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Examination of stride-to-stride independence of selected lower extremity kinematic and temporal variables during treadmill walking

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ABSTRACT

The purpose of this study was to examine the nature of the intra-subject independence among strides during treadmill walking. We investigated the strength of the relationships among strides sampled in different ways from a population of observed strides. Eighteen asymptomatic subjects walked on a treadmill at 1.4 ± 0.1 m/s. Maximum angles and ranges of motion from the ankle, knee and hip joints, as well as stride duration were obtained and autocorrelation coefficients (AC) for 3 lags were calculated among 12 strides sampled consecutively (CS), in order but non-adjacently (NA), and randomly (RA). Ninety-nine percent of AC values were within Bartlett's 95% confidence interval limits and thus the strides were not considered significantly autocorrelated. The results support the hypothesis that strides obtained from an individual walking on a treadmill can be statistically independent. This supports the theoretical assumption that in some circumstances humans can be modeled as random sample generators due to inherent movement variability. The ability to assess statistically clinical intervention provides objective rigor for evaluating rehabilitation outcomes.

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1. Introduction

Biomechanical human gait analysis often involves collecting multiple strides of data, either from consecutive or non-consecutive strides, to evaluate clinical interventions. The data from multiple strides may be collapsed to an average to represent a treatment condition or the strides may be viewed as a sample from a larger population of strides and the inter-stride variability can be utilized for analysis similar to the way a sample of subjects is used to represent a population of people. Since, clinical gait analysis has a different purpose than a traditional research group analysis, different approaches are required. A traditional group analysis uses each subject's average value on a given variable, combined with average values from other subjects, to compare groups or conditions in the presence of an impairment or treatment. However, in a clinical gait analysis the individual patient represents the "population" of interest, and generalization beyond that patient is irrelevant with regard to the efficacy of the treatment for that one individual. In this situation, data from multiple subjects are not available for aggregation nor would aggregation be appropriate. Consequently, the clinical researcher or gait analyst has a limited number of choices for statistically demonstrating an intervention effect. Therefore, an analysis at the level of the individual, a single subject analysis, is warranted. Single subject gait analysis typically involves measuring a sample of strides from an individual to represent his or her population of strides. The assumption is that these sampled strides appear random, and therefore independent, during the measurement interval. Unfortunately, one criticism of single subject analysis is that strides sampled from an individual might not be independent. Stride dependence would violate one of the major assumptions of almost all inferential statistical tests and thus invalidate comparisons between intervention or treatment conditions. However, there is debate among researchers whether strides from an individual are statistically dependent or independent. Some researchers argue that strides from the same individual are dependent because they originate from the same biological system [1], whereas others argue that such strides can be considered independent due to the complexity of the organism, the numerous functional degrees of freedom within the system, and resulting movement variability [2,3]. The perspective affects both the theoretical view of human gait and the appropriateness of applying statistical tests such as *t*-test or ANOVA to single subject gait data because these tests assume that trials are independent.

Recent studies have revealed long-term structural correlation in over-ground walking stride duration, defined as the time

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between consecutive heel contacts of the same foot [4–7]. The stride duration is usually measured using sensors inserted in the shoes over hundreds of strides [7]. However, long-term dependence does not necessarily reflect short-term dependence, which makes the practical meaning of the observed long-term dependence questionable because relatively short-term data are being collected in typical gait analyses. During biomechanical gait analysis, data collection volume is often limited in length, and only a few consecutive strides can be collected during a trial due to physical lab space limitations, camera placement configuration, or subject impairment. In over-ground gait tests, subjects typically have to progress through the calibrated data collection area and then return to the starting location and start over for the next trial. Due to the limitations of typical over-ground gait analysis, the relevance of long-term data dependence is rather small, but the investigation of short-term data dependence becomes important. The difficulties with collecting a large enough number of strides for kinematics with cameras fixed in place can be solved by using a treadmill. Although it may affect natural variability of gait compared to over-ground gait and reduce the stride-to-stride variability [8,9], it still should reflect the randomness of the stride in the condition. Additionally, long-term autocorrelation has been reported for stride duration during treadmill walking [5].

Despite the extensive literature describing the long-term characteristics of stride duration, there has been little analysis of the characteristics within other common gait variables such as joint kinematics. The purpose of this study was to examine the nature of the intra-subject independence among strides for selected joint kinematic variables and stride duration obtained during treadmill walking. We investigated the strength of the relationships among strides sampled in different ways from a population of observed strides. We hypothesized that strides would be independent because of the complexity of the human system and the inherent variability of human movement.

2. Methods

2.1. Subjects

The study sample consisted of 18 asymptomatic subjects (7 male, 11 female; M ± SD age: 40.3 ± 14.1 years, height: 1.75 ± 0.09 m, mass: 79.4 ± 20.1 kg) without any health or medical condition that would prevent normal gait. Prior to participation, all subjects signed an informed consent form approved by the Institutional Review Board at the affiliated university.

2.2. Protocol

Subjects walked on a treadmill at an average speed of 1.4 ± 0.1 m/s, which was preferred speed plus 10%, while a motion capture system was used to obtain sagittal plane lower extremity kinematic data (Vicon Motus 9.2, Centennial, CO) sampled at 120 Hz. Reflective markers were attached over the lateral acromion, greater trochanter, lateral femoral epicondyles, fibula head, lateral malleolus, lateral head of fifth metatarsal, and heel. Kinematic marker trajectory data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz.

2.3. Data and statistical analysis

Twenty-five consecutive strides were collected from each subject. Then, three different stride sampling conditions were imposed in order to reproduce the typical biomechanical gait analysis situation in which isolated strides from multiple trials are collected and mixed (sampling condition 1: strides sampled consecutively, CS; sampling condition 2: strides sampled in order but non-adjacently, NA; sampling condition 3: strides sampled randomly, RA). Maximum joint angles and ranges of motion (ROM) from the ankle, knee and hip, as well as stride duration were measured. Autocorrelation coefficient (AC) values for 3 lags were calculated in Matlab (v. 2015b; The MathWorks Inc.) according to Winter [10] for each subject and sampling condition. Each sampling condition contained up to 12 strides but the number of strides decreased by one with each lag step. The initial sample size of 12 strides was chosen because the NA condition limited the final sample size to 12 after selecting every other stride from the pool of 25 strides. The number of strides in the CS and RA conditions were matched to those in the NA condition. Three lags were chosen because AC values from lags that represent more than 40% of the sample size have been shown to be statistically unreliable [11]. The magnitude of a lag 1 AC value indicates the degree of association of one stride with the very next stride in the sample. Stride-to-stride independence of each variable was assessed within subject for each sampling method and lag by comparing AC values relative to Bartlett's 95% confidence interval limits:

$$\pm\frac{z_{1-\alpha/2}}{\sqrt{N}}$$

where N is the sample size, z is the quantile function of the standard normal distribution, and α is the significance level. The width of the confidence interval increased as sample size decreased with each lag. Stride independence was interpreted as AC values that did not exceed Bartlett's 95% confidence interval limits, thus indicating that the AC was not significantly different from zero and meaning that a random process was likely. Autocorrelation coefficient values outside the limits would indicate a significant chance that the true AC values were not zero, thereby suggesting that the observed variability was not a random process. This analysis was repeated for all subjects, sampling conditions and variables, and was explored for 90 and 85% confidence interval limits.

3. Results

The normality assumption was confirmed for all AC variables by visually assessing frequency plots and calculating Shapiro-Wilk and Kolmogorov-Smirnov tests. The distribution of AC values visually appeared normal and statistically were not different from normal ($p > 0.05$).

The consecutive strides observed within each sampling condition were independent. Nearly all of the AC values from the maximum joint angle (482/486 or 99%), joint ROM (484/486 or >99%), and stride duration (160/162 or 99%) variables were within the 95% confidence interval limits and no specific patterns of AC values were observed. Thus, the strides were not considered significantly autocorrelated (Figs. 1–3). One percent or less of the AC values exceeded the 95% confidence interval limits, but this number of significant values was expected by random chance.

Magnitudes of the AC values for the maximum angle variables ranged from 0.01-0.61, 0.01-0.57 and 0.01-0.57 for the CS, NA and RA sampling conditions, respectively. Magnitudes of the AC values for the ROM variables ranged from 0.01-0.58, 0.01-0.63 and 0.01-0.62 for the CS, NA and RA sampling conditions, respectively. Magnitudes of the AC values for the stride duration variable ranged from 0.01-0.64, 0.01-0.53 and 0.01-0.59 for the CS, NA and RA sampling conditions, respectively. In comparison, Bartlett's 95% confidence interval limits were 0.59 at lag 1, 0.62 at lag 2, and 0.65 at lag 3.

When AC values were examined with more liberal confidence interval limits, 475/486 (98%), 470/486 (97%) and 154/162 (95%) of values for the maximum angle, ROM and stride duration variables,