INTRODUCTION

Humans can stably locomote in the real world while being constantly subjected to multiple task constraints. The goal of this study was to investigate how stabilization of task level variables leg length and leg orientation changes when presented with locomotor task constraints. Our previous study showed that leg length and leg orientation are task level performance variables that are stabilized through the structuring of segment angle variance during human hopping in place [1]. We also found that as subjects hopped at non-preferred frequencies, there was an increase in the structuring of variance to stabilize leg length [1]. We determined the amount of task variable stabilization by quantifying the Goal-Equivalent Variance (GEV) and Non-Goal Equivalent Variance (NGEV) components of leg segment angle variance using an Uncontrolled Manifold approach [1,2]. The purpose of this study was two-fold. First, to determine if applying a leg orientation constraint through requiring accurate foot placement would elicit an increase in leg orientation stabilization. The second purpose is to determine how stabilization of leg length and leg orientation is affected when both variables are simultaneously constrained by both an accurate foot placement constraint and a toe clearance constraint.

Subjects hopped in place into a square target projected onto the ground. Three target sizes were used to vary task difficulty according to Fitts’ Law. We reasoned that decreasing target size should increase the need for leg orientation stabilization, as small errors in leg orientation during the small target task would lead to subjects hopping outside of the target. We hypothesized that as target size decreases, leg orientation stabilization should increase.

To constrain both leg length and leg orientation, we again constrained foot placement using different size targets, but this time during a forward hopping task on a treadmill. During hopping in place, leg length is stabilized during mid-stance while leg orientation is stabilized during mid-aerial phase [1]. The swing phase of forward locomotion has the added constraint of toe clearance. Consequently, we expect to see stabilization of both leg length and leg orientation in the aerial phase. With smaller targets during forward hopping, we hypothesized that leg orientation stabilization would increase due to the smaller targets while leg length stabilization sees no effect from changes in target size.

METHODS

Eleven subjects hopped in place and forward on a treadmill moving at 0.8 m/s on their dominant leg at 2.2Hz into three different targets (88, 213, and 466mm$^2$). 3-D lower body kinematics data were collected (VICON). Target sizes were determined using Fitts’ Law which describes a relationship between the distance traveled by the end effector and the target size. Sagittal plane segment angles were calculated using Matlab. An Uncontrolled Manifold (UCM) analysis was performed for each performance variable (leg orientation and leg length) at 1% bins over the entire hopping cycle for all hops (~180 hops per condition). The UCM analysis quantified the amount of kinematic motor redundancy used to stabilize either performance variables leg length or orientation [1,2,3]. The Index of motor abundance was calculated as the difference.
between GEV and NGEV divided by the sum of GEV and NGEV ((GEV-NGEV)/(GEV+NGEV)).

We calculated the IMA 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 results were further binned into each 10% of the hopping cycle.

RESULTS
Mean leg orientation stabilization across the entire hopping cycle increased and mean leg length stabilization decreased as target size decreased during hopping in place (Fig. 1a). There were no changes in mean leg orientation or leg length stabilization during forward hopping (Fig. 1b). Peak leg orientation stabilization was in aerial phase for both hopping in place and forward hopping and all target conditions (Fig. 2g-l). Leg length stabilization had a peak at mid stance during hopping conditions (Fig. 2a-f) and a second peak in swing phase during forward hopping (Fig. 2d-f).

DISCUSSION
The purpose of this study was to investigate the effects of specific constraints on task level performance variables. As we hypothesized, we found that as the target landing area got smaller during hopping in place, the subjects responded by increasing overall stabilization of leg orientation (Fig. 1a). This is consistent with the leg length stabilization changes we previously observed when an appropriate leg length constraint was placed on the task [1]. This suggests that when a constraint is placed on a task critical performance variable, there is increased structuring of kinematic variance to stabilize the appropriate performance variable.

The second purpose of our study was to determine how stabilization of leg length and leg orientation would change when simultaneously constrained through a toe clearance and accurate foot placement constraint. In forward locomotion, the importance of toe clearance requires that leg length also be stabilized during swing phase along with the typical leg orientation stabilization (Fig. 2d). With smaller targets during forward hopping, there was no change in leg length or leg orientation IMA. Further analysis reveals that the solution spaces for leg length and leg orientation stabilization are orthogonal to each other. While leg length and leg orientation can be individually stabilized when only one variable is critical to the task, when both need to be stabilized during the aerial phase of forward hopping, variance is appropriately structured to stabilize both leg length or leg orientation. Motor redundancy is maximized when task variables are stabilized only when necessary. This redundancy is then available to respond when additional task constraints are presented, such as with unexpected obstacles or even with neuromuscular injury.

REFERENCES