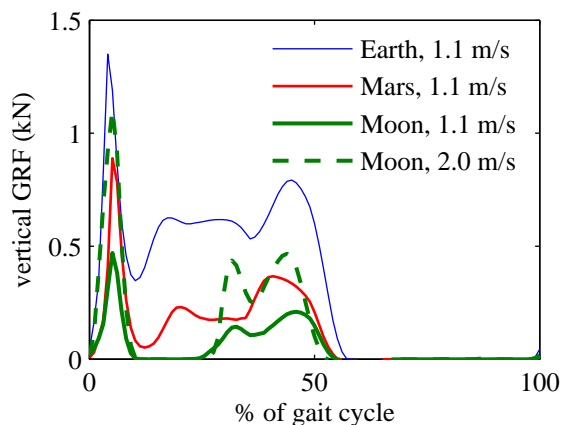


Figure 2. Ground reaction forces for the gait predictions shown in Figure 1.

Figure 2 shows the vertical ground reaction forces for the same conditions.

DISCUSSION

Normal-looking walking is predicted on Earth at 1.1 m/s. However, some details are different from typical normal gait, including a straight-leg pattern in the stance phase and high impact forces after heel-strike. These deviations will be the focus of future investigation by the authors.

On Mars, walking is predicted as the more “efficient” locomotion strategy at 1.1 m/s, although with significantly lower ground reaction forces than the occurring in walking on the Earth at the same speed. Reducing gravity to Moon levels further decreased predicted ground reaction forces and revealed an extra flight phase in the first half of the gait cycle, suggesting that skipping is a more “efficient” locomotion strategy than walking at 1.1 m/s and 2.0 m/s. This is consistent with the locomotion strategy favoured by astronauts from the Apollo Missions (Minetti, 1998). The extra flight phase may allow muscles to work more efficiently by increasing step length and decreasing cadence.

REFERENCES

- Anderson, FC and Pandy, MG (2001). *J Biomech*, 34:153-63.
- Betts, JT (1998). *J Guid Control Dynam*, 21:193-207.
- Gerritsen, KGM et al. (1998). *Motor Control*, 2:206-20.
- Kaplan, ML and Heegaard, JH (2001). *J Biomech*, 34:1077-83.
- Minetti, AE (1998). *Proc R Soc Lond B*, 265:1227-35.

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