Gait & Posture 60 (2018) 111–115

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

# Differences in pattern of variability for lower extremity kinematics between walking and running

Amanda Estep[a], Steven Morrison[b], Shane Caswell[a], Jatin Ambegaonkar[a], Nelson Cortes[a,c,*]

[a] *Sports Medicine Assessment Research & Testing Laboratory, Division of Health & Human Performance, George Mason University, Manassas, VA, 20110, United States*
[b] *School of Physical Therapy and Athletic Training, Old Dominion University, Norfolk, VA, 23529, United States*
[c] *Affiliated Faculty Department of Bioengineering, Volgenau School of Engineering, George Mason University, United States*

## ARTICLE INFO

*Keywords:*
Approximate entropy
Kinematics
Variability
Nonlinear
Linear
Regularity

## ABSTRACT

This study characterizes walking and running patterns in healthy individuals using linear and nonlinear methods Seventeen individuals (12 males, 5 females) volunteered for the study. 3D kinematic data during walking (WA) and running (RU) on a motorized treadmill were captured using reflective markers placed on lower body (200 Hz). A single 25 s trial (5000 data points) was collected for each gait task. WA speed was 1.39 ± 0.12 m/s, whereas RU speed was 2.56 ± 0.27 m/s. Variables of interest included ankle plantar/dorsi flexion, knee flexion/extension, knee abduction/adduction, hip flexion/extension, and hip abduction/adduction angles. For linear analysis, standard deviation (SD) and coefficient of variation (CV) were calculated for the entire time series for both conditions. Nonlinear analysis included assessing pattern of regularity of respective kinematic time series using approximate entropy (ApEn). Inferential analyses were conducted using MANOVA to compare selected dependent measures ($p < 0.05$). SD for knee flexion/extension angle (WA = 23.34 ± 4.17, RU = 27.51 ± 5.25) and ankle plantar/dorsi flexion angle (WA = 9.24 ± 2.37, RU = 12.88 ± 2.00) were both greater during running. For all other variables, there were no significant differences in degree of variability between walking and running (p's > 0.05). Running ApEn values were greater than walking ApEn values for knee flexion/extension (WA = 0.14 ± 0.02, RU = 0.23 ± 0.04), knee abduction/adduction (WA = 0.18 ± 0.07, RU = 0.24 ± 0.07), hip flexion/extension (WA = 0.09 ± 0.02, RU = 0.17 ± 0.04), and hip abduction/adduction (WA = 0.12 ± 0.03, RU = 0.21 ± 0.05). Greater variability was demonstrated during running across all joints compared to walking. This suggests that ApEn is more sensitive to detecting changes between different gait conditions than standard discrete measures of variability (SD).

## 1. Introduction

Walking and running are forms of locomotion that can be generally characterized as repeatable, rhythmical actions. The pervasiveness of these movement patterns across individuals often leads to the assumption that the performance of this action is highly regular and consistent [1,2]. However, despite the highly regular and repeatable features of these actions from cycle to cycle, they also exhibit a degree of intrinsic variability [3–6]. Indeed, changes in the pattern of variability of various gait metrics have provided unique insight as to the impact of increasing age, injury and disease on locomotion. The study of variability of gait is now seen as an established form of analysis for charting the declines in motor function [3,6,7].

A variety of different approaches, both linear and nonlinear, have been used to assess patterns of variability. Linear approaches are usually directed towards assessing the "amount" of variability using measures such as standard deviation (SD) and coefficient of variation (CV) of the signal in question [8]. In contrast, many of the nonlinear measures capture changes in the time-dependent nature of the signal [9,10], providing an assessment of the degree of variability from point to point across the entire time series. An argument is that such nonlinear measures are more sensitive to changes in the time-evolutionary properties of the signal and are therefore solely not dependent on differences in amplitude. Measure of system entropy (i.e. approximate entropy, sample entropy, multiscale entropy), long-term correlations (detrended fluctuation analysis), dynamic stability (Lyapunov exponent) and/or time-frequency properties (e.g., wavelets) arguably provide a more complete picture of the underlying movement dynamics

---

* Corresponding author at: Division of Health & Human Performance, Sports Medicine Assessment, Research & Testing (SMART) Laboratory, George Mason University, 10890 George Mason Circle, Bull Run Hall 220, MSN 4E5, Manassas, VA, United States.
*E-mail addresses:* acary4@gmu.edu (A. Estep), smorriso@odu.edu (S. Morrison), scaswell@gmu.edu (S. Caswell), jambegao@gmu.edu (J. Ambegaonkar), ncortes@gmu.edu (N. Cortes).

https://doi.org/10.1016/j.gaitpost.2017.11.018
Received 13 April 2017; Received in revised form 11 November 2017; Accepted 20 November 2017
0966-6362/

as they can capture the nonlinear features of the physiological processes [9,10]. For example, Hausdorff et al. [11] stated that stride-to-stride fluctuations during walking were not random noise, instead they reflect long-range correlations. In this regard, the stride intervals at any point in time are not independent of previous events, but rather related to stride interval dynamics at other parts of the overall walking pattern [5,7].

While much is known about the different kinematic and kinetic features of walking and running [12], less is understood about the underlying pattern of differences in variability between these two forms of locomotion. Of the few studies which have explicitly assessed the walking and running, Jordan and Newell [13] reported that walking demonstrated stronger long-range correlations compared to running, implying more predictability and hence, less variability between strides. Further, it was found that, for either walking or running, when the action was performed above or below the preferred speed, the amount of variability decreased, indicating the importance that speed plays for these two locomotor activities.

The aim of the current study is to assess the pattern of kinematic variability for a group of adults using a battery of standard measures of variability (i.e. SD and CV) as well as nonlinear measures of signal regularity (i.e. ApEn). Based on the results of Jordan and Newell [13], it was hypothesized that running would demonstrate greater kinematic variability than walking. In addition, it was also predicted that the nonlinear measures would provide a clearer picture of the differences in movement variability between running and walking.

## 2. Methods

### 2.1. Subjects

Seventeen individuals, between the ages of 20 and 58, (5 females and 12 males) were included in this study (age: 38 ± 11.6 years, height: 176.7 ± 9.3 cm and mass: 82.5 ± 23.7 kg). Fifteen of the participants were recreational runners, while 2 were competitive runners. Average running experience was 5.8 ± 6.4 years. Prior to testing, each participant signed a consent form that had been approved by the university's Institutional Review Board. Those who reported no current injury or history of injury on the intake form were included in the study. Participants were excluded if they had experienced any major upper or lower extremity surgery within the last two years, experienced acute low back pain or any type of injury to the spine or were pregnant at time of data collection.

### 2.2. Instrumentation/Data collection

A 3D gait analysis was conducted to quantify hip, knee, and ankle/foot biomechanics. Clusters of reflective markers were placed posteriorly on the pelvis, right and left thigh and shank. For the foot, three individual reflective markers were placed directly onto the back of the left and right shoe. Markers were placed on the distal, proximal and lateral aspect of the heel in the shape of non-equilateral triangles. All reflective shoe material was covered with athletic tape. Ten calibration markers were placed on anatomical landmarks including the left and right greater trochanter and the midline of knees and malleoli. Once markers were placed, a static trial was taken to establish a baseline orientation [14]. All kinematic data was collected at a sample rate of 200 Hz using 3D Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK). Dependent variables included ankle plantar/dorsi flexion, knee flexion/extension angle, knee abduction/adduction angle, hip flexion/extension angle and hip abduction/adduction angle. All variables were measured in degrees.

### 2.3. Procedures

Demographic information was collected prior to testing which included information regarding height, weight, current activities, running injuries, typical running distance and how long they had been running. Participants wore non-reflective spandex shorts and their own pair of running shoes during all gait conditions. Participants performed both gait tasks on a motorized Woodway treadmill (WOODWAY, Waukesha, WI).

For the walking task, participants were instructed to walk at a self-selected, comfortable speed between 1.12 m/s and 1.56 m/s for approximately 5 min. At the end of the 5 min, walking kinematic data was collected. Participants were then instructed to run at a self-selected, comfortable speed between 2.24 m/s and 2.91 m/s for approximately 5 min. At the end of the 5 min, running kinematic data was collected. Twenty-five seconds' worth of data was collected at 200 Hz for both walking and running trials. By collecting kinematic data at the end of each 5-min period, participants were able to adjust to the treadmill and establish their natural stride.

### 2.4. Data analyses

All data were analyzed and processed using Matlab (Matlab v7, Mathworks). Linear analyses of the dependent measures were performed using SD and CV of the respective joint angle. These analyses were conducted for the entire time series.

Nonlinear analysis was performed using Approximate Entropy (ApEn), a measure of signal regularity. This analysis measures the time-dependent repeatability of a signal ($X$) by calculating the natural logarithm of the ratio of the count of recurring vectors of length $m$ against that of $m + 1$ that repeat sequentially within a tolerance range of $r$ over the length of the time series being assessed ($N$). Based upon previous studies, the values of $m$ and $r$ were set at 2 and 0.2, respectively with a data length ($N$) being 5000 [15]. The output from this analysis is a single value within the range of 0–2, with higher values indicating increased irregularity/variability of the specific signal while lower values representing greater regularity or structure [15].

### 2.5. Statistical analysis

Inferential analysis was conducted using a multivariate analysis of variance (MANOVA) to compare the selected dependent measures. The statistical analysis was performed using SPSS statistical software (version 23, Chicago, IL), with the risk of Type I error set at $p < 0.05$.

## 3. Results

The average speed for walking and running was 1.39 ± 0.12 m/s and 2.56 ± 0.27 m/s respectively. Fig. 1 illustrates the typical pattern of change in knee flexion angle during the walking and running conditions.

### 3.1. Linear analysis

For the linear analysis, comparisons were made between the SD of walking to the SD of running for each dependent variable and the CV of walking to the CV of running for each dependent variable. The results revealed that the SD for knee flexion angle ($F_{1,32} = 6.563$, $p = 0.015$) and ankle dorsi/plantar flexion angle ($F_{1,32} = 23.453$, $p > 0.001$) were significantly different between conditions. Specifically, the SD for knee flexion/extension angle and ankle plantar/dorsi flexion (WA = 9.24 ± 2.37, RU = 12.88 ± 2.00) were both greater during running. For all other variables, there were no significant differences in the degree of variability between walking and running (p's > 0.05). The average pattern of change in the SD for the knee and hip during walking and running conditions is shown in Fig. 2.