Contribution of Joint Torque Coordination to Vertical Force Stabilization during Human Locomotion is Speed Dependent

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INTRODUCTION

High level performance task variables can be stabilized by structuring low level elements redundant for the task to vary within a goal equivalent solution space, or Uncontrolled Manifold (UCM) (Scholz & Schöner 1999). We previously found that humans hopping in place vary joint torques within the UCM to stabilize vertical force at the beginning middle and end of stance (Yen & Chang 2007). This stabilization can be due to a coordination of joint torques when the UCM lies obliquely to joint torque axes (Fig. 1A). Alternatively, when the UCM aligns with one or more joint torque axes, minimization of independent variance along the remaining joint axis is the sole contributor to performance stability (Fig.1B). Actual behavior likely reflects some combination of these two extremes (Fig.1C).

We hypothesized that the contribution of coordinated joint torque variance would decrease with increased hopping frequency due to the adoption of extended leg postures.

METHODS

We collected sagittal plane kinematics (120 Hz) and ground reaction forces (1080 Hz) from 11 subjects hopping in place on their right leg at 2.2, 2.8, and 3.2 Hz. Three trials were collected at each frequency and pooled for analysis (~100 hops). We created a three-link biomechanical model related ankle, knee, and hip torques to vertical end-point force (vGRF). The null space of the model represented the UCM. For every 1% of stance phase, we calculated relative amount of joint torque variance residing in the UCM as the Index of Motor Abundance for vGRF stabilization (IMA, Tseng & Scholz 2005). $\text{IMA} > 0$ indicates vGRF stabilization by structuring joint torque variance along the UCM.

We then permuted the data set into one containing every possible ankle, knee, and hip torque combination to nullify stabilization through interjoint coordination (Müller & Sternad 2003). E.g., a data set of 100 hops would result in 100$^3$ total hop cycles. We re-ran the IMA analysis on the permuted data set to distinguish the fraction of IMA due only to independent joint variance (IV-IMA). Subtracting this from IMA left only the contribution of coordinated joint torque variance (CoV-IMA).

RESULTS

At 2.2 Hz, the vGRF stabilizing joint torque variance ($||\text{UCM}||$) was unimodal in shape with a peak at mid-stance, while the destabilizing variance was bimodal (Fig.2A). The resulting IMA was ‘W’-shaped (Fig.2B).
IV-IMA revealed the source of vGRF stability at foot contact (Fig.2C). CoV-IMA retained its peak at mid-stance (Fig.2D).

**Fig.2.** Representative subject at 2.2 Hz. A) ||UCM and ‖UCM variance components. B) IMA. C) IV-IMA. D) CoV-IMA.

IMA retained the ‘W’ shape and exhibited little change across frequencies (Fig.3A). IV-IMA also did not change substantially with frequency. CoV-IMA decreased dramatically with frequency (Fig.3B). The extended leg posture at foot contact resulted in alignment of the UCM plane within 4° of the hip torque axis, 20° of the knee torque axis and 70° of the ankle torque axis.

**DISCUSSION**

The contribution of joint coordination to vertical force stability decreased as hopping rate increased. Yet, overall task stability was maintained at all frequencies. At high frequencies, greater alignment of the UCM plane with the hip and knee joint torque axes effectively decreased the influence of joint coordination on vGRF stability. This greater alignment was due to the increasingly extended limb postures adopted by our subjects at high frequencies. At these extended limb postures, the ankle joint was nearly orthogonal to the UCM plane and stability of vGRF was achieved by minimizing independent joint variance at the ankle joint.

**SUMMARY**

Two different strategies exist for structuring joint torque variance to stabilize vGRF during human hopping. Both strategies simplify control of vertical force generation during hopping through either coordinated action from multiple joints or through localized control of a single joint. Coordinating variance across the joints is the predominant contributor to vertical force stability at slow frequencies. At faster rates, an extended leg posture mechanically constrains the hip and knee torque axes within the UCM such that the controller need only minimize ankle torque variance independently. The degree to which each strategy contributes to task stability is rate dependent. Translational studies in walking and running may elucidate the ubiquity of these intralimb compensation principles for able-bodied and pathological locomotion.

**REFERENCES**


