Does lower-limb angular velocities scale linearly with walking speeds?

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INTRODUCTION

During human locomotion, lower limb segments form two kinematic chains linked at the pelvis and oscillates back and forth repetitively. The angular motion of each segment (foot, shank and thigh) is inherently constrained by the adjacent segments. Therefore, the movement for each segment is not totally independent and there exists a high degree of redundancy in the kinematic data for each segment due to the kinematic constraints as well as the 180° phase shift between the left and right leg. Previous work has demonstrated the kinematic co-variance between the elevation angles of lower limb segments [1]. Through principle component analysis (PCA), invariant features have been discovered that are independent of the walking speeds. However, little is known about the relationship between waveforms at different speeds, or one step further, whether there exists a linear relationship between the human gait waveforms at one walking speed compared to another. If a linear relationship does in fact exist, the brain or central pattern generator (CPG) could use this simple linear model to regulate the limb kinematics to produce walking at a predefined speed. Therefore, the objective of this paper is to determine whether the lower limb angular velocities scale linearly with walking speeds.

METHODS

Data collection: One subject was instructed to walk on a treadmill at 0.8, 1.0, 1.2, 1.4 or 1.6 m/s. Segment angular velocity data for both limbs were collected with an inertial sensor measurement system (XSENS MVN) with sensor placed on both feet, shanks, and thighs. For consecutive 10 gait cycles, a 101×6 matrix \( P \) was constructed for each gait cycle at each of the five walking speeds, which contains the sagittal plane angular velocities for all the six limb segments. Dimensionality reduction: PCA was first used to reduce the dimensionality of the data from five different speed (50×101×6 matrix) and eliminate the redundancies in the angular velocity measurements [2]. The first three principle components covers over 95% of the overall variance of the original data. Each set of data \( P \) (101×6) was reduced to a score matrix \( S \) (101×3). As the original angular velocities contain two frequency components, we were able to further reduce the data of the score matrix \( S \) using a model of two Sine functions at two different frequencies. After the model, the original angular velocity at one speed can be represented by a 42×1 velocity vector.

Angular velocity synthesis: with the angular velocity vectors \( W \) from speeds at 0.8 m/s and 1.6 m/s, we like to determine whether there is a linear model to synthesize the angular velocity data for other speeds (1.0 m/s, 1.2 m/s and 1.6 m/s). PCA was used again on the matrix \( W \) (a 42×20 matrix containing 10 angular velocity vectors from 0.8 m/s and 10 from 1.6 m/s). Within the new linear space, the angular velocity vectors are separated linearly through a linear classifier with a parameter \( \alpha = -1 \) at 0.8 m/s and \( \alpha = 1 \) at 1.6 m/s. With an \( \alpha \) varies between \([-1 1]\), we were able to linearly extrapolate the angular velocity vectors between the walking speeds at 0.8 m/s and 1.6 m/s.

RESULTS

The synthesized angular velocity waveforms at speed 0f 1.0 m/s (\( \alpha = -0.5 \)) and 1.4 m/s (\( \alpha = 0.5 \)) are almost identical to the measured angular velocity waveforms at the same speeds (Fig.1).

Figure 1: Synthesized measured angular velocities at 1.0 m/s and 1.4 m/s (thin black curves: measured; thick green curve: synthesized).

DISCUSSION AND CONCLUSIONS

The results confirm that there is a linear model that links the lower limb angular velocity waveforms between different walking speeds. This finding indicates that CPG may use a single scalar signal as input to generate a proper kinematic patterns when changing walking speed.

REFERENCES


ACKNOWLEDGEMENTS

I'd like to think A. Selagea-Popov for the assistance in data analysis.