EFFECTS OF EXTERNAL LOADING ON OPTIMIZATION PREDICTION OF VERTICAL GROUND REACTION FORCES DURING 0G WALKING

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Abstract: A model was developed to investigate how the vertical ground reaction forces (GRFs) are affected by variation of the external load (EL) applied to the body during locomotion in microgravity. The model predicts that more variation in the EL leads to larger magnitudes in GRF impact peaks and smaller magnitudes in GRF propulsive peaks.

Introduction

During long-term space missions, treadmill exercise is performed as an exercise countermeasure. An external load (*EL*) must be applied to the astronauts to return them to the treadmill during locomotion. The *EL* characteristics may be critical to the maintenance of bone mass [1]. On Earth, gravity provides the EL.

On the International Space Station (ISS), the astronauts wear a harness that is attached to the subject loading device (SLD) either with non-compliant extender straps or compliant bungees that pull them down to the treadmill during exercise. Originally, bungees were intended as a contingency if the SLD broke down, but instead they have become the most commonly employed method of loading. The problem with bungee loading is its non-linear force-length relationship resulting in an applied *EL* that can vary by 10-15% due to normal vertical oscillations of the center of mass during locomotion [2]. This variation in *EL*, which does not occur in normal g, could result in GRF trajectories that are different than on Earth.

The goal of this study was to use a computational model to investigate how the variations in applied EL affected the predicted vertical GRFs produced during locomotion in microgravity.

Methods

We used an existing 3D, 14 segment, 27 DOF full-body dynamical model along with published overground gait data [3]. The equations of motion were derived with Kane's method using Autolev symbolic manipulation software (OnLine Dynamics, Sunnyvale, CA) that accounts for gravity terms, which were then set to zero. Autolev was also used to derive the forces and torques on the pelvis created by the harness pulling on the subject. These equations were incorporated into a Matlab program (The Mathworks, Natick, MA) that performed inverse dynamics optimizations to predict gait patterns during microgravity.

Figure 1: Schematic of the 27 DOF full-body gait model used to perform predictive gait optimizations.

A variable force that simulated the bungee load was applied to the center of mass of the pelvis in the model. Simulations were completed with EL variations of 0%, 10%, 20%, and 30% BW. The mean and standard deviation data used to formulate the external loading equation was adopted from Schaffner et al. [2] for a subject walking at 1.34 m/s (3 mph), which is similar to the speed used for our model (1.4 m/s). The equations for the equivalent pelvis forces and torques (resulting from the applied external load) were calculated about the center of mass of the pelvis assuming quasi-static conditions. These equivalent forces and torques were applied to the existing model in lieu of gravitational forces acting on the pelvis. The predicted GRF magnitudes were compared with published data from Schaffner et al. [2]. The equation used to simulate the bungee forces acting on the subject in microgravity was

$$EL = -(x/0.66) * \cos((2\pi/0.25) * ST/2) + 0.55 \qquad (1)$$

where *EL* is the external load as a percentage of body weight, ST is the stride time or percentage of the gait cycle, 0.55 is the mean load as a percentage of body weight during walking in 0G [2], x is the mean standard deviation of each trial (how much the EL varies within a trial) as a percentage of body weight [2] (0%, 10%, 20%, and 30%), and 0.66 corrects for the variation due to the standard deviation. The period of the load curve was adjusted so that the maxima occurred at midstance and the minima occurred during double-support for one gait cycle (heelstrike to heelstrike) (Fig. 2). The maxima and minima of the loading curves correspond with the maxima and minima in height of the body center of mass that occur during the normal gait cycle.

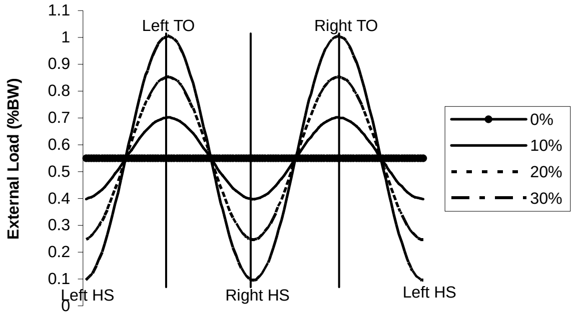

Figure 2: External load curves. HS: heel strike, TO: toe off

Results

The application of a simulated variable bungee force to the model reproduced a similar impact peak magnitude for a 30% BW variation and a similar propulsive peak magnitude for a 10% BW variation to that reported by Schaffner et al. [2] (Table 1, Experimental (0G); Fig. 3). The combined differences between experimental and simulated peak and impact GRFs were the least during the 20% variation simulations.

Table 1: Approximate magnitudes of impact (first) and propulsive (second) GRF peaks based on experimental data [2] and the model at four levels of EL variation

	Impact Peak Magnitude (N)	Propulsive Peak Magnitude (N)
Experimental (0G)	715	466
0% EL variation	581	487
10% EL variation	620	461
20% EL variation	676	409
30% EL variation	717	379

Discussion

Schaffner et al. [2] showed the magnitude of the propulsive peak is less in 0G (Table 1, Experimental (0G)). The difference between the model curves and the experimental vertical GRF (VGRF) curve could be due to the differences in the subjects used for data collection and for the model, although some of this variability was controlled by putting the GRFs in terms of a percentage of BW. Additionally, there may be hysteresis in the bungee loading resulting in EL variations that are not symmetrical throughout the gait cycle. Also, the bungee loads may need to be modeled more accurately.

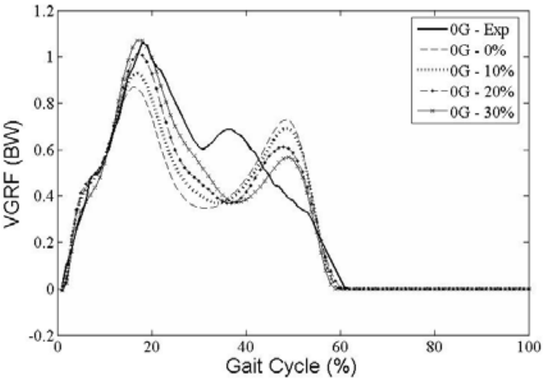

Figure 3: Predicted 0G VGRF curves using different levels of external load compared to experimental data

Other scenarios were investigated with this model. When the EL was set to 100% BW with no load variation, the model predicted the vertical GRF to be similar to that occurring in 1G [2]. We also investigated a baseline EL of 70% BW, but the predicted propulsive peaks were higher than the experimental values we were trying to predict.

Our computational environment may aid in the design of subject loading devices that optimize the effects of treadmill exercise in maintaining the bone, muscle, and cardiovascular heath of astronauts.

References

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