JOINT MOMENTS ARE COORDINATED TO STABILIZE VERTICAL ENDPOINT FORCES DURING HUMAN LOCOMOTION

Jasper Yen[1] and Young-Hui Chang[2]

[1] Dept. of Biomedical Engineering, Georgia Tech and Emory University, Atlanta, GA, USA
[2] School of Applied Physiology, Georgia Tech, Atlanta, GA, USA
E-mail: jaspery@gatech.edu Web: www.ap.gatech.edu/chang/cnlyhchang.html

INTRODUCTION

Because joints of the human leg are redundant for endpoint force production, there are infinite joint moment trajectory solutions for any given endpoint force trajectory. Therefore, there should exist a "buffer", or an uncontrolled manifold (UCM), where joint torques may vary without affecting the endpoint force. We hypothesized that locomotor systems do not choose specific joint moment trajectories during the locomotor cycle but instead allow solutions to vary within the UCM.

Previous studies have suggested similar hypotheses for upper extremity tasks.[1] The stability of a task level variable was assessed through across-trial variability. For each time point, the variance of local degrees of freedom was measured and split into two components: that which lay in the UCM (redundant variance) and that which lay outside the UCM (task error variance). If redundant variance was greater than task error variance, then the task level variable was deemed to be stabilized.

The purpose of the present study was to determine if joint moments are coordinated to vary within the UCM to stabilize endpoint force during human locomotion. We used human hopping because of its simple and reliable mass-spring-like dynamics, and it is a minimal locomotor behavior that can be studied under highly controlled conditions.[2]

METHODS

Sagittal plane kinematics and ground reaction forces were collected at 120 and 1080 Hz respectively from seven healthy, right-leg dominate subjects that gave informed consent to participate in this study. Subjects hopped in place on their right leg at frequencies of 2.2, 2.8, and 3.2 Hz. Three trials of each condition were collected in a random order for 30 seconds each. 30 hops were taken from each trial and pooled from each frequency condition for analysis.

We used a three link biomechanical model relating ankle, knee, and hip moments to endpoint force. The null space of the model represents the UCM. We normalized time and calculated the variance of joint moments for every one percent of stance phase. For each time point, we calculated the Redundant Fraction (RF) of total variance that lay in the UCM. An $RF > 0.5$ indicated that the joint moments were being coordinated to stabilize endpoint force.

RESULTS AND DISCUSSION

Variations of joint moments and GRF were evident from hop to hop. No clear correlation between joint moment variability and endpoint force variability, however, was evident without employing the UCM analysis. In accordance with the UCM hypothesis, coordination of joint moments acted to stabilize the vertical component of endpoint force (Fv).

Fv was stabilized at the beginning, middle, and end of stance phase (Figure 1). While redundant variance increased as the mean Fv value increased through the middle of stance, the task error variance decreased at mid-stance. This suggested that joint moments were coordinated synergistically to reduce Fv variability.

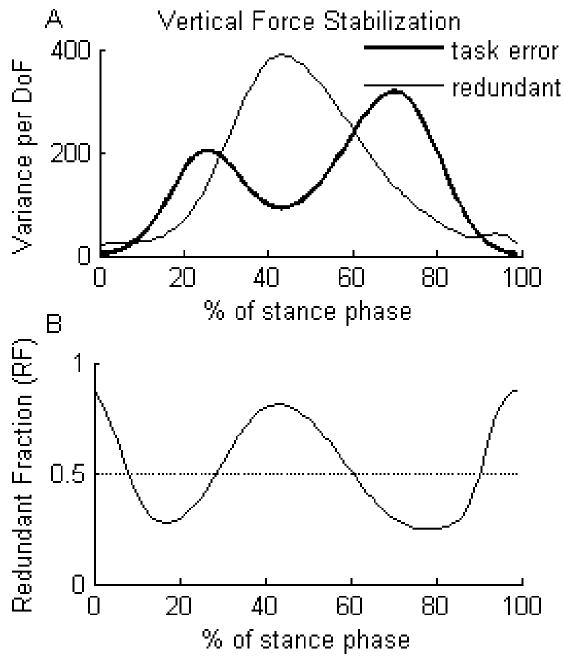

Figure 1: Total joint moment variance of a representative subject hopping at 2.2 Hz. The total variance was split into two components: task error and redundant (A), and RF was calculated as redundant / (redundant + task error) (B).

To test whether our results could be explained by interjoint coordination, any such coordination was artificially removed by randomly shuffling the joint moments at each time point. Hops were reconstructed by matching joint moments from random hops and re-running the UCM analysis. With no coordinating strategy, the RF during mid-stance was decreased to approximately 0.5, which corresponds to a random distribution of variance within and outside of the null space (UCM).

We did not observe significantly different control strategies for different hopping frequencies. The strategy employed between subjects was consistent. In contrast to Fv, the horizontal component of endpoint force (Fh) was consistently destabilized (RF < 0.5) throughout stance.

SUMMARY/CONCLUSIONS

Humans appear to coordinate joint moments to stabilize vertical endpoint force during hopping. Control of endpoint force generated by the leg may be especially important during mid-stance to ensure proper vertical acceleration of the CoM. Proper acceleration in this experimental scenario is linked to meeting the prescribed hopping frequency. The destabilization of Fh likely corresponded to subjects attempting to hop in place without looking down at their feet as instructed.

Redundant variance had the same unimodal trajectory as the average Fv trajectory. Task error variance had the same bimodal trajectory as the average time derivative of Fv. These results are in agreement with previous UCM analysis on finger force production tasks[3].

REFERENCES

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