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Largest Lyapunov Exponents of Ankle, Knee and Hip Flexion during Gait

Olivia McGleish, Wei-Qing Tan, Sophie Hill, Emma Hayashibara, Helena Watson, Philip Riches

University of Strathclyde, Glasgow, United Kingdom

Introduction

Chaos is the deterministic yet non-periodic behaviour of a system [1]: every chaotic cycle is physically determined by an unbroken chain of observations, but which gives results that appear unpredictable [2]. Chaos theory has been applied to gait variability previously (e.g. [3], [4]) and may be useful in providing an insight into the biomechanical effect of musculoskeletal pathology [3]. Current technology facilitates extensive data collection, ideal for gait variability studies, and we wished to utilise this capability to simultaneously investigate variability in ankle, knee and hip flexion over a 20 minute period.

Research Question

We aimed to assess gait variability by quantifying the chaotic behaviour of hip, knee and ankle joint flexion in healthy participants over a 20 minute time period to form a baseline healthy population measure.

Methods

7 participants (1 male, 6 females, height 168 +/- 7.95 cm, mass 61.1 +/- 9.25 kg) had the lower body Plug-in-Gait marker set attached, utilising a knee alignment device to assist in marker positioning. No participants were injured at the time of testing and self-certified their ability to walk for up to 30 minutes on a treadmill at a comfortable pace. Institutional ethical approval was approved in accordance with the Declaration of Helsinki.

Using the D-Flow control system, the treadmill was set to self-paced mode and the participants determined their comfortable walking speed. Volunteers walked at this pace on a dual belt treadmill with incorporated force plates, a safety harness, and a 180° projection screen (Motek CAREN Extended system) for 20 minutes separated into four 5-minute epochs. Twelve Vicon motion cameras captured marker trajectories at 100 Hz which were subsequently filtered with a fourth-order Butterworth filter, with a cut-off frequency of 10 Hz. A minimum of 1,000 strides was achieved for all participants during which right and left ankle, knee, and hip angles were calculated. Standard Vicon algorithms determined ankle, knee and hip flexion.

Largest Lyapunov exponents (LLEs), calculated using an open source function on Matlab (Mathworks, US), quantified the chaotic nature of the joints during gait [1]. LLEs greater than zero represent chaotic behaviour: the larger the positive Lyapunov exponent, the more chaotic the system, and consequently, a shorter timescale of predictability [1].

A full factorial repeated-measures ANOVA was performed on LLE measures to ascertain any differences between joint, side (left or right) or epoch. Significance was assumed if $p <= 0.05$.

Results

The average walking speed across all participants was 1.34±0.25 m/s.

LLEs ranged between 0.7 and 2.45. LLE significantly varied with joint ($p < 0.001$). The ankles demonstrated the highest LLEs, followed by the knees, then the hips. There was a potential tendency for the left side to have higher LLEs than the right ($p = 0.067$). No statistical differences were identified with epoch and no interaction effects were found between the variables.
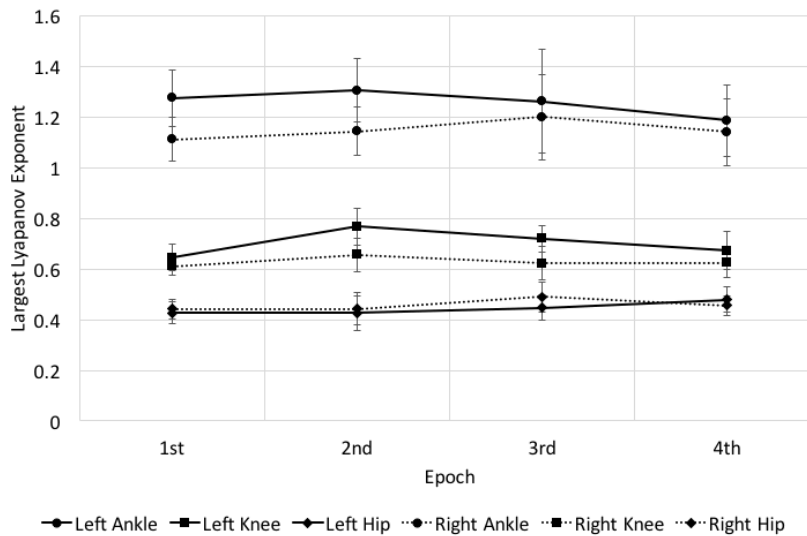
Figure 1: LLE values for each joint across the four epochs (n=7, mean +/- one standard error)

Discussion

LLEs obtained for all joints were greater than zero, indicating that hip, knee and ankle flexion, and hence gait, is chaotic. Distal joints were more chaotic compared to proximal joints indicating increased variability and potentially alluding to a reduction in the ability to control lower limb joint movement distally. Left sided joints potentially were more chaotic than right-sided, again alluding to potential differences in neuromuscular control. Data were consistent with time indicating both a repeatability of the measure over this time period and a lack of fatigue.

Repeatable chaotic measures have been determined for the lower limb joints, which may vary with the joint neuromuscular control. This suggests that these quantitative measures may be useful to diagnose and monitor the rehabilitation of lower limb musculoskeletal pathologies.

References

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