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Complexity of human gait pattern at different ages assessed using multiscale entropy: From development to decline

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A B S T R A C T

Multiscale entropy (MSE) has been applied in biomechanics to evaluate gait stability during human gait and was found to be a promising method for evaluating fall risk in elderly and/or pathologic subjects. The hypothesis of this work is that gait complexity is a relevant parameter of gait development during life, decreasing from immature to mature gait and then increasing again during old age. In order to verify this hypothesis, MSE was applied on trunk acceleration data collected during gait of subjects of different ages: toddlers at the onset of walking, pre-scholar and scholar children, adolescents, young adults, adults and elderlies. MSE was estimated by calculating sample entropy (SEN) on raw unfiltered data of L5 acceleration along the three axes, using values of τ ranging from 1 to 6. In addition, other performance parameters (cadence, stride time variability and harmonic ratio) were evaluated. The results followed the hypothesized trend when MSE was applied on the vertical and/or anteroposterior axis of trunk acceleration: an age effect was found and adult SEN values were significantly different from children ones. From young adults to elderlies a slight increase in SEN values was shown although not statistically significant. While performance gait parameters showed adolescent gait similar to the one of adults, SEN highlighted that their gait maturation is not complete yet. In conclusion, present results suggest that the complexity of gait, evaluated on the sagittal plane, can be used as a characterizing parameter of the maturation of gait control.

1. Introduction

Multiscale entropy (MSE) has been introduced to quantify the complexity (sample entropy, SEN) of a time series on multiple spatio-temporal scales [1]. In biomechanics, MSE and/or SEN have been applied to evaluate stability during human gait and were found to be promising quantitative methods for evaluating fall risk in elderly and/or pathologic subjects [2–4].

Leverick et al. [4] found that SEN measures experienced statistically significant increases in response to increasing age and gait impairment caused by cognitive interference on healthy adults and elderlies: they concluded suggesting that entropy appears to be a viable candidate for assessing the stability of human locomotion. In a previous work, Bisi et al. [2] evaluated the performance of different gait stability indices on young adults and toddlers at the onset of walking (toddlers were assumed as individuals whose gait is a priori unstable) and found that SEN was able to differentiate between unstable toddlers and stable healthy individuals.

The aim of the present study is to apply MSE to characterize the complexity and the development of human gait during a life span.

The onset of independent gait in children starts generally around age 1: the first 6 months of independent walking represent a process of integration of postural constraints into the dynamic mobility requirements during gait, after this period, a tuning phase begins, characterized by a more precise adjustment of gait parameters [5]. As children grow older, their gait pattern begins to approximate more closely that of an adult: by age 3–4, most of the adult kinematic patterns are present [6], however gait maturation continues.

In the literature, there is no common agreement regarding the age at which gait maturation is achieved. Some works refer to ages between 5 and 7 [6–8], indicating that changes after this age are more likely to be influenced by changes in height than by age. Other investigators [9–12] indicate that gait pattern continues to develop until adolescence or that the age of gait maturation is higher than 8. When gait maturation is achieved, mature gait remains steady during adult life until some deteriorations occur

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during ageing: gait performance decreases showing different changes in gait parameters and/or segmental kinematic patterns that are usually specific for different pathologies [13].

The hypothesis of the present work is that the complexity of gait could be a relevant descriptive parameter of these changes, decreasing from immature to mature gait and then increasing again during old age. The identification of a robust and sensitive indicator of gait complexity, able to describe the process of maturation during growth and to highlight possible deteriorations during the ageing process, would be useful for both understanding and monitoring gait pattern maturation/deterioration during life.

In order to preliminary explore and verify the validity of this hypothesis, MSE was applied on trunk acceleration data, collected during gait in 10 groups of subjects of different ages: from toddlers to elderlies. MSE was applied separately to the anteroposterior (AP), vertical (V) and mediolateral (ML) direction of the collected trunk acceleration. Participants were asked to walk at self-selected speed in a corridor: the choice to analyse gait at self-selected speed was guided (i) by the necessity not to influence the spontaneous control of gait and (ii) by knowing that imposing velocity, participants could alter their biomechanics in different uncontrolled ways (e.g. by changing stride length and/or cadence) [14]. In order to support the interpretation of MSE results as a characterizing aspect of gait maturation, other parameters of gait performance were evaluated: smoothness, variability of stride time and cadence.

2. Materials and methods

2.1. Study subjects

Ten groups of participants of different ages were included in the study. Group details are described in Table 1.

All of the children had no known developmental delay. All children and adults had no musculoskeletal pathology. The Review Board Committee of the authors' institution approved this study, and informed consent was obtained from the participants' parents for children and from adult participants.

2.2. Experimental setup

Two tri-axial wireless inertial sensors (OPALS, Apdm, USA) were mounted respectively on the lower back and on the right leg using straps.

Measures of accelerations of the trunk and of the right leg were recorded at 128 Hz. The participants were asked to walk at self-selected speed in a corridor. Tests were performed in kindergartens for toddlers, schools for children and adolescents, gait analysis laboratory for adults and care homes for elderlies. The selected corridors were always longer than 12 m. The procedures for collecting and selecting data on toddlers were the same as presented in [2].

2.3. Data analysis

Stride detection was estimated from the angular velocity around the medio-lateral axis of the lower leg [15]. The first two and last two strides of each test were excluded from the analysis in order to exclude gait initiation and termination phases. For all the participants 10 consecutive strides were analysed: 14 was the maximum number of strides obtained in the less experienced infants. Each time series data included a number of data points between 1000 and 1500 [1,16]. Cadence (Cad) was calculated for each participant as the median value obtained on the 10 strides. Stride-time variability [2] (STv) was estimated as the standard deviation of the stride time, for each participant.

No additional filtering procedure was applied on collected data to assure that information was not lost or altered due to filtering. Matlab R2012a (MathWorks BV, USA) was used for data and statistical analysis.

SEN was calculated applying the method on the V, AP and ML accelerations of the trunk (SENv, SENap and SENml). Values of τ ranged from 1 to 6, and m and r were fixed, respectively, at 2 and 0.2, as suggested by Pincus [17] and later applied by Richman and Moorman to biological time series [18].

Gait smoothness was estimated through the harmonic ratio (HR) [19] of L5 acceleration signals applying the method on the V, AP and ML axis (HRv, HRap and HRml).

A Jarque–Bera test [20] was performed to test normal distributions of the estimated parameters on the different groups: since the normal distribution was not verified on all the groups, median values and 25- and 75-percentiles of results were calculated.

A Kruskal–Wallis test [21,22] with minimum level of significance of 5% was performed to analyse the effect of age on SEN, Cad, STv and HR. When age effect was found, a multiple comparison test [23] was performed to evaluate which were the analysed ages showing significantly different results from the 27YA group (confidence level fixed at 95%). Dunn–Sidak correction was considered for post hoc analysis [24].

The potential influence between Cad and SEN was evaluated: Pearson correlation coefficients (ρ) between SEN along the three axes and Cad were calculated both per single age group and on all the collected data.

3. Results

SENap and SENv followed in general the hypothesized trend from toddlers to adults, showing median values decreasing with increasing group age: the differences among the groups increased with τ. SEN values for the group of adolescents did not follow the

Table 1
Details of age groups participating in the study.

Abbreviation	Group description	Age	Weight (kg)	Height (cm)
T2wks	10 toddlers at two weeks of walking experience	13 ± 2 months	10 ± 1[a]	78 ± 3[a]
T6mo	10 toddlers at 6 months of walking experience	19 ± 2 months	10 ± 2[a]	77 ± 3[a]
4YC	10 4-year old children	4 ± 0 years	17 ± 2	104 ± 4
6YC	10 6-year old children	6 ± 0 years	23 ± 1	121 ± 2
10YC	10 10-year old children	10 ± 0 years	40 ± 5	145 ± 8
15YA	10 15-year old adolescents	15 ± 0 years	61 ± 11	164 ± 6
27YA	10 27-year old adults	27 ± 1 years	67 ± 14	171 ± 9
45YA	10 45-year old adults	45 ± 2 years	71 ± 15	172 ± 10
67YA	10 67-year old adults	67 ± 2 years	83 ± 15	173 ± 6
84YA	10 84-year old elderlies	84 ± 2 years	75 ± 10	168 ± 7

[a] Weight and height of toddlers were measured at 12 months.
Data from groups T6mo and 27YA were already presented in Bisi et al. [2].