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Quaternions and joint angles in an analysis of local stability of gait for different variants of walking speed and treadmill slope

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ABSTRACT

The authors describe an example of application of a nonlinear time series analysis directed at identifying the presence of deterministic chaos in human gait kinematic data by means of the largest Lyapunov exponent (LLE). A positive LLE value is interpreted as an indicator of local instability. The research was aimed at assessment of the influence of both walking speed and ground slope on the resilience of gait control to infinitesimally small perturbations that occur naturally during walking. The analysis of treadmill gait data was carried out twofold: 1) for the time series representing the following joint angles: hip flexion/extension, knee flexion/extension and dorsiflexion/plantarflexion of the ankle, and 2) for the time series representing rotations of foot, tibia and femur segments through Euler angles converted to a quaternion representation. A comparison between both approaches as well as a dependency between treadmill inclination and LLE values constitute the original aspects of this study. The LLE value was estimated threefold for every time series: as the short-term LLE for both the first step and the first stride and as the long-term LLE over a fixed interval between the fourth and the tenth stride. It was confirmed that all considered movements are characterized by positive LLE values which quantify a local instability. Moreover, a tendency to attenuate the perturbation consequences is evident in all variants of walking speed and treadmill slope.

1. Introduction

A dynamical system is any system that evolves in time [20]. The state of a dynamical system at a given instant of time can be represented by a point in the phase space spanned by the state variables of the system. Successive points form a trajectory.

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Dynamics properties of a system can be determined on the basis of its model (provided that it is known) consisting of differential or difference equations or through an analysis of experimental data collected as a result of the system observation.

Many nonlinear or infinite-dimensional dynamical systems exhibit chaotic behavior. The presence of deterministic chaos is characterized by extreme sensitivity to initial conditions. This hallmark means that initially nearby points in the phase space can evolve quickly into very different states. In the case of an analysis of experimental data, fundamental components of the process of determining the existence of chaos in a signal represented by a time series are a phase space reconstruction and subsequent estimation of the Lyapunov exponents which quantify the average exponential rate of divergence of initially nearby phase space trajectories [20]. Thus, a positive value of the largest Lyapunov exponent (LLE) implies chaotic behavior.

Chaoticity was observed in a variety of systems from several areas including, among others, meteorology, physics, biology, economics and engineering. Chaotic dynamics exhibited by mobile robots interacting with the environment and behavior of passive dynamic bipeds are examples from robotics [45]. EEG, ECG and gait kinematic data are noteworthy among biomedical signals.

The chaotic characteristics of ECG signals (Lyapunov exponents spectrum, correlation dimension) were incorporated into a set of features for the purpose of biometric individual identification [6] but, first of all, the chaos theory has been applied to an analysis of an electrocardiogram for examination of cardiac disorders [7].

Chaos is also present in epileptic EEG signals. The brain activity during a seizure differs greatly from that of the normal state which can be observed as a decrease in chaoticity in the minutes before the seizure. Thus, an analysis of the changes in the LLE allows detection and prediction of the incoming epileptic seizure [30,32].

Detection of the presence of deterministic chaos with reference to human locomotion is closely linked to the problem of gait stability. Stability can generally be defined as the capacity of a system to respond to perturbations [13]. In the case of human locomotion it is necessary to mention that, depending on the size of a perturbation, gait stability can be divided into a global dynamic stability and a local one. *Global* stability is related to larger perturbations, such as tripping or slipping [13], whereas methods for estimating LLE from gait kinematic data provide a promising means for direct quantifying *local* dynamic stability (LDS) [10], which means, the degree of resilience of gait control to infinitesimally small perturbations that occur naturally during walking and are manifested as natural kinematic variability [13,39]. The LLE can be used to quantify the exponential attenuation of variability between neighboring kinematic trajectories [14]. The aforementioned perturbations are the result of internal and external influences – small variations in a walking surface, as well as natural noise present in the neuromuscular system [40]. These disturbances, resulting in stride-to-stride[1] differences in kinematic measurements, are attenuated in time – at least within the current stride and possibly across subsequent strides[2] – by a neuro-controller and musculoskeletal system in order to maintain a stable walking pattern. This interaction between the nervous and musculoskeletal systems which produces a desired effect or response to a stimulus is called neuromuscular control [17]. It is worthwhile to mention that positive LLE values indicate local instability – the larger the LLE, the greater the sensitivity to local perturbations.

The results based on thorax movements show different effects of walking speed on walking stability for different directions [5]. And as far as running is concerned, the influence of both speed and use of a leg prosthesis on the dynamic stability expressed by means of the LLE for subjects with and without unilateral transtibial amputations was studied in [27].

Another approach quantifying stability from experimental data was based on the Floquet multipliers and was used for post-polio patients [21]. However, this method, in contrast to the LLE, requires the assumption of strict periodicity of human walking, whereas humans do not walk in an exactly periodic manner [12]. A decrease in walking stability of elderly subjects in the lateral plane was reported in [1] on the basis of an analysis of variability of the center of mass using the approximate entropy (ApEn) technique. Both approaches – LLE and ApEn – were used to quantify local stability and to measure variability, respectively, in the anterior cruciate ligament deficient knee during walking [16,37]. Another method which evaluates balance during walking by means of the center of mass defines the margins of stability (MoS) [19,29] in order to detect movement of the extrapolated center of mass outside the area of ground between and beneath the feet covered by the subjects silhouette. The extrapolated center of mass is calculated taking into account not only the position of the center of mass but its velocity as well.

The analysis of results for experimental data requires application of relevant statistical methods enabling verification of proposed hypotheses. Estimation of the probability density function (PDF) can be an important element in a statistical analysis [43].

The methods presented in this paper are designed for a nonlinear analysis procedure for gait kinematic time series aimed to compute the LLE for reconstructed dynamics. The ‘quaternion angle’ approach proposed by the authors allows for an efficient reconstruction of underlying dynamics for multivariate gait kinematic time series. Benefiting from the diversity of experimental data collected for different variants of walking speed and treadmill slope, an analysis was carried out for both: 1) time series representing joint angles used for clinical description of lower extremity motion in the sagittal plane: hip flexion/extension, knee flexion/extension and dorsiflexion/plantarflexion of the ankle, and 2) time series including rotations of

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[1] A stride is defined as a full cycle of limb movement, the limits of which are determined by consecutive ipsilateral heel strikes.

[2] In practice 10 consecutive strides are taken into consideration.

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