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The gait standard deviation, a single measure of kinematic variability

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ABSTRACT

Measurement of gait kinematic variability provides relevant clinical information in certain conditions affecting the neuromotor control of movement. In this article, we present a measure of overall gait kinematic variability, GaitSD, based on combination of waveforms' standard deviation. The waveform standard deviation is the common numerator in established indices of variability such as Kadaba's coefficient of multiple correlation or Winter's waveform coefficient of variation.

Gait data were collected on typically developing children aged 6–17 years. Large number of strides was captured for each child, average 45 (SD: 11) for kinematics and 19 (SD: 5) for kinetics. We used a bootstrap procedure to determine the precision of GaitSD as a function of the number of strides processed. We compared the within-subject, stride-to-stride, variability with the, between-subject, variability of the normative pattern. Finally, we investigated the correlation between age and gait kinematic, kinetic and spatio-temporal variability.

In typically developing children, the relative precision of GaitSD was 10% as soon as 6 strides were captured. As a comparison, spatio-temporal parameters required 30 strides to reach the same relative precision. The ratio stride-to-stride divided by normative pattern variability was smaller in kinematic variables (the smallest for pelvic tilt, 28%) than in kinetic and spatio-temporal variables (the largest for normalised stride length, 95%). GaitSD had a strong, negative correlation with age. We show that gait consistency may stabilise only at, or after, skeletal maturity.

1. Introduction

Clinical gait analysis tends to focus on the shape of the kinematic and kinetic waveforms during a walking stride (e.g. [1]). However, variability of the gait pattern may provide additional, relevant, information about a condition or pre-post an intervention [2]. Mathematical tools to report the variability in kinematic, kinetic or electromyographic (EMG) data exist but there is no tool to summarise overall gait kinematic variability. The aim of this study was to propose and validate such a tool.

Research regarding variability in gait analysis data began with the reliability of electromyographic waveforms [3]. Hershler and Milner introduced the variance ratio (VR) to estimate the repeatability of EMG waveforms over several gait cycles. In [4], Kadaba et al. used the variance ratio for EMG data but later [5] introduced the Coefficient of Multiple Correlation (CMC) to estimate the repeatability of kinematic and kinetic waveforms. In [5], Kadaba et al. did not use VR or CMC to measure variability of EMG data but the waveform coefficient of variation (W-CV) described by Winter [6]. Subsequent research regarding variability in gait waveforms utilised these indices.

Dynamic stability is another field of human motion analysis interested in kinematic variability of gait. Researchers developed additional tools such as detrended fluctuation analysis, fractal dynamics or the Lyapounov exponent (e.g. [7,8]). Although related to variability, these tools do not measure variability per se but how well, or how fast, one adapts for the variability during movement. These tools require large number of strides and may not be easily used in the context of clinical gait analysis, where small number of strides, typically 10 or less, is captured during overground walking.

The VR, CMC or W-CV indices are all dimensionless ratios. This allows the comparison of variability in data expressed in different

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units or waveforms that vary over markedly different amplitudes. For example, Tirosh et al. used the VR to compare confidence in the mean waveforms from different treatment of EMG data and with respect to kinematic and kinetic data [9]. However, ratios cannot be combined to obtain a summary index across multiple variables. VR and CMC are two ways to express the same relationship in the data, and VR and W-CV ratios share the same numerator, the variance around the mean waveform. This variance can be combined across several variables to create a summary index of gait variability, which we will call GaitSD.

Most research efforts about gait variability have focused on the reliability of the gait experiment and researchers have mostly been interested in between-session variability (between days, between assessors or both) [10]. The within-session (and intra-subject) variability has been calculated in some studies, but mainly to compare with the variability between-sessions. Intra-subject gait variability per se has been studied in normal adults or children [5,6,11] as well as in populations with various motor control problems: ataxia [12], stroke [13], spastic diplegia [14] or spastic hemiplegia [15], or skeletal problems such as scoliosis [16]. Most of the above studies utilised Kadaba's CMC or Winter's W-CV to measure variability of the kinematic and kinetic waveforms. However, the precision of the measurement of variability may depend on the number of strides captured and processed. Researchers used varying number of strides to calculate variability, a minimum of 2 strides was reported in [13], 3 in [5], 4 in [15], 5 in [16], 9 in [6], and 10 in [11,12,14]. What is the precision of the waveforms variability calculated from two strides, and from ten strides? We will address this question and provide reference data for the precision of CMC, W-CV and the newly introduced GaitSD.

The definition of gait in the dictionary encompass two concepts. The first refers to the pattern of movement of the limbs that form the manner of walking. The second refers to different pace of forward progression adopted by horses and other animals (e.g. walk, trot, and gallop). In the scientific literature, search results about "gait variability" mostly refer to the second concept, and report the variability of spatio-temporal parameters such as walking speed, cadence and stride length. We will compare kinematic variability with the variability of spatio-temporal parameters.

Sutherland et al. have shown that gait pattern may mature as early as age 4 [17]. However, little is known about the consistency of the pattern once it has matured. Does gait consistency continue to improve after the pattern has matured? We will try to answer this question and provide reference data about the kinematic, kinetic and spatio-temporal variability in typically developing children.

2. Material and methods

2.1. Gait kinematic variability: GaitSD

In 1978, Hershler and Milner presented the analogy between the variance ratio and the analysis of variance [3]. If we consider N waveforms X defined over T time samples and a regression model of the data by the mean waveform:

$$X_{ij} = X_{\bar{j}} + \in_{ij}$$

with X_{ij} a waveform from the stride i defined over j time samples, $X_{\bar{j}}$ the mean of the N waveforms defined for each time instant j: $X_{\bar{j}} = \frac{1}{N}\sum_{i=1}^{N} X_{ij}$ and $\in_{ij}$ the residuals.

The variance of the residuals, which we will call $GVSD^2$ for later use, is calculated from the mean square of the errors, the ratio between the sum of the squares of the residuals (SSR) and the number of degrees of freedom of the residuals (DFR):

$$GVSD^2 = \frac{SSR}{DFR} = \frac{\sum_{j=1}^{T}\sum_{i=1}^{N}(X_{ij}-X_{\bar{j}})^2}{T(N-1)}$$

The total variance (TV) is the ratio between the total sum of squares (SST) and the total number of degrees of freedom (DFT):

$$TV = \frac{SST}{DFT} = \frac{\sum_{j=1}^{T}\sum_{i=1}^{N}(X_{ij}-X_{\bar{j}})^2}{TN-1}$$

with the overall mean $X_{\bar{-}}$ defined by:

$$X_{\bar{-}} = \frac{1}{TN}\sum_{j=1}^{T}\sum_{i=1}^{N} X_{ij}$$

Hershler and Milner's variance ratio VR is the ratio between the variance of the residuals and the total variance, that is $VR = \frac{GVSD^2}{TV}$. In regression analysis, VR is called the fraction of variance unexplained but it is seldom used because the coefficient of determination is preferred. Kadaba's CMC was defined as the square root of the coefficient of determination [5]:

$$CMC^2 = R^2_{\text{adj}} = 1 - \frac{GVSD^2}{TV} = 1 - VR$$

Hence, VR and CMC measure the same thing, which is how representative of the variance in the data is the variance of the mean waveform across time. However, the variability of the data around the mean waveform is solely described by the variance of the residuals: $GVSD^2$. $GVSD^2$ is also found in Winter's W-CV [6] where it is divided by the magnitude of the mean waveform. W-CV expresses how large the residuals around the mean waveform are with respect to the magnitude of the waveform.

$$W\text{-}CV = \frac{\sqrt{GVSD^2}}{\frac{1}{T}\sum_{j=1}^{T}|X_{\bar{j}}|}$$

In the remaining of the text we will refer to $GVSD^2$ as the gait variable variance and $GVSD$ as the gait variable standard deviation, hence the acronym.

We define GaitSD as the square root of the average variance over V kinematic variables. That is:

$$\text{GaitSD} = \sqrt{\frac{1}{V}\sum_{k=1}^{V} GVSD_k^2}$$

GaitSD expresses the standard deviation of the residuals around V mean kinematic waveforms in degrees. We chose the same set of kinematic variables as other index of kinematic normalcy in clinical gait analysis [18,19]. GaitSD for one subject is composed of 15 kinematic variables: pelvic tilt, pelvic obliquity, pelvic rotation, left and right hip flexion, left and right hip abduction, left and right hip rotation, left and right knee flexion, left and right ankle dorsiflexion and left and right foot progression angles. GaitSD for one side is made of 9 kinematic variables: 3 from the pelvis and the 6 from the right or left lower limb.