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A 'Fingerprint' of locomotor maturation: Motor development descriptors, reference development bands and data-set

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ABSTRACT

Background: When aiming at studying and monitoring locomotor development in childhood, innovative indexes for the characterization of motor control performance and wearable technologies have highlighted the potential of significant advances. In particular, quantitative assessment of motor performance during natural walking (NW) and tandem walking (TW) has been proposed to highlight manifestations of motor automaticity and complexity, respectively.

Research question: This work aims at providing a quantitative overview of metrics characterizing locomotor maturation in a typically developing population, by analysing NW and TW. The final goal is to propose a novel graphical representation of motor development from childhood to adulthood, providing metrics for quantitative assessment with reference bands and data-set, supporting data interpretation and longitudinal assessment.

Methods: 112 typically developing participants (age groups: 6-, 7-, 8-, 9-, 10-, 15-, and 25 years) walked in NW and in TW at self-selected speed. 3D acceleration and angular velocity of lower trunk and shanks were collected. Temporal parameters, their variability, and nonlinear metrics characterizing human movement (harmonic ratio, short-term Lyapunov exponents, multiscale entropy, and recurrence quantification analysis) were calculated. Effect of age was analysed on the different parameters and a graphical polar plot was defined to represent parameters that showed age effect in at least one of the two tasks.

Results: Age effect was shown on temporal parameters, their variability, multiscale entropy and recurrence quantification analysis. These parameters were selected for monitoring locomotor development and presented on an ad-hoc designed polar plot showing age-group reference bands.

Significance: Graphic results outline locomotor differences with maturation at first glance. The patterns in NW and TW allow to characterize specific aspects of locomotor maturation, to evaluate in which area changes occur and towards which direction, depending on the task. The novel database containing participants' raw collected data is made available as additional result of the present study.

1. Introduction

Motor development has been defined as the adaptive change towards competence implying that adjustment, compensation and changes to reach or maintain competences continue throughout the life span [1]. The study of these changes in human motor behaviour over the lifespan is meant to understand the underlying processes and the role of the influencing factors [1].

In this wide research field, the study of locomotor development in childhood has been investigated since the early eighties, providing reference and relevant information to the scientific community, often taking advantage of gait analysis methods [1–9].

The basic assumption is that the assessment and the understanding of motor development in typically developing children is crucial to understand what happens in atypically developing ones [1] and to design and provide developmentally appropriate and effective activities [1] to possibly improve individual movement performance.

Available literature provides a solid descriptive background on the development/maturation of gait, mostly based on data collected in laboratory using stereophotogrammetry, force platforms, pressure sensing mats and/or electromyography [2–7]. Recently, the availability of wearable technologies highlighted possible further advances, allowing widespread assessment in ecological conditions (e.g. inertial sensors [10–13]) and innovative measures for the characterization of different aspects of motor control performance (e.g. variability, complexity, automaticity, regularity, stability) [14–18].

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Wearable inertial sensors have proved to be effective not only for the assessment of gait parameters in children [13,19], but also for the monitoring of functional development of other locomotor tasks [10,11,14]. In particular, the assessment of children performance during tandem walking (TW) and natural walking (NW) recently provided novel quantitative information regarding motor control maturation [14,20], using nonlinear metrics to analyse trunk acceleration, measured with a single inertial sensor (i.e. multiscale entropy, MSE [21], and recurrence quantification analysis, RQA [16], to analyse motor complexity and pattern regularity, respectively). The two selected tasks (i.e. NW and TW) were proposed based on their specificities: NW can be considered a reference for assessing aspects related to the development of motor automaticity and TW aspects related to flexibility/adaptability of the system [14,20].

When aiming at studying and monitoring motor development, both temporal parameters (and their variability) [22] and nonlinear measures of human movement [18] provide relevant information for a complete overview of locomotor maturation. In particular, measures of gait temporal parameters [22] and, more recently, their variability (standard deviation of stride time, Poincaré plots [23]) are extensively used to characterize the peripheral realization of gait pattern [15]. On the other hand, nonlinear measures, usually applied on trunk acceleration data, have been proposed as descriptors of specific features characterizing the motor control underlying said realization of gait pattern, such as pattern regularity (RQA), motor complexity (MSE), gait stability (short Lyapunov exponents, [24]), and rhythmicity or symmetry (harmonic ratio [25]).

Given the multitude of these possible parameters, a synthetic overview of significant results is hard to attain, but necessary to provide a comprehensive picture of motor development as a whole and support the interpretation of its specific different components.

The present work aims at providing an overview of locomotor maturation in typically developing children: reference quantitative data, collected using wearable inertial sensors, and descriptors of performance of NW and TW in a typically developing population (6–25 years of age) were analysed with respect to age maturation and related to specific functional correlates. The novel data-set, containing participants' raw collected data, is made available as reference for result comparability in future works and possible replication studies.

The final goal is to propose a polar graphical representation for the quantitative longitudinal monitoring of motor development from childhood to adulthood, offering innovative assessment, reference bands and support results interpretation.

2. Materials and methods

2.1. Study subjects

Seven groups of 16 Italian participants each (8 females and 8 males) were included in the study (Table1).

All children were born at full term and had no known developmental delay. All children and adults had no musculoskeletal pathology and had a BMI between the 5th and the 95th percentile of the BMI-for-age [26]. The Review Board Committee of the authors' institution approved this study, and informed consent was obtained from the participant' parents for children and from adult participants.

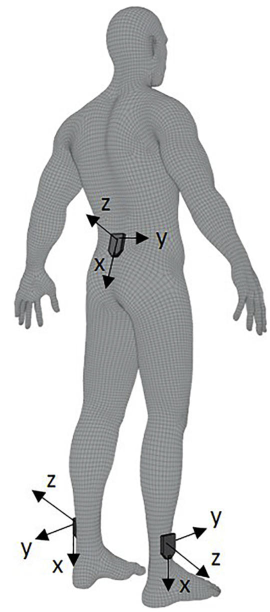

Fig. 1. Inertial sensor positions (lower trunk - L5 level, and shank - above lateral malleolus) and axis orientations.

2.2. Experimental setup

Three tri-axial wireless inertial sensors (OPALS, Apdm, USA) were mounted respectively on the lower back (L5 level) and on the shanks (above lateral malleolus) using straps (Fig. 1).

Data were recorded at 128 Hz while the participants walked in NW at self-selected speed back and forth in a 15 m long corridor and in TW on a 15 m long tapeline on the floor. None of the participants had previous experience of TW. Prior to data collection, all participants were allowed to perform a tentative trial (10 TW strides) to ensure they understood TW instructions [27]. Tests were performed in schools for the children and the adolescents and at the University for young adults.

2.3. Data analysis

Foot contacts and foot offs were identified from the angular velocity around the medio-lateral axis of the leg [28]; the algorithm [28], originally designed for NW, was adapted and used for TW identifying local minima at the beginning and end of the swing phase. For NW and TW, turns, the first two and the last two strides of each walking section were removed from the signal before further analysis [15]. For all participants 14 strides were analyzed, being the maximum number of tandem strides identified for all subjects.

Table 1
Details of age groups participating in the study. Schoolchildren data were presented in Bisi et al. [20].

Abbreviation	Description	Female/male	Age (years)	Height (cm)	Body mass (kg)
6YC	16 6-year old children	8F/8M	6 ± 0	119 ± 4	23 ± 2
7YC	16 7-year old children	8F/8M	7 ± 0	127 ± 5	29 ± 5
8YC	16 8-year old children	8F/8M	8 ± 0	130 ± 5	29 ± 6
9YC	16 9-year old children	8F/8M	9 ± 0	138 ± 6	34 ± 6
10YC	16 10-year old children	8F/8M	10 ± 0	141 ± 5	37 ± 5
15YA	16 15-year old adolescents	8F/8M	15 ± 0	168 ± 9	60 ± 13
25YA	16 25-year old adults	8F/8M	25 ± 1	171 ± 9	64 ± 11

Temporal parameters

Stride- (StrideT, in seconds), stance- (StanceT, expressed in % of StrideT), and double support- time (DS, expressed in % of StrideT) were calculated from foot contact events *per* test according to [28]. Median values were calculated per participant and per task. Fundamental frequency (FF, in *Hz*), associated to cadence in NW, was calculated on trunk acceleration signal [29]. Normalized StrideT and normalized Fundamental frequency were scaled according to Hof [30] (nStrideT and nFF). As StrideT and FF are inversely related, they offer theoretically the same kind of information. Authors included both of them in the investigation because of the different approach used for their estimation (time-domain for StrideT and frequency-domain for FF).

Variability of temporal parameters

Temporal parameter variability for each subject was calculated as standard deviation (stdStrideT, stdStanceT, stdDS) and for StrideT also as Poincaré plots (StrideD1 and StrideD2) [23].

Nonlinear measures

Harmonic Ratio (HR, related to rhythmicity), short Lyapunov Exponents (sLE, related to stability), Multiscale Entropy (MSE, related to complexity and automaticity) and Recurrence Quantification Analysis (RQA, related to pattern regularity) were calculated on trunk acceleration data along the 3 directions (vertical, V, medio-lateral, ML, and antero-posterior, AP) [18].

- Harmonic Ratio (HR) was calculated, decomposing the whole signal components into its harmonics, as the ratio between the sum of the first 10 even and the first 10 odd harmonic multiples of the FF [15,25].
- Short term Lyapunov exponents (sLE) calculated using the method defined by M.T. Rosenstein et al [24]. The state space reconstruction was composed by the delay embedded state spaces of each acceleration component (sLE_v, sLE_ml and sLE_ap); data were not normalized.
- Recurrence Quantification Analysis (RQA) implied the calculation of recurrence rate (RR), determinism (DET) and averaged diagonal line length (AvgL) for each acceleration component [16,20].
- Multiscale Entropy (MSE) was calculated by assessing Sample Entropy (SEN) on the 3 acceleration components, for values of τ ranging from 1 to 6 according to the methodology defined by previous analysis [14,21].

For sLE and RQA calculation, the state space was constructed with an embedding dimension $dE = 5$ and a time delay of 10 samples [15,20] for all the subjects and both the tasks, to ensure comparability. Raw unfiltered data were analysed to assure that information was not lost or altered.

HR was selected given its widespread application with a similar number of strides [31] even if, based on the work by Riva et al [32], its reliability is 30% when calculated over 14 strides. The other investigated nonlinear indexes were selected based on the available number of strides per trial, ensuring a reliability of at least 20% [32].

A Jarque-Bera test 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 25th and 75th percentiles of results were calculated per each age group.

A Kruskal-Wallis test with minimum level of significance of 1% was performed to analyse the effect of age on the different parameters.

A graphical polar plot was defined to represent parameters that showed age effect in at least one of the two tasks. The graphical solution was designed to highlight different areas of motor control performance descriptors: i) temporal parameters, ii) variability, iii) pattern regularity, iv) motor complexity, v) stability and vi) rhythmicity.

In order to improve readability and highlight differences between ages and conditions, calculated parameters were normalized with respect to the 2nd and 98th percentiles of the values found on all the available data (both from NW and TW task) for each parameter. Polar reference bands (25th, median and 75th percentiles) for each age group were represented.

3. Results

The reference data-set of acquired raw synchronized data of 3D acceleration and angular velocity of trunk, right and left shanks are available in the supplementary material, 14 complete strides for both NW and TW are included for each trial of each subject, together with the additional information for each participant: sex, age, height, weight.

Temporal parameters

No significant difference was found between temporal parameters calculated from the right or from the left lower leg inertial sensor, thus, results from the two limbs were averaged per each participant.

In NW, FF decreased significantly with age ($p < 0.001$) from 1.6 Hz (6YC) to 0.8 Hz (25YA) while median StrideT increased significantly with age, starting from 0.8 s for 6YC to 1.6 s for 25YA. The same trends were found for the corresponding adimensional parameters nFF and nStrideT. StanceT increased significantly with age, starting from a median value of 56% in 6YC and reaching 59% in 15YA and 25YA. DS increased significantly with age from 6YC to 15YA, starting from a median value of 13.8% in 6YC and reaching 20.8% and 18.7% in 15YA and 25YA, respectively.

In TW, no significant trend with age was found for FF (median values ranged between 1.6 Hz and 2.3 Hz). Median StrideT decreased significantly with age from 6YC (2.4 s) to 15YA (1.6 s), and increased again in 25YA (2.4 s). Similar trends were found for the corresponding normalized parameters nFF and nStrideT. No significant trend with age was found for StanceT%: median values per group were between 70% and 75%. No significant trend with age was found for DS(%): median values per group were between 40% (15YA) and 50% (6YC and 25YA).

Variability of temporal parameters

In NW, stdStrideT slightly but significantly ($p = 0.01$) decreased with age from 0.04 s (6YC) to 0.03 s (25YA). stdStanceT decreased with age ($p < 0.001$) from 2.7% (6YC) to 0.8% (25YA). stdDS decreased with age ($p < 0.001$) from 4.0% (6YC) to 1.2% (25YA). No significant trend with age was shown for StrideD1. StrideD2 (long term variability) slightly decreased with age ($p = 0.01$) from 0.04 s (6YC) to 0.03 s (25YA).

In TW, stdStrideT decreased significantly with age ($p < 0.001$) from 0.37 s (6YC) to 0.14 s (25YA). stdStanceT decreased with age ($p < 0.001$) from 4.7% (6YC) to 2.1% (25YA). stdDS decreased with age ($p < 0.001$) from 7% (6YC) to 3% (25YA). StrideD1 decreased significantly ($p < 0.001$) from 0.3 (6YC) to 0.1 (25YA), and StrideD2 ($p < 0.001$) from 0.42 to 0.17.

Nonlinear measures

In NW, HR and sLE did not show any significant trend with age. SEN values significantly decreased with age in all three directions for all τ values. RR, DET and AvgL calculated for ML and AP directions increased significantly with age ($p < 0.001$); no significant trend was found for V direction.

In TW, HR and sLE did not show any significant trend with age. SEN values increased significantly with age in all three directions for all τ values. RR, DET and AvgL calculated for ML and AP directions decreased significantly with age ($p < 0.001$). No significant trend was found for V direction.

Median values and 25th and 75th percentiles of all the analysed parameters for each group and both tasks are available in the supplementary material.

Graphical representation

Based on statistical analysis, the significant parameters selected for monitoring locomotor development were:

1) For 'Temporal parameters': nStrideT, StanceT, DS. Normalized StrideT was preferred to strideT, allowing accounting for height

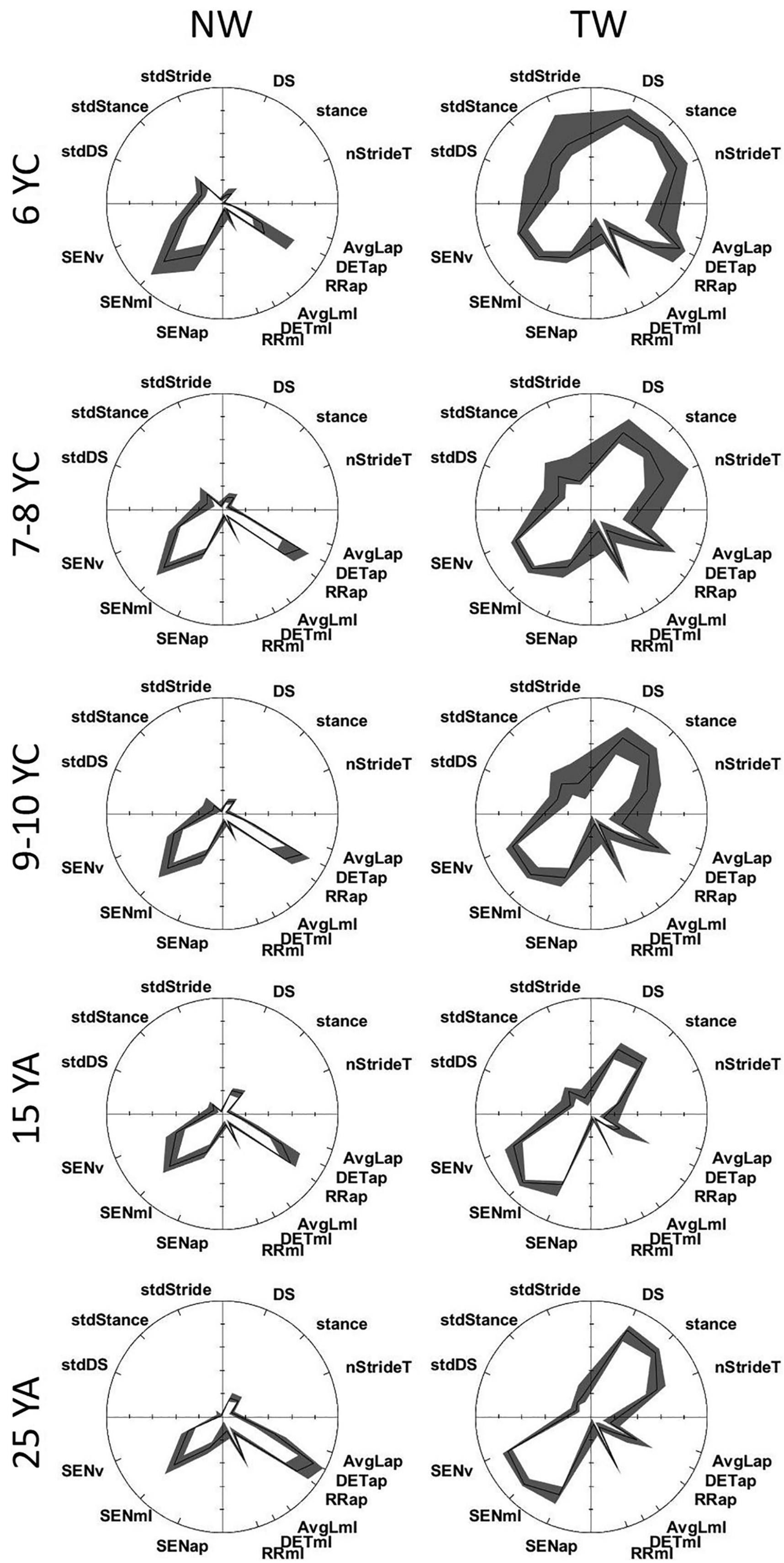

Fig. 2. Age reference bands for NW and TW. Sectors represent temporal parameters (nStrideT, Stance and DS), temporal parameter variability (stdStride, stdStance and stdDS), motor complexity (SENap, SENml and SENv, for $\tau = 6$) and pattern regularity (RRml, DETml, AvgLml, RRap, DETap and AvgLap).

differences. nFF was not selected as it provided the same (inverse) information as nStrideT in NW, according to expectations, while it showed no significant trend in TW.
2) For 'variability': stdStrideT, stdStance, stdDS.
3) For 'motor complexity' [20]: SENv, SENml and SENap ($\tau = 6$). Since SEN values showed similar trend for all the time-scales, only $\tau = 6$ was included in the graphical representation as the one showing the lowest p-value both in NW and in TW.
4) For 'pattern regularity' [20]: RR, DET and AvgL calculated on AP and ML.

No age maturation effect was found for HR and sLE in both NW and TW, thus, sectors representing 'rhythmicity' and 'gait stability' were not included in the final graphical representation.

Fig. 2 shows reference bands representing median, 25th and 75th percentiles of each parameter on a polar plot for each age group. Since no significant difference was found between 7YC and 8YC, and between 9YC and 10YC, the two groups were merged in the common age-reference bands (7–8YC and 9–10YC).

4. Discussion

In the present work, locomotor development descriptors for a typically developing population (aged 6–25 years) were proposed. The assessment was performed on data collected in typically developing children using wearable inertial sensors on trunk and shanks, and recent measures for the description of motor performance were calculated and analysed, with the purpose of outlining a quantitative approach for the monitoring of locomotor development in children.

Temporal parameters and their variability, along with nonlinear metrics for the characterization of specific aspects of motor performance [18] were estimated to highlight differences in motor control in 7 age groups from childhood to adulthood, during a paradigmatic (NW) and a non-paradigmatic (TW) locomotor tasks [14,20].

NW temporal parameters and their variability resulted in agreement with literature, showing trends and median values similar to those shown in other studies [3,6,33], supporting their reliability, despite the limited number of analysed subjects (16) per age group. FF, when analysed with respect to the values and trends of StrideT, was confirmed to be associated to cadence in children and adults during NW as resulting from the inverted pendulum mechanics [29].

To authors' knowledge, no information regarding TW temporal parameters and their variability is present in the literature. According to present results, TW Stance and DS in young healthy adults resulted to last 75% and 50% of stride time, respectively, showing no significant trends among the considered age groups. FF values did not differ significantly among groups (median FF range, 1.6 Hz–2.3 Hz) and, differently from NW, resulted not directly associated to TW cadence (median StrideT range, 1.5 s–2.4 s), supporting the non-applicability of the inverse pendulum model in the realization of TW biomechanics.

Variability of TW temporal parameters significantly decreased from childhood to adulthood, as could be reasonably expected with age maturation. Although a direct comparison of the present results with literature is not possible, the limited data dispersion per age group supports their reliability. These quantitative data can be considered a starting point for future studies on TW and could effectively integrate its standard clinical assessment (i.e. number of correct consecutive steps), providing a quantitative evaluation of different motor performance characteristics as related to the specific age-group and to others.

Among the nonlinear measures, MSE and RQA resulted to highlight differences in motor complexity and pattern regularity as related to age: motor complexity resulted to decrease in all three directions in NW, supporting the increase in automaticity of the pattern, while increasing in TW; the regularity of the pattern in AP and ML directions increased in NW and decreased in TW. The same measures in the same directions also resulted [20] to better quantify differences related to age in school children than the standard quantification of TW competence (i.e. number of correct consecutive steps [20]), supporting their potential for the assessment and monitoring of locomotor development. On the other hand, HR and sLE did not show any significant trend with age in the two analysed tasks, suggesting that rhythmicity and short term stability of 6 year old locomotor control in walking have already reached a level of maturation that will not further change significantly after this age. Clearly, the extension of this analysis to children younger than 6 and adults older than 25 could integrate the current results, broadening the overview of differences in motor control related to age. A possible limitation regarding HR estimation and analysis is the number of analysed strides, which allowed to reach a reliability lower than that of the other investigated nonlinear indices [32]; a higher number of strides could likely have improved or changed HR estimates providing different results.

Considering the proposed metrics as a whole, showing a significant trend with age in the reference motor tasks (NW and TW), an overall quantitative outline of how motor control maturation progresses with age can be drawn: as well-known [22], variability of temporal parameters decreases with time, but this is attained concurrently with an increase in automaticity exhibited in the performance of a paradigmatic motor task (trends of SEN and RQA in NW), and with an increase in complexity shown in the performance of a similar but non-paradigmatic task (trends of SEN and RQA in TW) [14,20].

With the scope of providing a tool to support the monitoring of motor control as a whole, in its concurrent and complex manifestations, the proposed graphical representation of the results provides a comprehensive overview of the parameters related to different characteristics of motor control that resulted to highlight differences related to age in the execution of the selected motor tasks. The patterns in NW and TW can be considered 'Fingerprints' of locomotor maturation, allowing to evaluate in which area differences are observed and towards which direction, depending on the task. As an example, from Fig. 2, it can be easily observed that motor complexity increases with age in TW and decreases with age in NW [14] or that variability of temporal parameters is significantly higher in TW when compared to NW in children, while tends to become comparable (even if still higher) in young adults.

The proposed representation does not only support result interpretation, but also offers a novel approach to the assessment of locomotor development, providing reference bands for typically developing children. With the inclusion of a higher number of subjects, the proposed plot has the potential to become a useful tool for screening and monitoring locomotor performance in developing children, and it could integrate clinical interpretation in the assessment of locomotor performance in atypically developing children.

Finally, the open data-set containing participants' raw collected data is shared as additional result of the present study, aiming to support research activity and collaboration in the emerging field of quantitative motion analysis for the assessment of motor control development.

Conflict of interest

None to declare.

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