



# IMU-based linear and nonlinear metrics for the characterization of fine motor development in early childhood

Maria Cristina Bisi<sup>a,b,\*</sup>, Rita Stagni<sup>a,b</sup>

<sup>a</sup> Department of Electrical, Electronic and Information Engineering “Guglielmo Marconi”, University of Bologna, Via del Risorgimento 2, Bologna 40136, Italy

<sup>b</sup> Interdepartmental Center for Industrial Research on Health Sciences & Technologies, University of Bologna, Bologna 40064, Italy

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## ABSTRACT

**Background:** Fine motor competence assessment plays a pivotal role in neuropsychological examinations for the identification of developmental deficits. The Placing Bricks (PB) test evaluates fine motor competence relying on the measurement of time to completion. Recently, the PB test was instrumented using wearable inertial sensors to complement its standard assessment with reliable and objective measures of performance (*i.e.*, cycle and placing durations). This work aims at extending the metrics that allow a quantitative fine motor assessment and at investigating fine motor trajectory from 3 to 7 years of age.

**Research question:** How can IMU-based linear and nonlinear metrics provide insight into fine motor development during early childhood?

**Methods:** 126 typically developing children (3–7 years) performed the PB test with inertial sensors on both wrists. Temporal parameters (Cycle and Placing durations), their variability (interquartile range, short-term and long-term variability, via Poincaré plots) were calculated on angular velocities, and nonlinear metrics (multiscale entropy and recurrence quantification analysis) on acceleration data. The effects of age, handedness, and sex were analysed: parameters showing age effects were visualized using a polar plot with age reference bands.

**Results:** Results revealed differences related to age and hand dominance: cycle and placing durations as well as variability decreased, while multiscale entropy increased and recurrence decreased with age and when using the dominant hand. Both age and the use of the dominant hand are associated with shorter, less variable cycles, with more complex movement patterns, reflecting more mature fine motor control.

**Significance:** The patterns highlight specific characteristics of fine motor maturation, showing in which domain changes occur and towards which direction. The proposed IMU-based approach effectively described fine motor control development in the analysed population.

## 1. Introduction

Fine motor competence in early childhood is a fundamental building block of psychological, physiological, behavioural, and cognitive development [1]. Evidence supports a close association between motor and cognitive development, and highlights the integral role of early fine motor skills in readiness for and adaptation to primary school [1]: promoting social inclusion, enhancing educational outcomes and academic success [2]. Therefore, assessing fine motor competence is pivotal in neuropsychological evaluation to ensure the timely assessment of fine motor development and, in case of delay, to allow the design of effective interventions. For assessing fine motor skills, graphomotor tasks and

bimanual prehension (*e.g.*, picking up and moving objects) remain standard practices [3]. Several tests have been proposed, although their evaluation is mainly based on qualitative observation, limiting quantitative assessment to measuring test duration or to counting errors [3]. Based on these tests [4], older vs younger children [5], females vs males [4], and the use of the preferred hand [6] perform tasks faster and with fewer errors, but no general consensus exists on the age at which adult-like performance is achieved, and little is known about the specific characteristics of the performance.

A recent review [7] emphasized the importance of integrating motion-capture devices with traditional observational methods to achieve a more comprehensive evaluation of children’s motor competence.

\* Corresponding author at: Department of Electrical, Electronic and Information Engineering “Guglielmo Marconi”, University of Bologna, Via del Risorgimento 2, Bologna 40136, Italy.

E-mail addresses: [mariacristina.bisi@unibo.it](mailto:mariacristina.bisi@unibo.it) (M.C. Bisi), [rita.stagni@unibo.it](mailto:rita.stagni@unibo.it) (R. Stagni).

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Technology-based assessment offers a deeper insight, allowing for the quantification not only of task outcomes (e.g., time measurements, error counts) but also the quality of task execution (e.g., fluidity, variability) with a more process-oriented perspective. Technology-based solutions for fine motor skill assessment primarily utilize force transducers, instrumented tablets and pens, surface electromyography, and optoelectronic systems [3,8]. Among these, only motion capture systems allow for a quantitative kinematic analysis of tasks such as reaching or prehension. However, motion-capture-based 3D kinematics, while effective, is time-consuming and resource-intensive, requiring a dedicated laboratory setup, limiting its widespread applicability. Inertial measurement units (IMUs) represent an alternative [9,10]: IMUs are robust, portable, and generally involve shorter setup times and faster data output, making them a practical and efficient tool for assessments in ecological conditions.

Recently, these authors proposed an instrumented version of Placing Bricks test (PBtest) [10]: participants are asked to attach 18 square-shaped ( $2 \times 2$ ) Duplo™ bricks onto a  $3 \times 6$  brick board as quickly as possible [11], time to completion is related to fine motor competence. The instrumented version, using data from a wrist mounted IMU, supplements the traditional assessment with reliable and objective, process-oriented performance measures, such as cycle and placing durations and their variability [10]. In a population of 6- and 7-year-old children, the proposed approach revealed age related differences: 6-year-olds exhibited longer cycle durations and greater variability, reflecting developmental progression and potential differences in hand dominance; 7-year-olds demonstrated faster and more consistent performance, and refined motor control associated with dominant hand training during the first years of school.

Beyond task phase durations and their variability, IMU-based PBtest allows to compute additional metrics related to motor control performance. Nonlinear metrics, in particular, demonstrated their effectiveness in revealing age-related changes [12,13] in locomotor development when applied to trunk acceleration signals: multiscale entropy (MSE) and recurrence quantification analysis (RQA) during normal and tandem gait highlighted the concurrent development, related to age maturation [12,13], of automaticity (during gait) and motor complexity (during tandem gait) in typically developing school-aged children [14, 15]. The same metrics can be expected to highlight a similar trend in fine motor competence: an increase in MSE and a decrease in RQA indexes with age, related to increased quality of the control of upper arm movement trajectory during the execution of PBtest, reflecting the availability of more complex motor solutions.

Since significant changes in fine motor skills mostly occur between 3 and 6 years of age [4], but the PBtest was originally designed for individuals aged 5–83 years, this study aimed primarily to evaluate fine motor performance in typically developing children aged 5–7 years using the instrumented version of the PBtest. However, to investigate motor skill development in early childhood, a smaller group of children, aged 3 and 4 years, capable of following the test instructions, was also included.

The ultimate goal of the present study is to characterize fine motor performance development in typically developing children during the PBtest through both linear and nonlinear metrics, examining the effects of age, hand dominance, and sex. Children identified as at risk for developmental coordination disorder (based on the Developmental Coordination Disorder Questionnaire [16]) were analysed separately and qualitatively compared to the other participants.

## 2. Methods

### 2.1. Study participants

One hundred and twenty-six Italian children with no known developmental delay or musculoskeletal pathology, as reported by parents via questionnaire, participated in the study (Table 1).

**Table 1**

Details of age groups participating in the study. Number of participants (n) and participants' characteristics (median (min–max)) for the different age groups. Part of schoolchildren data (6YC and 7YC) were presented in [10].

	n (Male/ Female)	age (months)	height (m)	body mass (kg)
3YC	12 (3 F/9 M)	43 (39–48)	1.03 (0.96–1.10)	17.8 (14.0–29.6)
4YC	11 (5 F/6 M)	53 (49–60)	1.10 (1.04–1.17)	19.5 (16.7–23.5)
5YC	18 (13 F/5 M)	67 (63–73)	1.17 (1.11–1.124)	20.5 (16.5–32.0)
6YC	36 (18 F/18 M)	78 (73–85)	1.23 (1.12–1.31)	26.2 (19.5–38.0)
7YC	49 (21 F/28 M)	92 (85–97)	1.28 (1.16–1.40)	28.0 (19.7–41.0)

Parents filled in the Developmental Coordination Disorder Questionnaire (DCDQ) [16].

Children were divided into 5 age groups based on the attended preschool/school year (3 to 4-year-old preschoolers, 3YC; 4 to 5-year-old preschoolers, 4YC; 5 to 6-year-old preschoolers, 5YC; 6 to 7-year-old first graders, 6YC; 7 to 8-year-old second graders, 7YC).

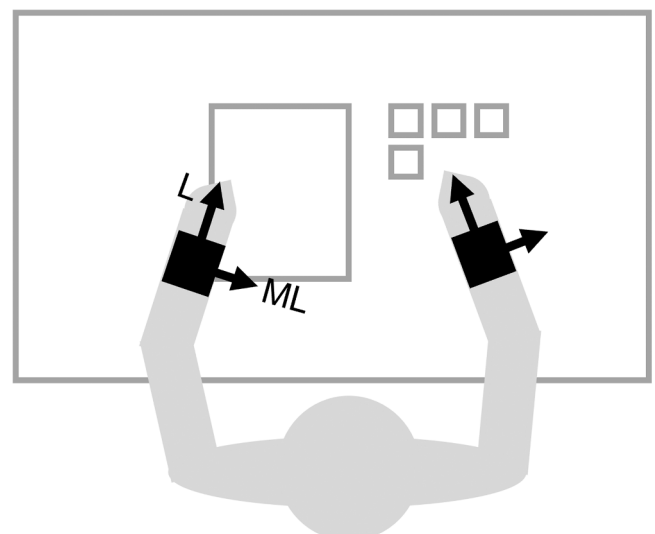
The Bioethics Committee of the authors' institution approved this study, and informed consent was obtained from the participant's parents.

### 2.2. Experimental protocol

All participants were asked to draw a circle on a piece of paper using a pencil placed in the middle of the desk [6]; the used hand, confirmed by the classroom teacher's report on hand preference [6], was considered dominant.

According to [10], 2 IMUs (OPALS, Apdm, USA) were mounted, one *per* wrist, using straps (Fig. 1). The sensing axes were aligned with the forearm anatomical directions: longitudinal (L-x), medio-lateral (ML-y), and antero-posterior (AP-z) (Fig. 1).

Participants performed the PBtest following Test of Motor Competence guidelines [11]: 18 square-shaped Duplo™ bricks are to be placed on a Duplo™ board ( $3 \times 6$  bricks) as fast as possible. Tests were performed in kindergartens and schools, in a well-lit and ventilated room with adequate heat and sound, during normal school hours. The children were assessed wearing comfortable clothes, while sitting on a school chair in front of a school desk; the bricks were positioned in horizontal



**Fig. 1.** Inertial sensor positions and axis orientations [10].

rows of 3 on the side of the active hand and the board was held firmly with the other hand. Children were tested individually; the experimenter explained and demonstrated the test using the same verbal and visual instructions for all ages. Before data collection, all participants were allowed to practice one run to ensure they understood instructions. Both hands were tested, one trial for each hand. Hand order was decided by the child and always coincided with starting with the dominant hand. To ensure accurate data analysis, children were instructed to keep their hands still on the desk at both the beginning and the end of the trial.

Time to completion in seconds (*i.e.*, standard PB assessment, PBtime) was recorded using a stopwatch. During testing, IMU data (3D angular velocity and 3D acceleration components) were recorded at 128 Hz.

### 2.3. Data analysis

Placing events were identified from wrist angular velocity as described in [10]: the algebraic sum of angular velocity components around the L and the AP axes was low-pass filtered with a 4th order Butterworth filter with a cut-off frequency of 6 Hz. Absolute peaks were identified as associated to flight phases (discriminating the direction of brick to board flight phase, positive, and board to brick phase, negative), then, minima after each brick to board flight peak and before each board

to brick flight were identified as associated to Initial Placing and Placing End, respectively [10].

The initial phase (*i.e.*, from rest at start to the first Initial Placing) and the final phase (*i.e.*, from the final Placing End to rest) were removed before further analysis. For all participants, only the 17 full task cycles were analysed. Temporal parameters and their variability were thus extracted from filtered IMU angular velocities [10], nonlinear metrics from raw acceleration components.

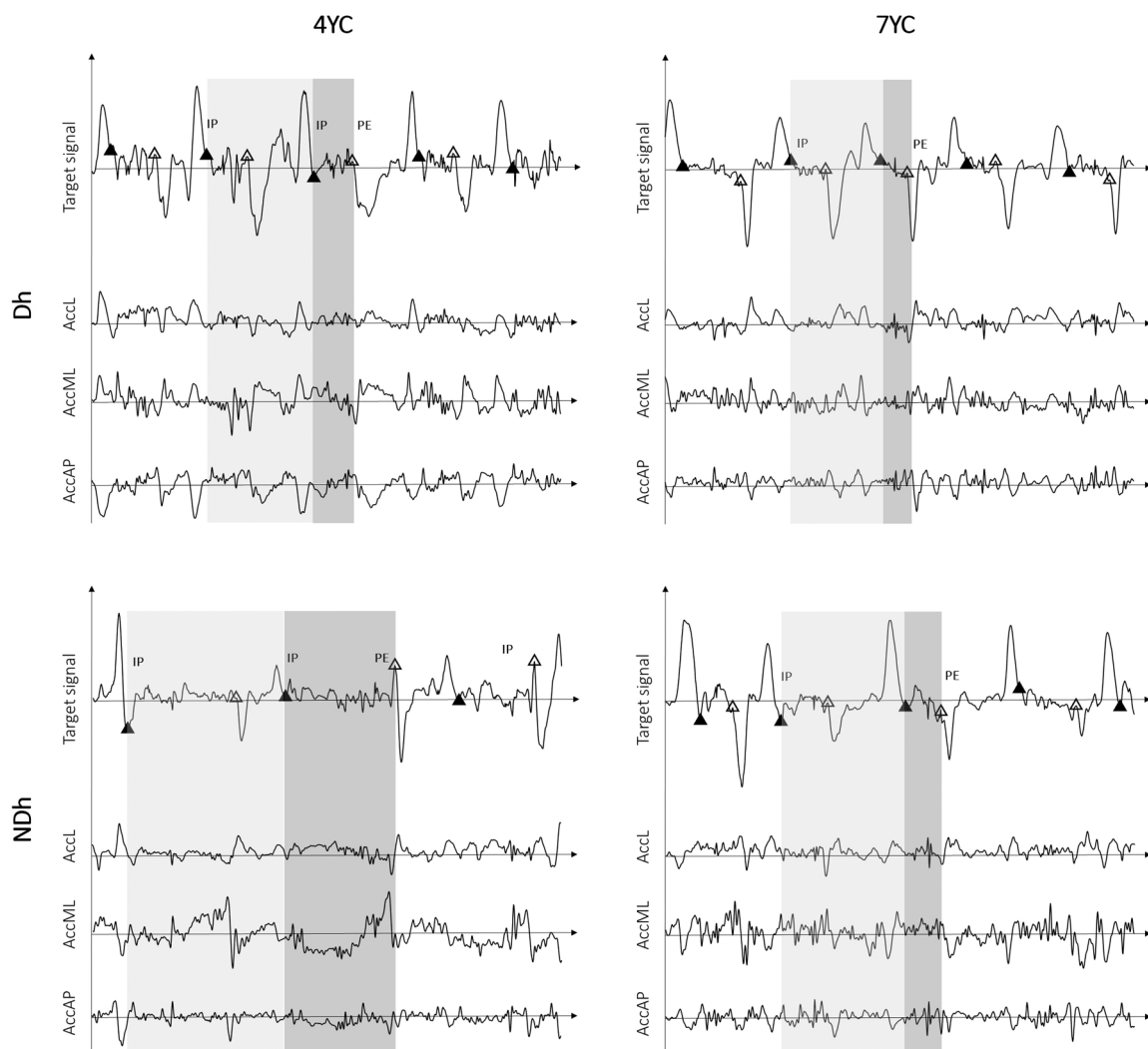
#### 2.3.1. Temporal parameters

Cycle [s] and Placing [%Cycle] duration were calculated *per test*: Cycle is the time duration from an Initial Placing to the following Initial Placing; Placing the time duration from an Initial Placing to the following Placing End [10] (see examples in Fig. 2).

#### 2.3.2. Variability of temporal parameters

Cycle and Placing variability was calculated as:

- interquartile (IQR);
- short- and long-term variability using Poincaré plots (SD1, short-term, SD2, long-term variability) [17].



**Fig. 2.** Exemplificative 10 s signals for a 4-year-old child (4YC) and a 7-year-old child (7YC), dominant hand (Dh) and non-dominant hand (NDh). In each figure, first row: target signal for events identification (algebraic sum of angular velocity components around the L and the AP axes), 2nd–4th row: wrist acceleration components along L, AP, and ML directions. Y-axis units and values are omitted as only the signal pattern is of interest. Full triangles represent Initial Placing (IP) and white triangles Placing End (PE). Each plot highlights one Cycle and one Placing phase in light grey and dark grey, respectively.

### 2.3.3. Nonlinear metrics

MSE [18] and RQA [19] were calculated from the 3 wrist acceleration components of the entire analysed signals, starting from the first Initial Placing to the last Placing End. Given the sampling frequency and that the fastest trials lasted 22 s, the number of data points was always higher than 2800.

MSE was calculated by assessing Sample Entropy (SEN) for values of  $\tau$  ranging from 1 to 6 [13,18]. Acceleration signals were normalized to have standard deviation 1. Consecutive coarse-grained time series were calculated by averaging increasing numbers of data points in non-overlapping windows of length  $\tau$ . For each coarse-grained time series, SEN was calculated as the conditional probability that two sequences of  $m$  consecutive data points ( $m = 2$ ) similar to each other will remain similar (i.e. distance of data points inferior to a fixed radius = 0.2), when one more consecutive point is included.

For RQA, state space was reconstructed by using the delay embedded state space of each acceleration component separately. Embedding dimension was fixed at 5; time delay was set at 10 samples. Distance between all the points of the embedded time series was calculated. If this distance was less than or equal to a threshold (threshold = 40 % of the maximum distance) the point is a recurrence. Recurrence rate (RR), determinism (DET), and averaged diagonal line length (AvgL) (number of points forming a line segment fixed at 4) were calculated for each acceleration component [14,19].

### 2.3.4. Statistical analysis

A Jarque-Bera test was performed to test normal distribution of PBtime, Cycle, and Placing in the age groups; since the normal distribution was not verified in all the groups, median values and 25th and 75th percentiles of results were calculated *per* age group. A Scheirer-Ray-Hare test (significance level 0.05) was applied to test the effect of age, handedness, and sex on estimated parameters. In absence of significant interactions, the subsequent statistical analysis was performed separately *per* factor.

Effect of age was analysed (Kruskal-Wallis test 5 %) *per* parameter, and for dominant (Dh) and non-dominant (NDh) hand. When a significant age effect was found, a multiple comparison test was performed to evaluate which of the analysed groups showed significant differences from the others. Dunn-Sidak correction was considered for post hoc analysis.

The effect of hand dominance was tested on the entire group of participants and *per* age group, using the Wilcoxon signed-rank test for repeated measures (significance level 0.05).

The effect of sex was analysed on the entire group of participants and, since males and females were unbalanced in the 3YC and 5YC groups, by combining preschool children (3YC, 4YC, 5YC) into one group and school children (6YC, 7YC) into another, using the Mann-Whitney  $U$  test (significance level 0.05).

A graphical polar plot was defined to represent parameters that showed age effect.

Polar reference band (25th, median and 75th percentiles) of the parameters was represented in a polar plot *per* age. The graphical solution was designed to highlight different areas of motor performance descriptors [13,15]: 2 sectors describe the peripheral realization of movement patterns (i) temporal parameters; ii) variability of temporal parameters) and 2 sectors describe the dynamic properties of the analysed kinematic signals, which relate to specific characteristics of the motor control underlying the realisation of the movement pattern (iii) pattern regularity (RQA parameters); iv) motor complexity (MSE)).

Represented parameters were normalized with respect to the corresponding 2nd and 98th percentile range of the full dataset.

Data and statistical analyses were performed in MATLAB2023a (MathWorks BV, Natick, MA, USA).

## 3. Results

Seven children were excluded from the statistical analysis: 2 6YC (1 M, 80 months, 1 F, 77 months) and 1 7YC (M, 96 months) with DCDQ results below age-adjusted threshold [20]; 4 (M, 6YC) without complete questionnaires. Three 3YC participants were unable to perform the PBtest with the NDh, only the tests performed with the Dh were considered.

Median values and 25th and 75th percentiles of all analysed parameters for each age group, divided by Dh and NDh, are provided in Table S1 (supplementary material).

### 3.1. Age effect

Age resulted to affect all the estimated temporal and nonlinear parameters for both Dh and NDh (Kruskal-Wallis test, level of significance 0.05), except for SD1 of Placing and RQA parameters calculated in the AP direction for the Dh. P-values and effect sizes, epsilon squared ( $\epsilon^2$ ), are shown in Table S1.

PBtime decreased significantly with age, showing the maximum values for 3YC (median, 25th-75th, Dh: 59 s, 54–66 s; NDh: 69 s, 60–78 s) and the lowest for 7YC (median, 25th-75th, Dh: 32 s, 28–37 s; NDh: 36 s, 31–40 s): median PBtime decreased constantly from 3YC to 7YC, with the exception of 5YC, showing PBtime significantly lower than 6YC with the Dh and comparable to 7YC (for NDh, the trend was similar, but not significant).

The same trend was observed for IMU-based Cycle and its variability for both Dh and NDh, resulting the highest in 3YC and the lowest in 7YC, with 5YC median values slightly lower than 6YC, although not significantly. For Dh, median Cycle ranged from 1.7 s (7YC) to 2.7 s (3YC), median Cycle IQR from 0.5 s (7YC) to 1.7 s (3YC), median Cycle SD1 and SD2 from 0.5 s and 0.5 s (7YC) to 1.5 s and 1.2 s (3YC), respectively. For NDh, median Cycle ranged from 2.0 s (7YC) to 3.3 s (3YC), median Cycle IQR from 0.6 s (7YC) to 2.4 s (3YC), median Cycle SD1 and SD2 from 0.6 s and 0.6 s (7YC) to 2.2 s and 1.9 s (3YC), respectively.

Placing decreased significantly and monotonically with age: it ranged from 38 % (7YC) to 51 % (3YC) for Dh and from 42 % (7YC) to 60 % (3YC) for NDh. Placing variability (i.e., IQR, SD1, and SD2) decreased from 3YC to 5YC, not changing from 5YC to 7YC. For Dh, Median Placing IQR ranged from 16 % (7YC) to 25 % (3YC), median Placing SD1 and SD2 from 14 % and 13 % (7YC) to 20 % and 19 % (3YC), respectively. For NDh, Median Placing IQR ranged from 18 % (7YC) to 26 % (3YC), median Placing SD1 and SD2 from 14 % and 14 % (7YC) to 26 % and 19 % (3YC), respectively.

MSE values increased with age in all directions, showing the lowest values in 3YC (e.g.,  $\tau=6$ , median [MSE-AP, MSE-ML, MSE-L], Dh: [1.2, 1.2, 0.9], NDh: [1.1, 1.1, 0.8]) and the highest in 7YC (e.g.,  $\tau=6$ , median [MSE-AP, MSE-ML, MSE-L], Dh: [1.5, 1.6, 1.2], NDh: [1.5, 1.5, 1.2]).

RQA parameters decreased with age in all directions, showing the highest values in 3YC (e.g., median RR-L, Dh: 18.2, NDh: 21.6) and the lowest values in 7YC (e.g., median RR-L, Dh: 10.3, NDh: 10.0). When considering ML and L directions, 6YC showed significantly lower SEN values and higher RQA parameters than 5YC, deviating from the overall age trend.

### 3.2. Differences between Dh and NDh

When comparing Dh and NDh (Wilcoxon signed-rank test, level of significance 0.05), considering the entire group of participants, PBtime, temporal parameters and their variability resulted significantly lower for Dh, except for SD2 of Placing. Among nonlinear metrics, MSE in ML resulted higher for Dh; RQA parameters lower in ML for the Dh and higher in AP (Det and AvgL).

When considering single age groups, PBtime was significantly higher for NDh in 3YC, 5YC, and 7YC; Cycle in all groups (except for 4YC where differences resulted not significant) and Placing in 4YC and 7YC. For

variability parameters, 3YC showed no significant difference between hands; 4YC, 5YC, and 7YC showed increased values in NDh for all the Cycle variability parameters but IQR for 4YC. Placing variability resulted similar between hands in the analysed groups: only Placing SD2 in 5YC and Placing SD1 in 6YC resulted higher for NDh.

MSE resulted significantly higher for Dh in 5YC and 7YC in the ML and in 5YC in the L direction. With Dh, RQA parameters resulted lower in 3YC in ML and L direction, in 5YC in ML; 6YC showed higher Det and AvgL in AP, 7YC lower RQA parameters in ML, higher RQA parameters in AP, and higher AvgL in L.

P-values and effect sizes ( $r$ ) per age group and for the entire group of participants are shown in Table S1.

### 3.3. Effect of sex

When evaluating the effect of sex (Mann-Whitney  $U$  test, level of significance 0.05), considering the entire group of participants, no effect of sex was found on temporal and nonlinear parameters.

When considering the preschool children (3YC, 4YC, and 5YC together), preschool females showed significantly longer Placing when using the Dh (median, 50 %, min-max, 34 %-63 %) than male peers (median, 45 %, min-max 33 %-66 %), higher SEN and lower RQA in AP than male peers when using NDh. P-values and Mann-Whitney effect sizes ( $r$ ) are shown in Table S1. No effect of sex was found on temporal and nonlinear parameters in school children (6YC and 7YC together).

Based on the above mentioned results, the following parameters were represented in polar plots per age group, divided in the pre-defined sectors (Fig. 3): i) Temporal parameters: Cycle and Placing; ii) Variability: SD1 and SD2 Cycle; iii) Pattern regularity: RR and AvgL calculated on AP, ML, and L axes; iv) Motor complexity: SENap, SENml, and SENl for  $\tau = 1$  (values showing the lowest p-values when analysing age-effect).

Polar plots for the 3 children with DCDQ below threshold, superimposed to the reference band of the corresponding age group and hand, show specific functional alterations in different domains in Fig. 4.

## 4. Discussion

Fine motor control, in particular manual dexterity, can be defined as precise, diverse, and flexible behaviour that involves the coordination of many segments and whose repertoire can be expanded through learning [21]. Thus, the study of manual dexterity in early childhood through technology-based assessment and quantitative interpretative metrics allows for the investigation of how the ability to generate complex behaviour develops. The present study aimed to characterise the development of fine motor control in early childhood (ages 3–7 years) using an instrumented, IMU-based version of the PBtest and both linear (i.e., temporal parameters and their variability) and nonlinear (i.e., MSE and RQA) performance metrics. Based on previous literature findings and the interpretative meaning of the metrics [4–6,15], with age and with Dh we expected a decrease in timing variables and variability, and

an increase in the ability to perform complex movements, quantified by an increase in motor complexity, measured by MSE, and a decrease in regularity, measured by RQA parameters, when calculated on wrist acceleration components.

PBtime, Cycle, and Placing durations and their variability, decreased with age when performing the task with the Dh, as expected [5]. PBtime, Cycle, and variability parameters showed a significant decrease between 3YC and 5YC, while no significant difference was observed with post-hoc analysis among the 5YC, 6YC, and 7YC. MSE increased and RQA decreased from 3YC to 5YC and then plateaued from 5YC to 7YC, supporting the hypothesised trend in motor complexity and regularity. Only Placing duration, expressed as a percentage of the Cycle, constantly decreased across all age groups from 3YC to 7YC and did not plateau after 5 years of age.

The observed trends agree with the literature [4] in showing that significant changes in fine motor skills occur between the ages of 3 and 6 years, complementing this general observation with the quantitative analysis of specific characteristics of motor control, i.e. variability, complexity, regularity, varying across different stages of motor development also beyond 6 years of age, continuing into adolescence and adulthood [6].

Differences between the Dh and NDh were evident in PBtime and Cycle duration across all groups (in 4YC, differences were present but not statistically significant). This aligns with findings from other dexterity tests (e.g., the Functional Dexterity Test), which show that children perform faster with their Dh compared to their NDh at all ages, starting from 3 years of age [5]. The other parameters estimated in the present work extended the insights into handedness development: variability of temporal parameters was comparable between Dh and NDh in the 3YC and 4YC groups, whereas it was higher with NDh in older children (5YC, 6YC, 7YC). Based on the Dynamical Systems Theory [22], these results suggest that 5 to 7 year-old children are at different learning stages with the 2 hands, reaching more stable behaviour earlier with the Dh [4]. Among nonlinear metrics, RQA parameters calculated along the ML axis were higher for the NDh in the 3YC, 5YC, and 7YC groups, highlighting a less regular acceleration pattern, consistent with maturation trends, as more mature performance was associated with lower RQA values, tasks performed with the Dh were characterized by reduced RQA parameters. As it is generally acknowledged that learning and experience contribute to refining performance in both Dh and NDh [5], the experience matured by children appeared to lead to a more effective motor performance with the Dh, characterized by lower variability, higher complexity, and reduced recurrence, compared to the NDh. Future studies must understand how performance differences between Dh and NDh hands evolve beyond 7 years of age in this specific task.

In our population, the results for 5YC and 6YC require a dedicated discussion. 5YC group exhibited significantly lower PBtime compared to 6YC group, at first glance, this would suggest a better motor performance for the 5YC based on standard PB assessment. This trend is also reflected in most of the estimated quantitative parameters, although

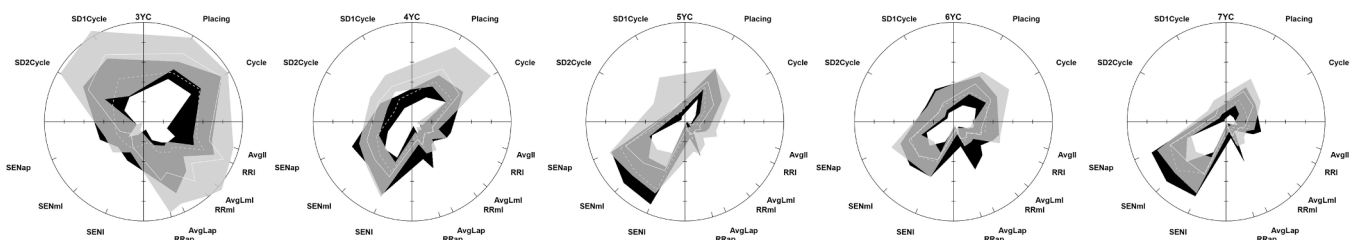
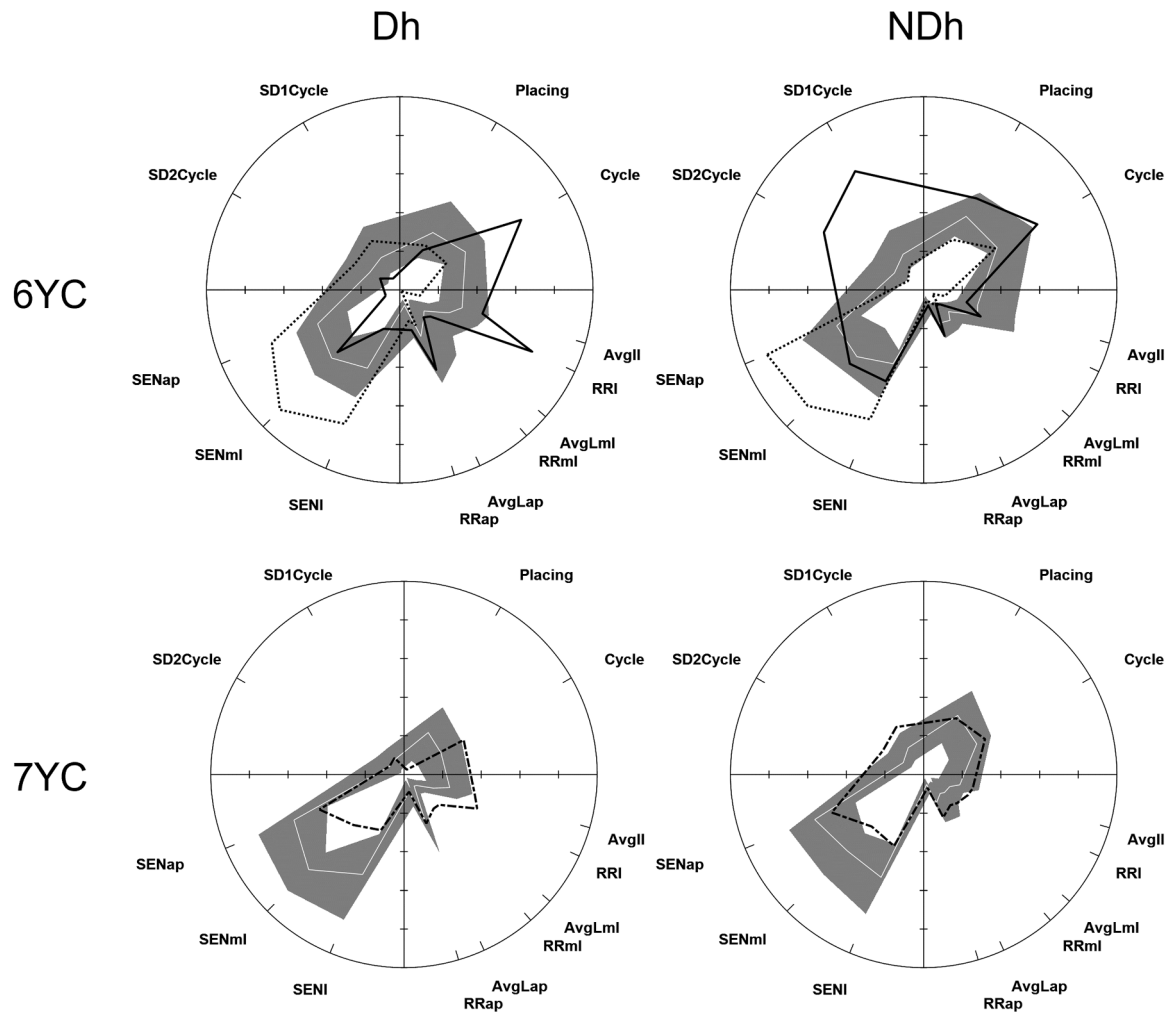


Fig. 3. Age reference bands for dominant hand, Dh, (white dashed line, median; dark grey band, interquartile) and non-dominant hand, NDh, (white solid line, median; light grey band, interquartile). Sectors represent temporal parameters (Cycle and Placing), temporal parameter variability (short and long term variability, SD1 and SD2, of Cycle), motor complexity (sample entropy calculated on AP, ML, and L acceleration signal components, SENap, SENml, and SENl, for  $\tau = 1$ ) and pattern regularity (recurrence rate, RR, and averaged diagonal line length, AvgL, for the three axes, AP, ML, and L). Represented parameters are normalized with respect to the corresponding 2nd and 98th percentile range of the full dataset.



**Fig. 4.** Polar lines for the children resulting with an indication of developmental coordination disorder according to the Developmental Coordination Disorder Questionnaire (black lines with solid, dashed, and dash-dotted patterns representing three children) are shown on the age-matched reference polar bands (white solid line, median; grey band, interquartile range). Represented parameters are normalized with respect to the corresponding 2nd and 98th percentile range of the full dataset.

only MSE and RQA values calculated along the ML and L directions showed significant deviations from the expected age-related trends. Interestingly, Placing did not follow this trend and decreased monotonically from 3YC to 7YC. A possible explanation is that, while younger children first focus on the flight phase of the task, the 6YC group adopted simpler motor solutions (characterized by decreased SEN and increased RQA) and extended flight durations to better plan and execute the placing phase (e.g., planned from the beginning of the flight of the brick to the board). In this perspective, these findings suggest that motor control initially focuses on developing the gross motor components of the task (e.g., the flight phase in 5YC), and, refining the specific fine motor elements (i.e., the placing phase in 6YC), it may rely on simpler or less mature motor strategies for the gross motor component. On the other hand, the analysed sample size was limited, and future studies must investigate better this hypothesis with larger sample size and longitudinal design.

When analysing the effect of sex, only preschool females (3YC-4YC-5YC) exhibited longer Placing with the Dh, and higher SEN and lower RQA parameters in the AP direction with the NDh. No difference was observed between males and females when considering all the participants and school children (6YC-7YC). Literature suggests that female children develop fine motor control earlier and tend to be more skilled than their male peers [4]. However, PBtest assesses dexterity and previous studies indicate that, in similar tests (e.g., the Functional Dexterity

Test), no gender difference is observed up to 17 years of age [5]. Due to the limited sample size, these findings cannot be generalized. Nevertheless, they highlight the value of this tool in detecting potential sex-related differences in fine motor control.

Polar plots show the described differences at first glance (Fig. 3), as well as alterations exhibited by children with potential DCD (Fig. 4) against age-matched reference ranges [15]. Since DCD is recognized as a heterogeneous condition with diverse functional presentations, further investigation will require clinically diagnosed DCD patients alongside their clinical evaluation. The proposed sensor-based quantitative metrics can be further investigated and compared to scores of gold-standard tools designed specifically to assess motor performance in children with DCD (e.g., MABC-2).

A limitation of the present study is the varying number of participants included in each age group: between 44 and 58 children were invited *per* group (corresponding to two school classes *per* age group), resulting in a minimum of 11 recruited children in the 4YC group and a maximum of 49 children in the 7YC group. Since all participants attended the same institution, no environmental effect is hypothesized; however, there may be a potential effect of fear or reluctance to participate, particularly among parents of younger children.

In conclusion, the proposed IMU-based approach effectively described fine motor control development in the analysed population. The present findings confirm the applicability of the proposed parameter

set for assessing fine motor control during the execution of the PB test across different developing populations (e.g., varying age groups) and specific individuals (e.g., those with DCD). Future work should focus on expanding the use of these metrics to larger and more diverse groups of children (e.g., from different schools, socio-economic backgrounds, and countries), enabling their potential application in interventional studies to evaluate the effectiveness of interventions and guide their design.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.gaitpost.2025.06.025](https://doi.org/10.1016/j.gaitpost.2025.06.025).

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