WHOLE-BODY LOCAL DYNAMIC STABILITY DURING WALKING AND RUNNING

Mu Qiao, and Devin, L. Jindrich

Department of Kinesiology and Center for Adaptive Neural Systems
Arizona State University, Tempe, AZ, 85287, USA
email: Mu.Qiao.2@asu.edu, web: http://www.limblab.org/

INTRODUCTION

Highly-simplified models of walking and running can show passive dynamic (i.e. mechanical) stability[1-2]. Although these models capture many important aspects of locomotor dynamics, the extent to which they can describe the stability properties of human locomotion is still unclear. Human locomotion involves coordinating many degrees of freedom (DOFs), which are coupled (mechanically, kinematically, and neutrally) in the control of multi-joint moments. Humans also commonly perform maneuvers (acceleration and deceleration, for example) in addition to constant-velocity locomotion. Several studies have focused on reducing multiple DOFs in a static behavior[3] or on the dynamic behavior of single DOF[4]. However, using individual DOFs to characterize locomotor stability could be incomplete because 1) some DOFs such as joint angles and vertical COM are constrained to limited ranges; 2) individual DOF may only reflect local dynamic behavior, and not the dynamics of the entire system[4]. Moreover, the effects of different maneuvers or gaits on dynamic stability have not been fully characterized. For example, walking might be expected to be more stable than running because there are more opportunities for continuous neural feedback to contribute to stability[5]. This study therefore sought to characterize whole body within-stride stability by analyzing many DOFs. We used Principal Component Analysis (PCA) and calculated Lyapunov exponents on the 1st principal component, which accounts for limb rotation with minor translation[3], to determine the stability among body DOFs within a stride[4]. Specifically, we hypothesized that 1) different joint DOFs do not show differences in stability properties during locomotion; 2) constant speed walking or running is more stable than acceleration or deceleration; 3) walking is more stable than running.

METHODS

We used a VICON® 612 3-D motion tracking system (120Hz), and two force platforms (Bertec) to record kinematics and Ground Reaction Forces (GRFs) (3000Hz). The platforms were obscured by a 120cm × 160cm, 2mm-thick rubber mat. 18 male participants (age = 27.2 ± 4.2yrs; body weight = 70.8 ± 8.3kg; height = 178.9 ± 7.3cm) performed 6 trials in each of 6 locomotion tasks: running and walking at constant velocity, acceleration, and deceleration.

RESULTS AND DISCUSSION

Across all trials the 1st principal component of generalized coordinates (x) ($R^2 = 0.75\pm0.1$) and corresponding time derivatives (y) ($R^2 = 0.65\pm0.2$) accounts for considerable variance. By reconstructing whole-body kinematics using x, motion is constrained to relative limb rotation motion with minor translation[3]. By using x and y together to reconstruct the system's mechanical energy (translational, rotational, and potential energy) and comparing it with original mechanical energy still shows considerable matching (Fig. 2). This again verifies x and y capture fundamental aspects movement dynamics. Fig. 3 shows a representative of $x(t)$ with delays in 3-D space. In each trial Lyapunov exponents were calculated from x, vertical COM, left elbow and left knee. Positive Lyapunov exponents, which indicate an unstable
system, were found for within-stride dynamics during both running and walking.

![Figure 2](image1.png)

**Figure 2:** Raw and reconstructed whole body mechanical energy. (Top, running; Bottom, walking, lower bars indicates stance phase)

![Figure 3](image2.png)

**Figure 3:** Reconstruction of \( x(t) \) in 3D-space using time delayed copies of \( x(t) \). (Left constant speed running; Right, constant speed walking)

For \( x \) a two-factor (gait; speeding) repeated measure ANOVA showed a significant main effect: running is more unstable than walking \((p < 0.01)\) (Fig. 4, UL). Although not significant, all Lyapunov exponents are greater in running than walking. In contrast, if only vertical COM is used (Fig. 4, UR), although running is more unstable than walking manifested by a higher Lyapunov exponent, it is not significant \((p = 0.08)\), and speed has main effect \((p < 0.05)\). This suggests that using only COM dynamics alone may over-simplify the system's behavior. Similarly, using only data from select DOFs such as individual joint angles (left elbow (Fig. 4, LL, significant interaction, \( p < 0.05 \)), left knee (Fig. 4, LR, no main effect)) can result in conflicting conclusions and may only reflect local dynamic behavior. These conflicts show that individual joints may not effectively represent the whole system's dynamic behavior. Moreover, using \( x \) to capture the dynamics of many DOFs shows that movements of the entire body (Fig. 4, UL) may be less stable than individual DOFs such as the vertical COM (Fig. 4 UR).

![Figure 4](image3.png)

**Figure 4:** Lyapunov exponent as a function of speeding and gait. (Upper Left (UL), \( x \); Upper Right (UR), vertical COM; Lower Left (LL), left elbow; Lower Right (LR), left knee)

**CONCLUSIONS**

Our results suggest that stability analysis of individual DOFs may not faithfully capture the dynamics of the entire body during locomotion. The current results focus on within-stride dynamics of the whole body. Humans appear to show less within-stride stability than stability over multiple strides, which has been measured by several studies[4]. Running is more unstable than walking, and maneuvers involve additional decreased stability. These results suggest that considering segmental dynamics and interactions is important for evaluating locomotor stability.

**REFERENCES**