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Nonlinear analysis of human movement dynamics offer new insights in the development of motor control during childhood.

AUTHORS

Maria Cristina Bisi [a], Paola Tamburini [a], Giulia Pacini Panebianco [a], Rita Stagni [a]

AFFILIATION

[a] Department of Electrical, Electronic and Information Engineering "Guglielmo Marconi", University of Bologna, Viale Risorgimento 2, Bologna, Italy

Corresponding author:

Maria Cristina Bisi, Ph.D.

e-mail: mariacristina.bisi@unibo.it

Ph. +39 0547 338953

Fax. +39 0547 339208

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Abstract

When aiming at assessing motor control development, natural walking (NW) and tandem walking (TW) are two locomotor tasks that allow analysing different characteristics of motor control performance. NW is the reference locomotor task, expected to become more and more automatic with age. TW is a non-paradigmatic task used in clinics to highlight eventual impairments and to evaluate how a child deals with a new challenging motor experience.

This work aims at investigating motor development in school-aged children, by assessing quantitatively their performance during TW and NW. 80 children (6-10 years) participated in the study. Trunk acceleration data and nonlinear measures (recurrence quantification analysis, RQA, and multiscale entropy, MSE) were used to characterize trunk postural control and motor complexity. Results were analysed with respect to age and standard clinical assessment of TW (number of correct consecutive steps), by means of Spearman correlation coefficients.

RQA and MSE allowed highlighting age-related changes in both postural control of the trunk and motor complexity, while classic standard assessment of TW resulted uniformly distributed in the different age groups. Present results suggest this quantitative approach as relevant when assessing motor development in schoolchildren and complementary to standard clinical tests.

Introduction

Still, it is not clearly understood how human motor control system matures, and develops the capacity of coordinating the numerous available degrees of freedom to perform a specific motor task efficiently. After infancy, motor development is characterized by a gradual increase in agility, adaptability, and ability to make complex movement sequences [1]. On the other hand, when focusing on daily living tasks, such as walking, motor development is also characterized by a higher and higher level of automaticity of performance [2].

For walking in general, the mechanisms of propulsion, stabilization, kinematic coordination, power transfer, and metabolic expenditure can be considered guiding principles governing the dynamics of motor performance [3]; however, depending on the specific challenge and goal of the motor task, different factors are expected to be prioritized differently by the system when aiming at controlling numerous degrees of freedom [4]. In this perspective, natural walking (NW) and tandem walking (TW) [5] are two locomotor tasks both allowing the controlled progression of the Centre of Mass (CoM), but characterized by different constraints, allowing to highlight different characteristics of motor performance [6], in particular as related to the maturation of motor control during childhood.

NW has been extensively analysed in the literature [3,7–10] from biomechanical and clinical point of view. In healthy adults, its characteristic pattern is generally considered to be achieved using an energy-saving strategy, the inverted pendulum: the CoM of the body vaults over the stance leg in an arc, allowing an efficient exchange between kinetic and potential energy with partial recovery of mechanical energy at each stride [9]. Thus, CoM arc trajectory during walking can be considered the manifestation of the solution found by the control system: this idea is supported by the fact that different solutions (e.g. solutions that minimize vertical CoM displacement [7]) result in increased metabolic energy costs, associated to increased mechanical work performed at the hip, knee, and ankle joints [7,8].

TW is a locomotion pattern where the toes of the back foot touch the heel of the front foot at each step, with the longitudinal axis of both feet aligned in the anterio-posterior (AP) direction during the double-support phase. TW challenges postural control system as compared with NW [11], as its successful execution requires the ability to ambulate with a narrow basis of support and to have accurate balance and leg control [5]. When analysing TW from a control dynamics perspective, the control system has to deal with very different constraints with respect to NW, thus probably prioritizing different factors [4]. Unfortunately, although used for specific assessment in the clinics (e.g. to test children after 6-7 years of age to highlight signs of truncal ataxia, neurological immaturity, problems with control of balance and poor proprioceptive awareness) [12], this task has not been studied in detail from the biomechanical/control point of view yet. Given the narrow base of support and the constrained step length, the maintenance of stability (maintaining CoM projection within the basis of support) is likely a leading factor to achieve a safe performance, while metabolic cost minimization is not expected to be a major constraint, particularly when observing subjects at their first experience with TW [13].

When aiming at studying motor control maturation, given the specificities of the two tasks, NW can be considered a reference for assessing aspects related to motor automaticity and TW aspects related to flexibility of the system. A wearable inertial sensor on the trunk to track its acceleration, together with the use of non-linear metrics for its analysis [14–16] can provide innovative and quantitative information regarding motor control maturation.

In particular, Sample Entropy (SEN) values of trunk acceleration signal, assessed at different time scales (Multiscale Entropy, MSE), were related to movement automaticity and complexity in NW and TW, respectively, at different ages of maturation [2,6]. Similarly, recurrence quantification analysis (RQA) [17] was found to describe the expected trend a higher postural control stability with walking experience in toddlers [18], and was also associated with fall history in elderly populations and with clinical scales in sub-acute stroke patients [19], analysing NW.

The aim of the present work was to investigate the development of motor control in terms of postural and motor complexity, analysing MSE and RQA of trunk acceleration signals in school-aged children performing NW and TW. Since maturation and motor development are not only related to age, quantitative results were analysed with respect to both age maturation and standard clinical evaluation of TW performance (number of correct consecutive steps [5,20]).

Materials and Methods

Study participants

Five age groups of 16 children each were included in the study (Table1)

Table 1. Details of age groups participating in the study.

age (years)	female/male	height (cm)	body mass (kg)
6	8F/8M	1.19±0.4	23±2
7	8F/8M	1.27±0.05	29±5
8	8F/8M	1.29±0.04	29±5
9	8F/8M	1.38±0.06	34±6
10	8F/8M	1.40±0.05	37±5

All children had no known developmental delay, no musculoskeletal pathology and had a BMI between the 5th and the 95th percentile of the BMI-for-age [21]. They had no previous experience of TW. The Review Board Committee of the authors' institution approved this study, and informed consent was obtained from the participant' parents.

Experimental setup

One tri-axial wireless inertial sensor (OPALS, Apdm, USA) was mounted on the lower back (at L5 level) using an elastic band. 3D components of trunk acceleration (vertical (V), anteroposterior (AP) and mediolateral (ML), anatomical reference frame) were recorded at 128Hz while children walked in NW and in TW at self-selected speed back and forth along a 15m long tapeline, wearing comfortable shoes. Tests were performed in schools. Videos were also recorded during the tests using two different video recorders (one fixed camera for the frontal plane, Canon Legria FS20, Canon Europe, 25 fps and one for the sagittal plane, GoProHero 4, GoPro Inc. USA, 120 fps).

Data analysis

Standard assessment of TW (TW-competence) was implemented by analysing the videos (Kinovea, Version 0.8.15, 2011) and counting, for each participants, the number of correct consecutive steps from the beginning of the tapeline [20], as conventionally done for clinical assessment (errors included taking a side step and making a space between the feet).

For both NW and TW, U-turns, and the first two and the last two strides of each trial were excluded, to avoid transitions, and initiation and termination patterns [22,23]. For all participants 14 consecutive strides were analyzed.

Multiscale Entropy

MSE was calculated according to [2,18,24] on the V, AP and ML components of trunk acceleration for NW and TW, considering τ ranging from 1 to 6. All time series have been normalized to have standard deviation 1 [25]. Consecutive coarse-grained time series were calculated by averaging increasing numbers of data points in non-overlapping windows of length τ. Each element of the coarse grained time series $y_j^{(\tau)}$, was calculated starting from the original time series $\{x_1,\ldots,x_i,\ldots, x_N\}$, according to

$$y_j^{(\tau)} = {}^{1}/_{\tau} \sum_{i=(j-1)\tau+1}^{j\tau} x_i, \tag{1}$$

where τ represents the scale factor and $1 \le j \le {}^{N}/_{\tau}$. [24].

Sample Entropy (SEN) was then calculated for each coarse grained time series, quantifying the conditional probability that two sequences of *m* consecutive data points similar to each other will remain similar (i.e. distance of data points inferior to a fixed *radius*), when one more consecutive point is included [24]. The length of sequences to be compared, *m*, has been fixed at 2 and the tolerance for accepting matches, *radius*, at 0.2 [25].

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<u>*Recurrence Quantification Analysis*</u>

State space reconstruction

State space was reconstructed by using the delay embedded state space of each trunk acceleration component separately (V, AP and ML). Embedding dimension was fixed at 5, according to literature [17,26]. Time delay was obtained using the first minimum of the average mutual information algorithm and was set at 10 samples (corresponding to of 0.078 s given the sampling frequency of 128Hz) [23,26,27].

Recurrence plot generation

Distance between all the points of the embedded time series was calculated. If this distance was less than or equal to a *threshold* the point is a recurrence. *Threshold* was fixed at 40% of the maximum distance between data points in the embedding space-state, in order to minimize the floor and ceil effects [28].

Features extracted from the recurrence plot

i) Recurrence rate (RR). RR was calculated as the number of recurrent points in the recurrence plot expressed as a percentage of the number of possibly recurrent points (percentage of points within a *threshold* distance of one another) [17,18].
ii) Determinism (DET). DET was calculated as the percentage of recurrent points falling on upward diagonal line segments. Number of points forming a line segment was fixed at 4 [29].
iii) Averaged diagonal line length (AvgL). AvgL calculated as the average upward diagonal line length, where the diagonal lines are defined following determinism definition [17,18].

In order to compare directly the assessment of motor control performance during the two tasks, each index obtained *per* participant in NW was expressed in percentage of the corresponding value in TW (NW/TW) to represent the ratio, R-index.

A Kolmogorov–Smirnov test was performed to test normal distributions of the estimated parameters on the different groups and on the entire dataset and normal distribution was not verified

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for all the parameters.

A Kruskal-Wallis test with minimum level of significance of 5% was performed to analyse the eventual effect of age on TW-competence. To test difference between male and female participants, a Mann–Whitney U test was performed on TW-competence and on all the indices.

Spearman correlation coefficients ρ (significance level, 0.05) were calculated separately for TW, NW and NW/TW for i) indices and age and ii) indices and TW-competence.

Data and statistical analyses were performed in Matlab 2017 (MathWorks BV, USA).

Results

TW-competence

TW-competence distribution resulted similar in all the age group, covering the entire span of possible results (from only 1 correct step to 28 correct consecutive steps). Kruskal-Wallis test showed no age effect on TW-competence (Figure 1 shows TW-competence distribution for each age group). The Mann–Whitney U test showed that female participants had a significantly higher TW-competence than boys did (p=0.003). A higher number of female children performed correctly the entire test (28 correct consecutive TW steps) with respect to male participants (15 girls and 7 males). Figure 2 shows TW-competence distribution for male (left panel) and female (right panel) participants.

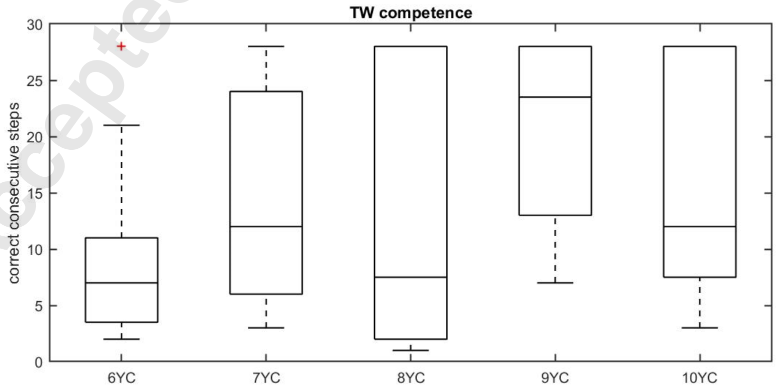

Figure 1. Boxplot (median, 25th and 75th percentiles) of TW-competence for each age group.

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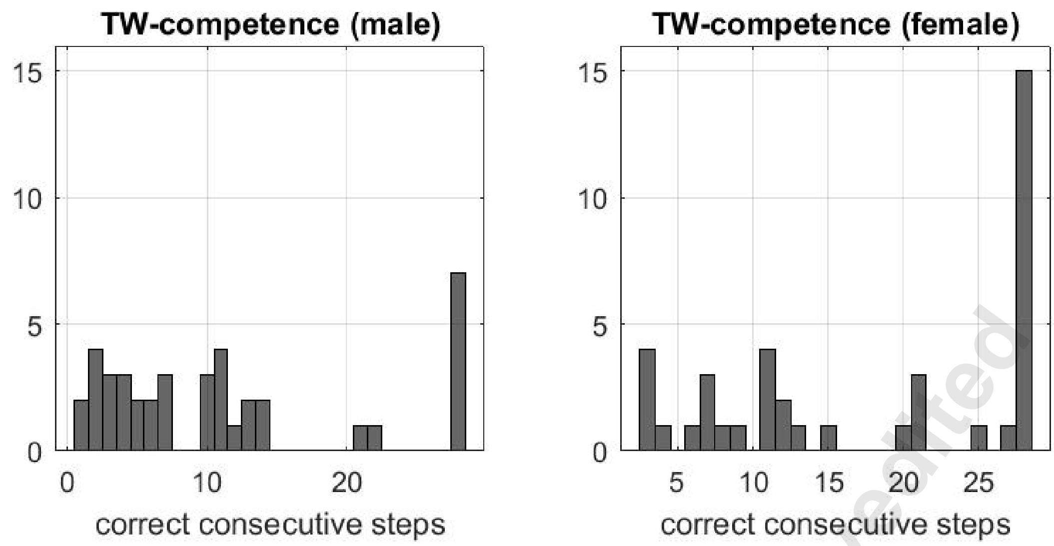

Figure 2. TW-competence distribution for male (left) and female (right) participants.

Nonlinear indices

No differences were found in the estimated nonlinear indices between male and female participants.

Correlations between age and nonlinear indices.

Age was significantly correlated with RQA parameters on the ML and AP axis in TW and on the AP axis in NW. No significant correlation was found for the V axis. In particular, positive correlations were found in NW, and negative correlations in TW ($0.2<|\rho|<0.4$). Positive correlations were found between age and R-indices ($0.2<|\rho|<0.5$) in NW/TW on AP (RR, DET and AvgL) and ML directions (RR, DET and AvgL).

Age also significantly correlated with SEN at different values of τ, on the ML and AP directions in NW, and on all three directions in TW. In NW, significant negative correlations were found between age and SEN (ML τ =2:5; AP $\tau \geq 4$). In TW, correlations resulted to be positive and significant for all directions (V $\tau>2$; ML τ =1:6; AP τ =1:6): correlations found were stronger in AP than in V and ML. In NW/TW, negative correlations were found on the AP axis ($0.4<|\rho|<0.5$) and on the ML axis ($0.3<|\rho|<0.4$).

Correlations between TW-competence and nonlinear indices.

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Significant results found between TW-competence and RQA indices were obtained when evaluating NW and NW/TW. Positive correlations were found on the AP (NW, DET and AvgL; NW/TW, DET) and on the V axis (NW, AvgL; NW/TW, DET and AvgL). No significant correlations were found in TW.

SEN, assessed during TW, was positively correlated with TW-competence, showing significant correlations on all the three axes (V τ =1:6, ML τ <5, AP τ =1:6). In NW/TW, significant negative correlations were found for TW-competence and R-indices on all the three axes (V $\tau \leq 5$, ML $\tau \leq 3$, AP τ =1:6). No significant correlation was found between SEN assessed during NW and TW-competence.

Table 2 shows ρ values of significant correlations.

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Table 2. Spearman correlation coefficients ρ for i) indices and age and ii) indices and TW-competence, in NW, TW and NW/TW.

		Age			TW-competence		
		NW	TW	NW/TW	NW	TW	NW/TW
V	RR	--	--	--	--	--	--
	DET	--	--	--	--	--	0.23
	AvgL	--	--	--	0.24	--	0.25
ML	RR	--	-0.25	0.25	--	--	--
	DET	--	-0.26	0.27	--	--	--
	AvgL	0.21	-0.26	0.30	--	--	--
AP	RR	--	-0.31	0.36	--	--	--
	DET	0.22	-0.38	0.43	0.29	--	0.23
	AvgL	0.23	-0.37	0.41	0.22	--	
		Age			TW-competence		
		NW	TW	NW/TW	NW	TW	NW/TW
V	SEN τ=1	--	--	--	--	0.43	-0.30
	SEN τ=2	--	0.23	--	--	0.46	-0.30
	SEN τ=3	--	0.25	--	--	0.48	-0.29
	SEN τ=4	--	0.29	--	--	0.45	-0.29
	SEN τ=5	--	0.27	--	--	0.45	-0.23
	SEN τ=6	--	0.35	--	--	0.35	--
ML	SEN τ=1	--	0.25	-0.29	--	0.35	-0.25
	SEN τ=2	-0.25	0.28	-0.36	--	0.38	-0.29
	SEN τ=3	-0.29	0.28	-0.38	--	0.36	-0.26
	SEN τ=4	-0.27	0.26	-0.33	--	0.30	--
	SEN τ=5	-0.26	0.23	-0.35	--	0.28	--
	SEN τ=6	--	0.26	--	--	--	--
AP	SEN τ=1	--	0.40	-0.43	--	0.37	-0.32
	SEN τ=2	--	0.39	-0.45	--	0.37	-0.32
	SEN τ=3	--	0.36	-0.45	--	0.38	-0.31
	SEN τ=4	-0.29	0.33	-0.46	--	0.35	-0.26
	SEN τ=5	-0.33	0.25	-0.40	--	0.31	-0.31
	SEN τ=6	-0.31	0.30	-0.45	--	0.30	-0.36

Discussion

In the present work, MSE and RQA indices were applied on trunk acceleration data collected on schoolchildren during NW and TW, with the aim of characterizing the development of postural control of the trunk, motor complexity and motor automaticity. Results were analysed with respect to age and to a standard assessment of children motor competence (TW-competence, corresponding to the number of correct consecutive steps during TW).

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Despite no age effect was found on TW-competence results, showing that different age groups had comparable TW-competence distribution, nonlinear indices were significantly correlated with children age.

In particular, RQA results correlated with age on the transverse plane in NW and TW. Results showed that AP and ML axes are the most sensitive to age maturation, suggesting that the coupling of AP and ML oscillations is a key component of the integrated posture-in-locomotion system, not only during the emergence of independent bipedal walking [30], but also in schoolchildren motor development. By analysing the direction of found correlations, results showed that age maturation was associated with increasing values of DET and AvgL in NW, and with decreasing values of RR, DET and AvgL in TW. This opposite trend indicates an increasing and a decreasing regularity of trunk acceleration pattern in the two tasks, respectively. AP and ML oscillation coupling in NW is optimized with age maturation, becoming more automatic. On the other hand, in TW, motor control has to stabilize the trunk on the constrained base of support, thus showing a less regular trunk acceleration pattern with age, due to an increased capacity of controlling posture with efficiently tuned strategies.

RQA parameters resulted weakly related to the standard assessment of TW (TW-competence). Only DET and AvgL on AP axis and AvgL on V axis during NW increased with increasing capacity of correctly performing tandem gait, suggesting that children performing correctly TW tended to show a higher regularity in NW on the sagittal plane.

Correlation results of SEN with age confirmed what was previously found in the literature [6]. Motor complexity, assessed by SEN, decreased with increasing age in NW (in AP and ML direction), indicating a higher automaticity of the task with age maturation, and increased in TW, indicating a higher capacity of manifesting motor complexity when dealing with a new challenging task. In this work, no correlation has been found between SEN in the V direction and age, while in a previous works by the same authors [2,6] SEN decreased significantly with age on V; this difference is probably due to the smaller age range chosen in this study (6-10 year old children) with respect to previous ones that included adolescents, adults and elderlies. Since SEN provides a measure of unpredictability or irregularity of the time series (at different time scales, τ), results showed that trunk acceleration signal becomes more predictable with age in NW (less predictable in TW). While RQA results correlated with age only on ML and AP axes, SEN results showed significant correlation on V axis too. SEN results in TW also correlated with TW-competence, showing that children able to perform a higher number of correct consecutive steps in TW, are those manifesting less predictable trunk adjustments during the same task, corresponding to a higher motor complexity.

When analysing correlations found between R-indices and age (obtained from the ratio of each index assessed in NW with respect to the one assessed in TW, NW/TW), and age/TW-competence, correlation strength resulted to be similar or stronger than the ones obtained by assessing a single task. Thus, the combination of the assessment of both tasks could be considered preferable when aiming at monitoring changes in motor development.

In this work, participants had no previous experience of TW, as the aim was to test their performance when dealing with a new challenging locomotor task. Thus, the performance observed can be considered related mainly to primary variability (characterized by variation in motor behaviour and the absence of the ability to adapt to the specifics of the situation [1]). Future works should investigate the effect of specific training on TW performance in order to evaluate the possibility of studying, by using RQA and MSE, the shift from primary variability to secondary variability, which is characterized by the use of the afferent information produced by behaviour and experience for the selection of the motor behaviour that fits the situation best [1]. Analysing changes in motor control performance with training would be particularly interesting for understanding the potential effectiveness of training interventions in developing children.

In conclusion, the present study showed the advantages of test instrumentation (by means of inertial sensors) and nonlinear analysis of trunk acceleration data for the assessment of motor development in children. RQA and MSE allowed highlighting changes in motor control development with age that classic standard assessment of TW did not allow assessing. Thus, these measures can be considered relevant when assessing motor development in schoolchildren and complementary to standard clinical tests.

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Table captions

Table 1. Details of age groups participating in the study.

Table 2. Pearson correlation coefficients *r* for i) indices and age and ii) indices and TW-competence, in NW, TW and NW/TW.

Figure captions

Figure 1. Boxplot (median, 25th and 75th percentiles) of TW-competence for each age group.

Figure 2. TW-competence distribution for male (left) and female (right) participants.