Nonlinear Analysis of Human Movement Dynamics Offers New Insights in the Development of Motor Control During Childhood

When aiming at assessing motor control development, natural walking (NW), and tandem walking (TW) are two locomotor tasks that allow analyzing different characteristics of motor control performance. NW is the reference locomotor task, expected to become more and more automatic with age. TW is a nonparadigmatic 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. Eighty 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. The results were analyzed 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. The present results suggest this quantitative approach as relevant when assessing the motor development in schoolchildren and complementary to standard clinical tests. [DOI: 10.1115/1.4040939]

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, the 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, the 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 center 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.

Natural walking has been extensively analyzed 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 with increased mechanical work performed at the hip, knee, and ankle joints [7,8].

Tandem walking 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 antero-posterior (AP) direction during the double-support phase. TW challenges postural control system as compared to 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 analyzing 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 yr 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 nonlinear 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...
and the 95th percentile of the body mass index-for-age [21]. They
recorders (one fixed camera for the frontal plane, Canon Legria
at self-selected speed back and forth along a 15 m long tapeline,
mediolateral (ML), directions in the anatomical reference frame)
nents of trunk acceleration (vertical (V), anteroposterior (AP), and
(at L5 level) using an elastic band. The three-dimensional compo-
sion was fixed at 5, according to the literature [17,26]. Time
delay was obtained using the first minimum of the average
mutual information algorithm and was set at ten samples (corre-
sponding to 0.078 s given the sampling frequency of 128 Hz
[23,26,27].

Recurrence Quantification Analysis
State space reconstruction. State space was reconstructed by
using the delay-embedded state space of each trunk acceleration
component separately (V, AP, and ML). The embedding dimen-
sion was fixed at 5, according to the literature [17,26]. Time
delay was obtained using the first minimum of the average
mutual information algorithm and was set at ten samples (corre-
sponding to 0.078 s given the sampling frequency of 128 Hz
[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): calculated as the number of recur-
rent 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): calculated as the percentage of recur-
rent points falling on upward diagonal line segments. Number
of points forming a line segment was fixed at 4 [17].
(iii) Averaged diagonal line length (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 partici-
 pant 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 dis-
tributions of the estimated parameters on the different groups
and on the entire dataset; normal distribution was not verified for
all the parameters.

Kruskal–Wallis test with minimum level of significance of
5% was performed to analyze 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) indi-
ces and age and (ii) indices and TW-competence.

Data and statistical analyses were performed in MATLAB 2017
(MathWorks BV, Natick, MA).

Results

Tandem Walking-Competence. TW-competence distribution
resulted similar in all the age groups, 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 (Fig. 1 shows TW-competence distribution for each

\[
y_j^{(s)} = \frac{1}{\tau} \sum_{t=(j-1)/\tau+1}^{j} x_t
\]

where \(\tau\) represents the scale factor and \(1 \leq j \leq N/\tau\) [24].

Sample entropy 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].

Materials and Methods

Study Participants. Five age groups of 16 children each were
included in this study (Table 1).

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

Experimental Setup. One tri-axial wireless inertial sensor
(OPALS, APDM, Portland, OR) was mounted on the lower back
(at L5 level) using an elastic band. The three-dimensional compo-
nents of trunk acceleration (vertical (V), anteroposterior (AP), and
mediolateral (ML), directions in the anatomical reference frame)
were recorded at 128 Hz while children walked in NW and in TW
at self-selected speed back and forth along a 15 m long tapeline,
wearin comfortable shoes. Tests were performed in schools. Vir-
idos 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, GoPro-
Hero 4, GoPro Inc., San Mateo, CA, 120 fps).

Data Analysis. Standard assessment of TW (TW-competence)
was implemented by analyzing the videos (Kinovea, Version
0.8.15, 2011) and counting, for each participant, 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 TW and NW, 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 Refs.
[2], [18], and [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 nonoverlapping
windows of length τ. Each element of the coarse grained time
series \(y_j^{(s)}\), was calculated starting from the original time series
\(\{x_1, \ldots, x_n\}\), according to

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>Female/male</th>
<th>Height (m)</th>
<th>Body mass (kg)</th>
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<tbody>
<tr>
<td>6</td>
<td>8F/8M</td>
<td>1.19 ± 0.04</td>
<td>23 ± 2</td>
</tr>
<tr>
<td>7</td>
<td>8F/8M</td>
<td>1.27 ± 0.05</td>
<td>29 ± 5</td>
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<tr>
<td>8</td>
<td>8F/8M</td>
<td>1.29 ± 0.04</td>
<td>29 ± 5</td>
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<tr>
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<tr>
<td>10</td>
<td>8F/8M</td>
<td>1.40 ± 0.05</td>
<td>37 ± 5</td>
</tr>
</tbody>
</table>

Table 1 Details of age groups participating in the study
The Mann-Whitney U test showed that female participants had a significantly higher TW-competence than male ones did ($p = 0.003$). A higher number of females performed correctly the entire test (28 correct consecutive TW steps) with respect to male participants (15 females and 7 males). Figure 2 shows TW-competence distribution for male (left panel) and female (right panel) participants.

Nonlinear Indices. No difference was found in the estimated nonlinear indices between male and female participants.

Correlations Between Age and Nonlinear Indices. Age significantly correlated with RQA parameters on ML and AP axis in TW and on AP axis in NW. No significant correlation was found for 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 $\tau$, on 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 $\tau = 2.5$; AP $\tau \geq 4$). In TW, correlations resulted positive and significant for all directions ($V \tau > 2$; ML $\tau = 1.6$; and AP $\tau = 1.6$): correlations found were stronger in AP than in V and ML. In NW/TW, negative correlations were found on AP axis ($0.4 < |\rho| < 0.5$) and on ML axis ($0.3 < |\rho| < 0.4$).

Correlations Between Tandem Walking-Competence and Nonlinear Indices. Significant results found between TW-competence and RQA indices were obtained when evaluating NW and NW/TW. Positive correlations were found on AP (NW, DET and AvgL; NW/TW, DET) and on V axis (NW, AvgL; NW/TW, DET and AvgL). No significant correlation was found in TW.

Sample entropy, assessed during TW, was positively correlated with TW-competence, showing significant correlations on all three axes ($V \tau = 1; ML \tau < 5$; and AP $\tau = 1.6$). In NW/TW, significant negative correlations were found for TW-competence and R-indices on all three axes ($V \tau < 5$; ML $\tau < 3$; and AP $\tau = 1.6$). No significant correlation was found between SEN assessed during NW and TW-competence.

Table 2 shows $\rho$ values of significant correlations.

Discussion

In this 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. The results were analyzed 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).

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. The 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 [29], but also in schoolchildren motor development. By analyzing the direction of found correlations, the 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.

Recurrence quantification analysis parameters resulted weakly related to the standard assessment of TW (TW-competence). Only
the aim was to test their performance when dealing with a new task. Thus, the combination of the indices obtained from the ratio of each index assessed in NW with respect to the one assessed in TW, NW/TW, and age/TW-correlation showed that children able to perform a higher number of correct steps in TW, are those manifesting less predictable behavior that fits the situation best [1]. Analyzing changes in motor control performance with training would be particularly interesting for understanding the potential effectiveness of training interventions in developing children.

In conclusion, this 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.

Acknowledgment
Authors would like to thank participants, their parents, and teachers and coordinators of the school “Istituto San Giuseppe Lugo” (Italy) that allowed data acquisition.

Table 2  Spearman correlation coefficients $\rho$ for (i) indices and age and (ii) indices and TW-competence, in NW, TW, and NW/TW

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<tr>
<th></th>
<th>Age</th>
<th>TW-competence</th>
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<tbody>
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<td>NW</td>
<td>TW</td>
<td>NW/TW</td>
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<td>V</td>
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**References**


