Effects of Increased Task Difficulty on Performance Variable Stabilization during Human Locomotion

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INTRODUCTION

Evidence for the simplification of motor control of kinematic performance variables during human locomotion exists in areas of biomechanics, neurophysiology, computational neuroscience, and robotics[1,3,4,6]. Human hopping in place is the simplest form of a human bouncing gait that can be modeled as a spring-mass system [2,5]. We recently showed that leg length and orientation are stabilized (i.e., decreased variance) through the purposeful structuring of joint angle variance during human hopping[1]. Our data showed that overall leg length stabilization increased as hopping frequency increased while leg orientation stabilization showed no change (**Fig. 1**). Hopping at non-preferred frequencies likely created a more difficult task that required increase stabilization of leg length. As the index of difficulty (ID) for an upper extremity task increases, local variable variance becomes increasingly structured to stabilize the performance variables in local variables [8]. The purpose of this study is to test more directly whether greater task difficulty during locomotion causes increased structuring of variance to meet the increased demands of stabilizing leg orientation.

The Uncontrolled Manifold (UCM) analysis allows us to analyze whether segment angle variance is structured to exploit motor redundancy and stabilize a kinematic performance variable [7]. We investigated 2.2Hz one-legged human hopping in place with increased demands for foot placement precision to study the use of motor abundance in stabilizing leg length and leg orientation. Increased foot placement precision requires a smaller margin of error for take-off and landing leg orientation but should have little effect on leg length demands. We hypothesized that a task with a higher ID for foot placement precision will result in increased structure of joint angle variance to stabilize leg orientation but not leg length.

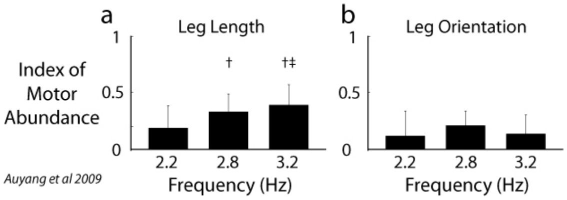

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Fig. 1. Average Index of Motor abundance (IMA) shows selective stabilization of **(a)** leg length and **(b)** leg orientation at three hopping frequencies. Data are average IMA ±1 standard deviation (n=10). †denotes significant difference from 2.2 Hz ($p<0.01$). ‡ denotes significant difference from 2.8 Hz ($p<0.01$).

METHODS

Subjects hopped on their dominant leg at 2.2Hz on three different target sizes (88, 213, and 466mm^2) while 3-D lower body kinematics data were collected. Target sizes constrained foot placement thus requiring increased precision. Target sizes were determined using Fitts' Law which describes a relationship between the distance traveled of the end effector and the target size, where smaller targets correspond to greater ID. Sagittal plane segment angles (Vicon) were calculated using Matlab. We ran the UCM analysis for each performance variable (leg length and leg orientation) at 1% bins over the entire hopping cycle for all hops (~62 hops per condition). The UCM analysis tells us whether motor redundancy is used to stabilize the performance variables leg length and orientation by selecting a certain set of goal oriented joint kinematic combinations. We calculated an Index of Motor Abundance (IMA, [1]) at each time point to test whether subjects selectively utilized motor redundancy in the joints to stabilize each performance variable, indicated by an IMA greater than 0. IMA was averaged across 100% of the hopping cycle for Fig. 1 and 3.

RESULTS

Preliminary data from 2 subjects showed that as the index of difficulty (ID) increased (i.e., smaller targets), the average total variance of the four segment angles (foot, shank, thigh, pelvis) also increased (**Fig. 2**). Overall variance of leg orientation, however, decreased (**Fig. 3**) as ID increased. UCM results of both subjects showed higher ID resulted in increased coordination of segment angles to stabilize leg orientation (**Fig. 4b**) but not leg length (**Fig. 4a**).

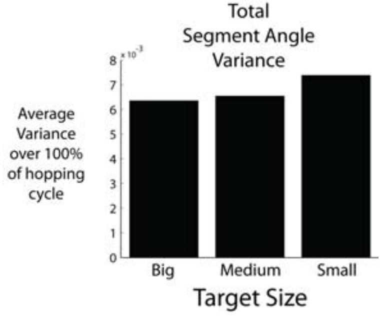

Fig. 2. Average total segment angle variance over 100% of the hopping cycle for leg orientation when hopping with increased ID i.e. smaller targets. Representative subject.

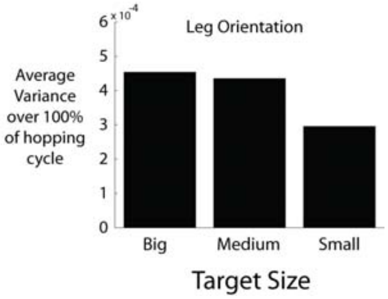

Fig. 3. Average variance over 100% of the hopping cycle for leg orientation when hopping with increased ID i.e. smaller targets. Representative subject.

DISCUSSION

Preliminary results support our hypothesis that utilization of motor redundancy can be appropriately and selectively up regulated to meet increased locomotor task demands. By constraining the target landing area, landing and take-off angle of the leg become increasingly important to completing the task. The average variance over 100% of the hopping cycle reveals that as difficulty of the task increases, leg orientation variance decreases despite increases in total segment angle variance. Furthermore, our results from a UCM analysis show that as task difficulty increases, IMA for leg orientation also increases while IMA for leg length does not (**Fig. 4**). These results explain how a lower leg orientation variance in a more difficult locomotor task (**Fig. 3**) can be achieved through increased interjoint coordination (**Fig. 4b)**.

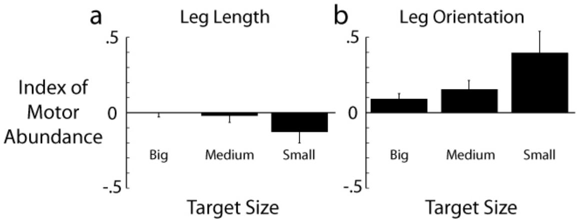

Fig. 4. Average Index of Motor abundance (IMA) ±1 standard deviation **(a)** for leg length and **(b)** leg orientation at three target sizes. Preliminary data for 2 subjects.

Our preliminary findings suggest that as task performance is increasingly constrained, the locomotor system responds with greater exploitation of motor redundancy by both increasing use of those joint kinematics combinations that meet the performance goal and decreasing combinations that do not meet the performance goal. This also shows evidence for how interjoint coordination might be used to stabilize performance variables when presented with real world task constraints caused by different gait pathologies and neuromuscular injuries.

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