Gait & Posture 49 (2016) 309–314

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

Daily changes of individual gait patterns identified by means of support vector machines

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 19 July 2016
Accepted 21 July 2016

Keywords:
Gait patterns
Inter-session variability
Repeatability
Movement variability
Individuality
Support vector machines

ABSTRACT

Despite the common knowledge about the individual character of human gait patterns and about their non-repeatability, little is known about their stability, their interactions and their changes over time. Variations of gait patterns are typically described as random deviations around a stable mean curve derived from groups, which appear due to noise or experimental insufficiencies. The purpose of this study is to examine the nature of intrinsic inter-session variability in more detail by proving separable characteristics of gait patterns between individuals as well as within individuals in repeated measurement sessions. Eight healthy subjects performed 15 gait trials at a self-selected speed on eight days within two weeks. For each trial, the time-continuous ground reaction forces and lower body kinematics were quantified. A total of 960 gait patterns were analysed by means of support vector machines and the coefficient of multiple correlation. The results emphasise the remarkable amount of individual characteristics in human gait. Support vector machines results showed an error-free assignment of gait patterns to the corresponding individual. Thus, differences in gait patterns between individuals seem to be persistent over two weeks. Within the range of individual gait patterns, day specific characteristics could be distinguished by classification rates of 97.3% and 59.5% for the eight-day classification of lower body joint angles and ground reaction forces, respectively. Hence, gait patterns can be assumed not to be constant over time and rather exhibit discernible daily changes within previously stated good repeatability. Advantages for more individual and situational diagnoses or therapy are identified.

1. Introduction

Gait analysis is a standard practice for diagnosis, assessment, monitoring and discussion of diseases that affect gait and/or quantification of interventions [1]. Therapists, clinicians, and researchers must be able to interpret the results of such analysis with respect to their meaningfulness [2–4]. Due to the natural variability in data from humans, this problem is not trivial. Variability is described as an inherent feature of human motor control, which occurs throughout multiple levels of movement organisation and contributes to variations in the output of the motor system [5]. Various intrinsic and extrinsic sources for movement variability can be distinguished that contribute to the total variability of gait data [6]. Extrinsic variability includes experimental errors that are candidates for quality improvements, whereas other variations occur naturally and can only be identified and discussed [6]. Intrinsic gait variability has been prevalently specified within a single recording or measurement session (intra-session variability) [6,7]. In addition to the assessment of the magnitude of variability [6], concepts and tools from nonlinear dynamics, fractal analysis and chaos theory unravel more details about the nature of human gait and indicate that variability can no longer be considered to be equivalent to insignificant noise [5,8–10]. Intrinsic variability is rather dominated by deterministic and stochastic processes that reflect a functional feature of walking [for further review see,e.g.,5,9,10–12].

Although variability is a well-described phenomenon, most approaches of biomechanical diagnoses and therapeutic interventions are orientated on the idea of average behaviour and normality as well as quasi-stationary behaviour at least for the duration of a therapeutic intervention. Clinical analysis commonly describes gait variables based on mean waveforms (e.g., joint angle-gait stride-curve) and treats variability operationally as random deviation within distributional statistics [5,9,10].

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http://dx.doi.org/10.1016/j.gaitpost.2016.07.073
0966-6362/

Variability between and within subjects is often neglected as insignificant and variations are inherently treated as errors that need to be reduced [5]. Mean waveforms based on high numbers of trials are recommended in order to obtain stable and reliable gait characteristics. In practice, these curves are assumed to remain constant over time without an intervention or injury [13–15].

Although the magnitude and nature of intra-session variability has been described, there is a lack of research for the description of intrinsic variability between sessions (inter-session variability) [3]. McGinley et al. (2009) state in their review that, the exact level of intrinsic persistence of gait patterns over hours, days, weeks, months or years has not been well detailed [3]. Studies on gait variability between days are so far solely based on measures of variance and/or covariance (e.g., standard deviation, coefficient of variation, coefficient of multiple correlation, intra-class correlation coefficient) and state that the magnitude of variability is smaller when analyzing gait patterns within a day compared with gait patterns between different days [e.g., 16,17]. However, it is not known whether gait patterns on different days exhibit intrinsic changes with specific characteristics. The present study examines discernible changes in gait patterns between days (inter-session variability) in more detail. A classification should verify whether gait patterns between and within subjects can be distinguished within the magnitude of previously described inter-session variability. Long term stride-to-stride fluctuations in intra-session variability show temporal dependencies in terms of long range correlations [8,9,18] and it is hypothesised that gait patterns show time-dependent characteristics between sessions. The aim of this study is to examine intrinsic inter-session variability in time-continuous gait stride patterns by (1) quantifying the persistence of individual gait patterns over two weeks and (2) quantifying intra-individual differences in gait patterns between different days.

2. Methods

2.1. Data acquisition

Eight healthy and physically active subjects (six female, two male; 23.5 ± 2.3 years; 1.75 ± 0.08 m; 66.9 ± 7.7 kg) without gait pathology and free of lower extremity injuries participated in the study. The study was carried out according to the Declaration of Helsinki and all subjects provided their informed written consent. The approval from the ethical committee of the medical association Rhineland-Palatinate in Mainz was received.

The subjects performed 15 gait trials on each of eight days within two weeks, during which they did not undergo any specific intervention. The data acquisition was conducted at the same time each day. For each trial joint angles of the lower body as well as the ground reaction force were measured, while the subjects walked on a 10 m path. Kinematic data of 34 retro-reflective markers, placed on the lower body, were captured by nine Oqus 310 infrared cameras (Qualisys AB, Sweden) at a sampling frequency of 250 Hz. Markers were placed on anatomical landmarks according to Fig. 1. On the first day, the anatomical landmarks were palpated and marked with a permanent pen to ensure a consistent marker placement over the duration of the investigation. The ground reaction force was recorded by two force plates (Type 9287CA) (Kistler, Switzerland) at a frequency of 1000 Hz. The recordings were controlled and time-synchronised by the Qualisys Track Manager 2.7 (Qualisys AB, Sweden). Two experienced assessors applied the markers and conducted the analysis. Every subject was analysed by the same assessor on each day.

The subjects were instructed to walk barefoot at a self-selected speed. On the first day, each subject performed test trials in order to become accustomed to the experimental setup and to assign a starting point for a walk over the force plates. On each of the following days, four test trials were performed to control the starting point of the walk. The procedure has been reported to minimise the impact of targeting at the force plates on the measured gait variables [19]. Additionally, the subjects were instructed to watch the picture of a neutral smiley on the opposing wall of the laboratory to direct their visual attention away from targeting the force plates and ensure a natural walk with an upright body position.

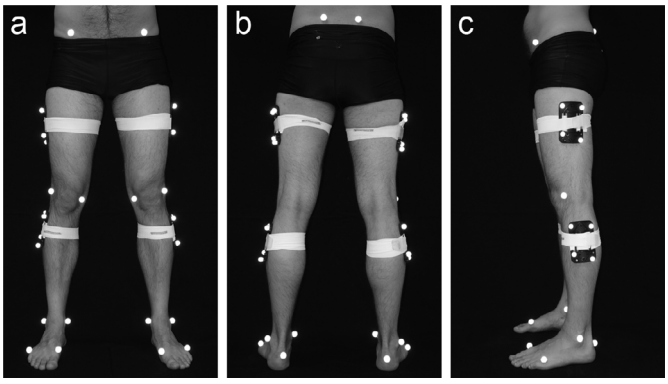

Fig. 1. Lower body marker set in (a) anterior (b) posterior (c) left lateral view. Specifically, markers were placed on the left and right anterior superior iliac spine, posterior superior iliac spine, femur lateral epicondyle, femur medial epicondyle, fibula apex of lateral malleolus, tibia apex of medial malleolus, posterior surface of calcaneus, head of 1st metatarsus, head of 5th metatarsus and clusters with four markers each at the thigh and shank.

2.2. Data processing

The analysis was conducted for the time-continuous gait patterns of one stride. The stride was defined from right foot heel strike to left foot toe off and was determined using a vertical ground reaction force threshold of 10 N. The computation of the lower body kinematics was carried out by Visual3D Standard v4.86.0 (C-motion, USA) and the joint angles for hip, knee and ankle were calculated for sagittal, transversal and coronal plane. The resulting joint angles were filtered with a second order Butterworth bidirectional low-pass filter and a cut off frequency of 18 Hz. The ground reaction force was normalised to the body weight of each day to exclude the impact of changes in the body mass between the eight test days. Further data processing and analysis was executed by a self-written script within the software Scilab 5.4.1 (Scilab Enterprises, France). Each variable time course was time normalised to 101 data points and scaled to a mean of 0 and two standard deviations of 1. The scaling was done separately for each trial. The amplitudes were normalised in order to ensure an equal contribution of all variables to the support vector machines classification and thereby avoid that variables in greater numeric ranges dominate those in smaller numeric ranges [20].

2.3. Data analysis

In order to ensure comparable walking conditions during the investigation and control familiarisation effects to the experimental setup, gait velocity, step length, step width and step time duration were assigned and statistically tested for differences between the eight test days by a repeated measures ANOVA using SPSS 21 (IBM, Armonk, New York, USA). The significance level was set to $p < 0.05$. Normal distribution is fulfilled by the test of Shapiro-Wilk ($p \geq 0.084$). The Mauchly test shows a significant result ($p = 0.000$) and the degrees of freedom were corrected according to Greenhouse-Geisser.