Human motor control: Is a subject-specific quantitative assessment of its multiple characteristics possible? A demonstrative application on children motor development

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HUMAN MOTOR CONTROL: IS A SUBJECT-SPECIFIC QUANTITATIVE ASSESSMENT OF ITS MULTIPLE CHARACTERISTICS POSSIBLE? A DEMONSTRATIVE APPLICATION ON CHILDREN MOTOR DEVELOPMENT

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Abstract:	In synergy with the musculoskeletal system, motor control is responsible of motor performance, determining joint kinematics and kinetics as related to task and environmental constraints. Multiple metrics have been proposed to quantify motor control from kinematic measures of motion, each index quantifying a different specific aspect, but the characterization of motor control as related to a specific subject or population during the execution of a specific task is still missing. In the present work, the performance of a novel approach for quantitative parametrization of motor control is tested over 86 primary school children: 36 I grade, 50 II grade; 40 females, 46 males. Children were assessed performing natural and tandem gait using 3 inertial measurement units, and gait variability, regularity and complexity indexes were calculated from gait temporal parameters and trunk acceleration. Standard Test of Motor Competence and Developmental Coordination Disorder Questionnaire were used to assess reference motor competence. The proposed set of parameters allowed to discriminate the level of motor competence as related to age and standardised scales, while differences related to sex resulted negligible. The proposed method can effectively integrate musculoskeletal dynamic models, allowing the parametric characterization of motor control of specific subjects and/or populations.

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Article Title: HUMAN MOTOR CONTROL: IS A SUBJECT-SPECIFIC QUANTITATIVE ASSESSMENT OF ITS MULTIPLE CHARACTERISTICS POSSIBLE? A DEMONSTRATIVE APPLICATION ON CHILDREN MOTOR DEVELOPMENT

Submitted To Medical Engineering & Physics by M.C. Bisi, R. Stagni.
For publication consideration in ***Special Issue ESB-ITA***.

We received communication of requested review for the above-mentioned manuscript and are now resubmitting the revised version of the manuscript.
We would like to thank the reviewers for their comments that certainly helped to improve the manuscript.
We are providing a point by point response to the reviewer comments and the revised version of the manuscript, where modified sections are highlighted.
We hope that this revised version of the manuscript can be suitable for publication on *Medical Engineering & Physics.*

We declare that the material within has not been and will not be submitted for publication elsewhere except as an abstract and that there are no competing interests to declare.
Each author has been fully involved with the work, has read and concurs with the content in the final manuscript.

Best regards,

Maria Cristina Bisi
Rita Stagni

*Declaration form

Journal: MEDICAL ENGINEERING & PHYSICS

Title of Paper: HUMAN MOTOR CONTROL: IS A SUBJECT-SPECIFIC QUANTITATIVE ASSESSMENT OF ITS MULTIPLE CHARACTERISTICS POSSIBLE? A DEMONSTRATIVE APPLICATION ON CHILDREN

Declarations

The following additional information is required for submission. Please note that failure to respond to these questions/statements will mean your submission will be returned to you. If you have nothing to declare in any of these categories then this should be stated.

Conflict of interest
All authors must disclose any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work. Examples of potential conflicts of interest include employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

Ethical Approval
Work on human beings that is submitted to *Medical Engineering & Physics* should comply with the principles laid down in the Declaration of Helsinki; Recommendations guiding physicians in biomedical research involving human subjects. Adopted by the 18th World Medical Assembly, Helsinki, Finland, June 1964, amended by the 29th World Medical Assembly, Tokyo, Japan, October 1975, the 35th World Medical Assembly, Venice, Italy, October 1983, and the 41st World Medical Assembly, Hong Kong, September 1989. You should include information as to whether the work has been approved by the appropriate ethical committees related to the institution(s) in which it was performed and that subjects gave informed consent to the work.

Competing Interests

None to declare.

Please state any sources of funding for your research

None.

DOES YOUR STUDY INVOLVE HUMAN SUBJECTS? Please cross out whichever is not applicable.

Yes

If your study involves human subjects you MUST have obtained ethical approval.
Please state whether Ethical Approval was given, by whom and the relevant Judgement's reference number

Ethical Approval by Comitato di Bioetica (Bioethical Committee) of the University of Bologna, 25/05/2016.

This information must also be inserted into your manuscript under the acknowledgements section prior to the References.

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POINT-BY-POINT RESPONSES TO REVIEWERS' COMMENTS:

First, we would like to thank the reviewers for their comments that helped improving the manuscript.

We modified the manuscript according to reviewers' comments and hope that it will be now suitable for publication in *Medical Engineering & Physics*.

In the following lines, we reported the point-by-point answers to reviewers' comments, referring to changes to the manuscript that were highlighted in yellow in the revised version.

Reviewer #2:

In this submission, the performance of a method for quantitative parametrization of motor control has been tested over 86 children. These children were assessed performing natural and tandem walking using 3 inertial measurement units. The proposed set of parameters allowed to discriminate the level of motor competence as related to age and standardised scales, while differences related to sex resulted negligible. That method could integrate musculoskeletal dynamic models, allowing the parametric characterization of motor control of specific subjects and/or populations. I thought this was an interesting and meaningful work. Although I cannot evaluate all details, I can support this submission; however, I am not in favor of some expressions of this submission. For example, there are many brackets in the text to explain certain words. This affects the readability.

I am a non-native English speaker. I'm not sure if it's better to call a group of children "male/female" or "boy/girl". I just proposed this question.

We thank the reviewer for the positive comments and the supporting of the manuscript. The overall manuscript was re-checked thoroughly and modified to improve its readability.We chose to refer to the two analysed groups as males and female since we performed the identification based on the biological sex of each subject and not based on an specific characterisation of gender, which would have been necessary to refer to boys and girls.

Specific comments:

P3, Line 14, Please remove the bracket and its content.

Agreed.

P4, paragraph 2, I agree with these sentences, but please provide some references here.

Agreed. The following references have been added to support the indicated sentences.

[2] Bruijn SM, van Dieën JH. Control of human gait stability through foot placement. J R Soc Interface 2018;15:20170816. https://doi.org/10.1098/rsif.2017.0816.

[3] Bisi MC, Riva F, Stagni R. Measures of gait stability: performance on adults and toddlers at the beginning of independent walking. J Neuroengineering Rehabil 2014;11:131. https://doi.org/10.1186/1743-0003-11-131.

[4] Tamburini P, Mazzoli D, Stagni R. Towards an objective assessment of motor function in sub-acute stroke patients: Relationship between clinical rating scales and instrumental gait stability indexes. Gait Posture 2018;59:58–64. https://doi.org/10.1016/j.gaitpost.2017.09.033.

P4, Line 21, Please remove the closing bracket

Agreed.

P5, Line 20-21, I though the full name of NW and TW should be "natural walking" and "tandem walking". Also, you should give more introductions about tandem walking, because it is not a common activity.

Natural- and Tandem gait were modified in Natural- and Tandem Walking as suggested.

We agreed with reviewer's suggestion and added the following paragraph in the introduction section, describing the tandem walking task.

Introduction, page 5, line 16-24

Recently, a cluster of these metrics, exploiting kinematic measures from wearable inertial sensors, has been proposed for the parametric subject-specific characterization of motor control during the execution of two selected motor tasks, natural walking (NW) and tandem walking (TW) [18,22]. NW was chosen being a paradigmatic locomotor task, expected to become more and more automatic with age. TW is different locomotion pattern where the heel of the front foot is lowered to the ground touching the toes of the rear foot at each step, keeping the longitudinal axis of both feet aligned along the anterio-posterior direction during the double-support phase; the narrow basis of support and the required accurate leg control and balance increase the challenge to postural control system as compared to NW [18].

P6, Line 5-6, F/M should be defined here.

Agreed.

P7-8, Data analysis, please remove quotation marks of the parameters.

Agreed.

P8, Line 8,11, only a, where is b?

Sorry, only one point was present for the two sectors. We modified the list and used bullet points instead of letters.

Discussion is too simple. You should discuss the meaning of the results in depth and list the limitations of the study.

Agreed. We further discussed the results, added limitations of the study, and provided suggestions for future directions.

Discussion from page 13 line 19 to page 15 line 15.

Despite the small 24 month age range considered in the present study, results showed a significant decrease in variability, and an increase in automaticity (in NW) and complexity (in TW) with increasing age, in agreement with previous literature [18,23]. While only small significant differences has been highlighted in NW between male and female participants, reported results allow some preliminary inferences regarding the two groups: female, as a group, result more homogenous, showing, in TW, lower dispersion of the polar band in many parameters (see Figure 3), indicating a lower inter-subject variability as compared to the male group. Moreover, the parametric *characterisation depicted in the polar plots of female participants tends to show a more mature pattern than the one of males when compared to age reference polar bands present in the literature [23]. Given the relatively small sample of subjects analysed in the present study, and the focused population of Italian children attending the same primary school, these results cannot be generalized to other populations of children; on the other hand, they support the use of this tool for the characterization of potential sex differences in motor control performance.*

Interestingly, the trend of motor development associated to age maturation resulted even more evident when comparing the less competent children with the more competent ones, as identified according to TMC assessment. Less competent children, according to TMC, showed a motor performance, according to proposed metrics, comparable to that of younger/less experienced ones, and more competent ones to that of older/more experienced children. When aiming at characterizing a specific population or a single child, it is thus possible to relate the proposed metrics and polar plots to an 'age equivalent' one in order to understand if possible delays in motor development are present and in which area (variability, motor complexity etc.).

Finally, the examples of specific children with indication of DCD (see Figure 5) show how the locomotor control performance of a participant can be quantitatively characterized and compared to age reference bands. The analysis of a singular curve with respect to the corresponding age reference band allows i) understanding in which area the child shows a possible motor delay; ii) understanding which components of motor control are mostly affected (e.g. ineffective peripheral realization of a movement, immature control of centre of mass progression, insufficient automaticity etc.) and iii) supporting the definition of effective focused interventions. Ideally, if a child shows a TW complexity (SEN) lower than expected, he/she should be encouraged to explore different movements and strategies in order to enrich his/her ability to adapt and develop effective motor solutions; on the other hand, if NW variability is too high (or complexity is too high), training with task repetitions should be encourage in order to improve automaticity.

A possible limitation of the present study is that children with indication of DCD were identified based on DCDQ, a questionnaire parents fill in, and no gold standard assessment specifically designed for evaluating the motor performance of DCD children was available (e.g. MABC-2 [31]). DCD is recognised as a heterogeneous condition with different functional manifestations [32] and, in order to investigate specifically this developmental disorder by means of the proposed cluster of metrics, a novel study including patients with diagnosed DCD together with their clinical assessment is necessary.

Future developments must extend the use of the proposed metrics to the characterization of larger groups of children, possibly from different schools, socio-economic backgrounds, and countries, to then possibly proceed to their exploitation in interventional studies, in order to evaluate intervention effectiveness and/or support their definition.

Reviewer #4: The manuscript "Human motor control: is a subject-specific quantitative assessment of its multiple characteristics possible? A demonstrative application on children motor development" analyses the use of cluster of parameters in characterizing the efficiency of motor control system. The authors used inertial sensors to study two specific motor tasks (natural gait and tandem gait) in specific subjects (86 primary school children). The authors analyse the motor control performance under different aspects: temporal parameters, variability, motor complexity and pattern regularity.

General comments:

Discussion: It is clear that the use of this cluster of parameters is a valid tool to study the motor control in specific motor tasks and specific subjects. In my opinion it could be useful if in the discussion there were a deeper explanation of the results in terms of the most important data reported in the three figures and about the interpretation in physiological aspects.

Furthermore, in some points of the work (such as for the explanation of the selected parameters and for the algorithm implemented) the authors refer to other articles. Maybe it would be better explain the highlights in this article and leave the references for more details.

We thank the reviewer for the positive comments.

We expanded the Discussion section, as suggested (see paragraph below).

In order to improve readability and clarity of the work, as suggested, we provided more details in some parts of the manuscript where, in the previous version, we referred to other papers. In particular, a paragraph on the metrics proposed in literature and one on the choice of the two locomotor tasks were added in the Introduction (page 5, line 7-24); a figure describing sensor placement (Figure 1) and a more detailed description of parameters' estimation were added in Methods (page 5).

Discussion from page 13 line 19 to page 15 line 15.

Despite the small 24 month age range considered in the present study, results showed a significant decrease in variability, and an increase in automaticity (in NW) and complexity (in TW) with increasing age, in agreement with previous literature [18,23]. While only small significant differences has been highlighted in NW between male and female participants, reported results allow some preliminary inferences regarding the two groups: female, as a group, result more homogenous, showing, in TW, lower dispersion of the polar band in many parameters (see Figure 3), indicating a lower inter-subject variability as compared to the male group. Moreover, the parametric characterisation depicted in the polar plots of female participants tends to show a more mature pattern than the one of males when compared to age reference polar bands present in the literature [23]. Given the relatively small sample of subjects analysed in the present study, and the focused population of Italian children attending the same primary school, these results cannot be generalized to other populations of children; on the other hand, they support the use of this tool for the characterization of potential sex differences in motor control performance.

Interestingly, the trend of motor development associated to age maturation resulted even more evident when comparing the less competent children with the more competent ones, as identified according to TMC assessment. Less competent children, according to TMC, showed a motor performance, according to proposed metrics, comparable to that of younger/less experienced ones, and more competent ones to that of older/more experienced children. When aiming at characterizing *a specific population or a single child, it is thus possible to relate the proposed metrics and polar plots to an 'age equivalent' one in order to understand if possible delays in motor development are present and in which area (variability, motor complexity etc.).*

Finally, the examples of specific children with indication of DCD (see Figure 5) show how the locomotor control performance of a participant can be quantitatively characterized and compared to age reference bands. The analysis of a singular curve with respect to the corresponding age reference band allows i) understanding in which area the child shows a possible motor delay; ii) understanding which components of motor control are mostly affected (e.g. ineffective peripheral realization of a movement, immature control of centre of mass progression, insufficient automaticity etc.) and iii) supporting the definition of effective focused interventions. Ideally, if a child shows a TW complexity (SEN) lower than expected, he/she should be encouraged to explore different movements and strategies in order to enrich his/her ability to adapt and develop effective motor solutions; on the other hand, if NW variability is too high (or complexity is too high), training with task repetitions should be encourage in order to improve automaticity.

A possible limitation of the present study is that children with indication of DCD were identified based on DCDQ, a questionnaire parents fill in, and no gold standard assessment specifically designed for evaluating the motor performance of DCD children was available (e.g. MABC-2 [31]). DCD is recognised as a heterogeneous condition with different functional manifestations [32] and, in order to investigate specifically this developmental disorder by means of the proposed cluster of metrics, a novel study including patients with diagnosed DCD together with their clinical assessment is necessary.

Future developments must extend the use of the proposed metrics to the characterization of larger groups of children, possibly from different schools, socio-economic backgrounds, and countries, to then possibly proceed to their exploitation in interventional studies, in order to evaluate intervention effectiveness and/or support their definition.

Introduction page 5 line 7-15

A variety of quantitative measures have been proposed and can be used when aiming to characterizing different aspects of motor control from kinematics data [4,15]. Traditional kinematic- and spatio-temporal parameters of movement, and their variability [16] are extensively used to characterize the peripheral realization of movement patterns. On the other hand, nonlinear measures of human movement have been proposed and used to quantify dynamic properties of the analysed kinematic signals, and have been related to different specific characteristics of the motor control underlying said realization of the movement pattern (e.g. short Lyapunov exponents related to stability [17], recurrence quantification analysis to pattern regularity [18,19], multi scale sample entropy to motor complexity [20], harmonic ratio to rhythmicity or symmetry [21]).

Introduction, page 5, line 16-24

Recently, a cluster of these metrics, exploiting kinematic measures from wearable inertial sensors, has been proposed for the parametric subject-specific characterization of motor control during the *execution of two selected motor tasks, natural walking (NW) and tandem walking (TW) [18,22]. NW was chosen being a paradigmatic locomotor task, expected to become more and more automatic with age. TW is different locomotion pattern where the heel of the front foot is lowered to the ground touching the toes of the rear foot at each step, keeping the longitudinal axis of both feet aligned along the anterio-posterior direction during the double-support phase; the narrow basis of support and the required accurate leg control and balance increase the challenge to postural control system as compared to NW [18].*

Methods page 8 line 21 – page 9 line 7

Foot contacts and foot offs were identified from shank angular velocity around the ML axis applying the algorithm proposed by Salarian t al. [23,26]. The first two and the last two strides of each trial and, for NW, U-turns were excluded, to avoid transitions, and initiation and termination patterns [23]. For all participants 14 strides were analysed, being the maximum number of non interrupted tandem strides identifiable for all subjects.

Parameters quantifying NW and TW timing and their variability were calculated starting from the identified foot contacts and foot offs. Recurrence and complexity measures [18,23] were calculated on trunk acceleration components to quantify specific aspects of motor control (i.e. regularity, automaticity, complexity).

Specific comments:

Page 5, line 9: "these index". The index are not specified. Could you report some example of these index?

We expanded the mentioned paragraph providing a brief description of the indexes that have been proposed in the literature.

Introduction page 5 line 7-15

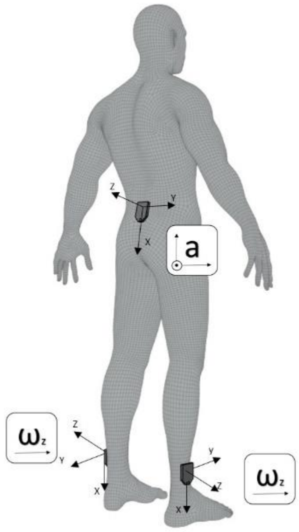
A variety of quantitative measures have been proposed and can be used when aiming to characterizing different aspects of motor control from kinematics data [4,15]. Traditional kinematic- and spatio-temporal parameters of movement, and their variability [16] are extensively used to characterize the peripheral realization of movement patterns. On the other hand, nonlinear measures of human movement have been proposed and used to quantify dynamic properties of the analysed kinematic signals, and have been related to different specific characteristics of the motor control underlying said realization of the movement pattern (e.g. short Lyapunov exponents related to stability [17], recurrence quantification analysis to pattern regularity [18,19], multi scale sample entropy to motor complexity [20], harmonic ratio to rhythmicity or symmetry [21]).

Page 6, lines 17-19. In this paragraph the authors described the use of inertial sensors. Could you add information about the positioning of them such as axes directions? Furthermore, the use of these tools is affected by the soft tissue artifact. How much could this affect the measurements acquired? Could the soft tissue artifact be more relevant to the sensor on L5 than the shanks?

We inserted in the manuscript a new Figure (Figure 1) describing sensor positioning and axis orientation. With respect to the second question, we agree with the reviewer that small soft tissue artefacts may be present and contribute as possible source of error to the measurements of segments kinematics. However, in order to minimize this possible source of error, areas with “wobbling” soft tissues (fat or muscles) and areas close to joints were avoided in both sites (L5 and shank), in agreement with the ‘Guidelines for Magnetic and Inertial Measurement Unit Use’ [Camomilla V, et al 2018]. Moreover, as the reviewer pointed out in the following question, the locomotor tasks under study are not ‘explosive tasks’, thus reducing the possible influence of these artefacts on the measures [Camomilla V, et al 2018]. Two brief paragraphs clarifying these concepts with respect to soft tissue artefact issue have been added in Methods.

> Camomilla V. et al, Trends Supporting the In-Field Use of Wearable Inertial Sensors for Sport Performance Evaluation: A Systematic Review. Sensors (Basel). 2018 Mar 15;18(3):873

Figure 1. Inertial sensor positions (lower trunk and shanks) and axis orientations. Boxes indicate the signals analysed per each sensor (trunk: 3D acceleration components; shanks: angular velocity around the ML axis).



Methods, page 7 line 9-12

Areas with “wobbling” soft tissues (fat or muscles) and areas close to joints were avoided to minimize soft tissue artifact, in agreement with the ‘Guidelines for Magnetic and Inertial Measurement Unit Use’ [16].

Methods, page 8 line 18-20

Collected raw data were consistent and relative movements between sensors and segments negligible given i) sensor positioning in agreement with the ‘Guidelines for Magnetic and Inertial Measurement Unit Use’ [16] and ii) the ‘not explosive’ nature of NW and TW [16].

Page 6, lines 17-19. The author should underline that the relative movement between the sensors and the skin is not relevant because the motor task is slow and so the relative collected data could be considered consistent. I think it is better to specify this topic in the text.

Agreed. See answer to previous question.

Page 6, lines 19. Could you add a figure of the set up of the test (position of the sensors)?

Agreed. As indicated above we inserted a new Figure (Figure 1) describing sensor positioning and axis orientation.

Page 6, lines 20. Which types of data were analysed using Opal (the data recorded by accelerometers, gyroscopes or magnetometers)? The inertial sensors used for this study were in real-time or they stored the data during the test and only later the data were downloaded for the elaboration?

We thank the reviewer for the suggestion of better clarifying these methodological aspects. 3D trunk acceleration components were analysed for the estimation of motor complexity and pattern regularity parameters and ML angular velocity of the shanks for the estimation of timing and variability parameters. Data was synchronized and wirelessly streamed from the three sensors to the computer using “Robust Synchronized Stream Mode’ (Opal, APDM, USA). Data was buffered on the sensors to prevent data loss in the case of wireless interruption.

We agreed to insert these methodological aspects in the manuscript.

Methods page 7, line 17-19

Inertial sensor data were recorded at 128Hz, synchronized and wirelessly streamed from the three sensors to the computer using “Robust Synchronized Stream Mode’ (Opal, APDM, USA). Data were buffered on the sensors to prevent data loss in the case of interruption of the wireless connection.

Methods page 8, line 21 – page 9, line 7

Foot contacts and foot offs were identified from shank angular velocity around the ML axis applying the algorithm proposed by Salarian t al. [23,26]. The first two and the last two strides of each trial and, for NW, U-turns were excluded, to avoid transitions, and initiation and termination patterns [23]. For all participants 14 strides were analysed, being the maximum number of non interrupted tandem strides identifiable for all subjects.

Parameters quantifying NW and TW timing and their variability were calculated starting from the identified foot contacts and foot offs. Recurrence and complexity measures [18,23] were calculated on trunk acceleration components to quantify specific aspects of motor control (i.e. regularity, automaticity, complexity).

Methods page 9, 8 -24

The extracted parameters were represented in polar plots organised in the following four sectors, representing different areas of motor control performance:

1) *Temporal parameters:*
    - *Normalized Stride time (nStrideT, scaled according to Hof [27])*
    - *Stance time (StanceT, expressed in % of stride time)*
    - *Double Support time (DS, expressed in % of stride time)*
2) *Variability:*

  - *standard deviation of stride time (stdStrideT)*
  - *standard deviation of StanceT (stdStance)*
  - *standard deviation of DS (stdDS).*
3) *Motor complexity:*
  - *Sample Entropy on the three trunk acceleration components (τ=6) (SENv, SENml and SENap) [20,28].*
4) *Pattern regularity:*
  - *Recurrence Quantification Analysis (RQA) parameters: Recurrence rate (RR), determinism (DET) and averaged diagonal line length (AvgL) for antero-posterior (AP) and medio-lateral (ML) trunk acceleration components [18,19].*

Page 6, lines 20: Could you add in the text the accuracy and precision of the sensors used?

Agreed. We inserted sensors' technical details.

Methods page 7, line 14-16

For the applied sensors, accelerometer and gyroscope noise were 0.0012 m/s2/√Hz and 0.05 deg/s/√Hz, respectively, while sensors dimensions were 48.4 × 36.1 × 13.4 mm (L × W × H), weight <22grams (with battery).

Page 7, lines 2. The NW walk was done both forth and back. What about TW? Is it only forth? Also for this motor task, was the speed self-selected speed?

Different path lengths for the two tasks were selected in order to obtain a priori a comparable number of strides per task (NW strides are theoretically more than double in length than TW strides). Moreover, TW is a challenging task for children, and asking to perform it for a longer distance would have led to showing a fatigue effect. In Methods, we specified the number of strides used for data analysis (fourteen), that was the maximum number of non interrupted tandem strides identifiable for all subjects.

NW and TW were performed at self-selected speed: the choice to analyse gait at self-selected speed was guided by the necessity not to influence the spontaneous control of gait (e.g. in NW, by imposing velocity, participants could alter their biomechanics in different uncontrolled ways, by changing stride length and/or cadence).

We agree with the reviewer to describe these aspects in the manuscript.

Methods page 8 line 3-6

Different path lengths for the two tasks were selected in order to obtain comparable number of strides per task (NW strides are theoretically more than double in length than TW strides). Participants were asked to perform NW and TW at self-selected speed in order not to influence the spontaneous control of gait [22].

Methods page 8, line 23 – page 9, line 3

The first two and the last two strides of each trial and, for NW, U-turns were excluded, to avoid transitions, and initiation and termination patterns [23]. For all participants 14 strides were analysed, being the maximum number of non interrupted tandem strides identifiable for all subjects.

Highlights

- **Motor control determines motor performance in synergy with musculoskeletal system**
- **A parametric method for subject-specific assessment of motor control is tested**
- **Testing was performed on 86 primary school children from I and II grade**
- **Proposed parameter cluster effectively characterised motor competence**

HUMAN MOTOR CONTROL: IS A SUBJECT-SPECIFIC QUANTITATIVE ASSESSMENT OF ITS MULTIPLE CHARACTERISTICS POSSIBLE? A DEMONSTRATIVE APPLICATION ON CHILDREN MOTOR DEVELOPMENT

AUTHORS

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- **Motor control determines motor performance in synergy with musculoskeletal system**
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- **Testing was performed on 86 primary school children from I and II grade**
- **Proposed parameter cluster effectively characterised motor competence**

Human motor control: is a subject-specific quantitative assessment of its multiple characteristics possible? A demonstrative application on children motor development

Abstract.

In synergy with the musculoskeletal system, motor control is responsible of motor performance, determining joint kinematics and kinetics as related to task and environmental constraints.

Multiple metrics have been proposed to quantify motor control from kinematic measures of motion, each index quantifying a different specific aspect, but the characterization of motor control as related to a specific subject or population during the execution of a specific task is still missing.

In the present work, the performance of a novel approach for quantitative parametrization of motor control is tested over 86 primary school children: 36 I grade, 50 II grade; 40 females, 46 males. Children were assessed performing natural and tandem gait using 3 inertial measurement units, and gait variability, regularity and complexity indexes were calculated from gait temporal parameters and trunk acceleration. Standard Test of Motor Competence and Developmental Coordination Disorder Questionnaire were used to assess reference motor competence.

The proposed set of parameters allowed to discriminate the level of motor competence as related to age and standardised scales, while differences related to sex resulted negligible.

The proposed method can effectively integrate musculoskeletal dynamic models, allowing the parametric characterization of motor control of specific subjects and/or populations.

Keywords: motor assessment, motor control, dynamics of gait, motor development, motor parameters, wearable sensors

Introduction

Motor control is the regulation of movement in organisms provided of a nervous system; it regulates balance and dynamic stability, and allows to correctly perform activities of daily living [1]. Its performance depends on the ability to implement both anticipatory control and continuous adaptation to constraints.

Considering a daily living activity as '*simple*' as walking, properly functioning motor control provides us with anticipatory activation patterns for bipedal motion and the concurrent stabilization of the trunk and head, as well as the continuous adaptation in response to external perturbations (e.g. uneven surface, obstacles, visual or auditory disturbances) [2]. The integrity of the musculoskeletal system is necessary, but not sufficient to guarantee a proper biomechanical function, as it results evident considering a toddler [3] (i.e. immature motor control) or stroke patients [4] (i.e. motor control altered by pathology): in both cases motor function is hindered by lacking motor control with an appropriate musculoskeletal system.

Motor control includes reflexes as well as movements, both voluntary and not, directed by the central nervous system through the integration of multimodal sensory information (both from the external world as well as proprioception) and the recruitment of muscles to carry out a task [5]. Its complex structure and function have been tackled from different perspectives (from physiology to control theory), and different methods have been proposed for its characterization: i) dynamic control models aiming to simulate the different sensory and activation pathways and control levels (e.g. vestibular, visual, somatosensory) in simplified conditions such as static posture, or mobilization of a single limb [6–10]; ii) statistical models for the characterization of the variability of muscle activation patterns [11,12]; iii) musculoskeletal dynamic models for the estimation of biomechanical changes related to different muscle activation patterns [13,14]. From the fundamental interaction among sensory and control pathways (i), to the identification of specific schemes in the variability of the measured muscle activation patterns (ii), to the analysis of how the different activation patterns vary the biomechanical behaviour and function (iii), all these modelling approaches contribute to gain a better understanding of the complex relationship between motor control and motor function. Nevertheless, the actual characterization of motor control underlying the execution of a specific task by a specific subject or population remains unavailable.

A variety of quantitative measures have been proposed and can be used when aiming to characterizing different aspects of motor control from kinematics data [4,15]. Traditional kinematic- and spatio-temporal parameters of movement, and their variability [16] are extensively used to characterize the peripheral realization of movement patterns. On the other hand, nonlinear measures of human movement have been proposed and used to quantify dynamic properties of the analysed kinematic signals, and have been related to different specific characteristics of the motor control underlying said realization of the movement pattern (e.g. short Lyapunov exponents related to stability [17], recurrence quantification analysis to pattern regularity [18,19], multi scale sample entropy to motor complexity [20], harmonic ratio to rhythmicity or symmetry [21]).

Recently, a cluster of these metrics, exploiting kinematic measures from wearable inertial sensors, has been proposed for the parametric subject-specific characterization of motor control during the execution of two selected motor tasks, natural walking (NW) and tandem walking (TW) [18,22]. NW was chosen being a paradigmatic locomotor task, expected to become more and more automatic with age. TW is different locomotion pattern where the heel of the front foot is lowered to the ground touching the toes of the rear foot at each step, keeping the longitudinal axis of both feet aligned along the anterio-posterior direction during the double-support phase; the narrow basis of support and the required accurate leg control and balance increase the challenge to postural control system as compared to NW [18].

The proposed cluster of metrics includes gait temporal parameters and their variability as well al indexes quantitatively characterising the dynamics of the lower trunk, related to the control of the centre of mass, and demonstrated promising preliminary results in characterizing variability, recurrence, automaticity, and complexity of motor control in healthy subjects, aged 6 to 25 years [18,23].

The aim of the present research work was to test the performance of the proposed cluster of parameters [23] in characterizing motor control underlying specific motor tasks (NW and TW) in specific subjects (school children analyzed by age, sex, motor competence, evaluation for Developmental Coordination Disorder) exploiting kinematic measures from wearable inertial sensors.

Materials & Methods

Study subjects

Eighty-six children attending the first and second year of the primary school were included in the study (Table1): 36 children (18 females (F)/18 males (M)) attending the first year of primary school (Grade1, age range 73-85 months), 50 children (22F/28M) attending the second year (Grade2, age range 85-97 months). All children had no known developmental delay and no musculoskeletal pathology. Children were excluded from the study if they had any severe visual or hearing impairment, used aids (except for glasses), had cochlear implantations, or when there was a lack of cooperation.

TABLE 1 HERE

The Bioethical Committee of the authors' institution approved this study (25/05/2016), and informed consent was obtained from the participant' parents.

Experimental setup

The assessment was performed in schools, in a well-lit and ventilated room with adequate heat and sound. 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. Areas with "wobbling" soft tissues (fat or muscles) and areas close to joints were avoided to minimize soft tissue artifact, in agreement with the 'Guidelines for Magnetic and Inertial Measurement Unit Use' [16]. Figure 1 shows Sensor positioning and axis orientation.

FIGURE 1 HERE

For the applied sensors, accelerometer and gyroscope noise were 0.0012 m/s2/√Hz and 0.05 deg/s/√Hz, respectively, while sensors dimensions were 48.4 × 36.1 × 13.4 mm (L × W × H), weight <22grams (with battery).

Inertial sensor data were recorded at 128Hz, synchronized and wirelessly streamed from the three sensors to the computer using "Robust Synchronized Stream Mode' (Opal, APDM, USA). Data were buffered on the sensors to prevent data loss in the case of interruption of the wireless connection.

Data were collected while participants performed the following two tasks:

- NW back and forth along a 15 m corridor;
- TW along a 15m long tapeline on the floor.

Different path lengths for the two tasks were selected in order to obtain comparable number of strides per task (NW strides are theoretically more than double in length than TW strides). Participants were asked to perform NW and TW at self-selected speed in order not to influence the spontaneous control of gait [22].

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 [18].

As reference for the assessment of children motor development, they were asked to complete the Test of Motor Competence (TMC) [24], which is a product based test including two gross (heel to toe walking and walking/running in slopes) and two fine (placing bricks and building bricks) motor tasks. TMC standard assessment (time duration of execution) was recorded, higher duration is associated to lower motor competence. In addition, parents were asked to complete the Developmental Coordination Disorder Questionnaire (DCDQ) [25].

Data analysis

Collected raw data were consistent and relative movements between sensors and segments negligible given i) sensor positioning in agreement with the 'Guidelines for Magnetic and Inertial Measurement Unit Use' [16] and ii) the 'not explosive' nature of NW and TW [16]. NW and TW tasks were analysed as described by Bisi and Stagni [23]. Foot contacts and foot offs were identified from shank angular velocity around the ML axis applying the algorithm proposed by Salarian t al. [23,26]. The first two and the last two strides of each trial and, for NW, U-turns were excluded, to avoid transitions, and initiation and termination patterns [23]. For all participants 14 strides were analysed, being the maximum number of non interrupted tandem strides identifiable for all subjects.

Parameters quantifying NW and TW timing and their variability were calculated starting from the identified foot contacts and foot offs. Recurrence and complexity measures [18,23] were calculated on trunk acceleration components to quantify specific aspects of motor control (i.e. regularity, automaticity, complexity).

The extracted parameters were represented in polar plots organised in the following four sectors, representing different areas of motor control performance:

1) Temporal parameters:
    - Normalized Stride time (nStrideT, scaled according to Hof [27])
    - Stance time (StanceT, expressed in % of stride time)
    - Double Support time (DS, expressed in % of stride time)
2) Variability:
    - standard deviation of stride time (stdStrideT)
    - standard deviation of StanceT (stdStance)
    - standard deviation of DS (stdDS).
3) Motor complexity:
    - Sample Entropy on the three trunk acceleration components ($\tau=6$) (SENv, SENml and SENap) [20,28].
4) Pattern regularity:
    - Recurrence Quantification Analysis (RQA) parameters: Recurrence rate (RR), determinism (DET) and averaged diagonal line length (AvgL) for antero-posterior (AP) and medio-lateral (ML) trunk acceleration components [18,19].

For comparability purposes, results were normalized to the 2nd and 98th percentiles obtained in [23], which included participants aged 6-25 years.

Participants were the grouped and analysed based on:

i) Age (Grade1 versus Grade2 children);

ii) Sex (Males versus Females);

iii) Level of motor competence (upper quartile versus lower quartile, *i.e.* 21 children scoring the highest TMC values, lower competence, versus 21 with the lowest one, higher competence).

Finally, iv) Children with a DCDQ score below threshold (age adjusted) for Indication of, or Suspect for, DCD versus children with no indications of DCD [29] were analysed based on the proposed parameters for motor control characterization.

For each group 25th, median and 75th percentiles of the estimated parameters were calculated; a Kruskal-Wallis test with minimum level of significance of 5% was performed to highlight differences for each parameter between groups in the two tasks.

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

Results.

Statistical analysis and polar plot representation, allowed to quantitatively identify specific differences related to age, sex, and level of motor competence in the target population. Moreover, specific alterations could be identified in the parameters of children with indication/suspect of DCD.

Polar plots resulting for each comparison (i to iv) are reported: sectors represent temporal parameters (nStrideT, Stance and DS), temporal parameter variability (stdStride, stdStance and stdDS), motor complexity (SENap, SENml and SENv) and pattern regularity (RRml, DETml, AvgLml, RRap, DETap and AvgLap).

i) Age (Grade1 vs Grade2 children)

In NW, complexity on the vertical axis SENv, and nStrideT resulted significantly reduced in Grade2 children (SENv, [25th, 1.02, median, 1.13, 75th, 1.35], nStrideT [25th, 3.06, median, 3.25, 75th, 3.56]) with respect to the Grade1 group (SENv, [25th, 1.10, median, 1.27, 75th, 1.39], nStrideT [25th, 3.20, median, 3.40, 75th, 3.74]).

In TW, only DETap resulted significantly lower in Grade2 children (DETap, [25th, 72.1, median, 80.9, 75th, 85.9]) when compared to the Grade1 (DETap, [25th, 79.8, median, 83.8, 75th, 87.6]). Figure 2 shows polar plots describing differences in locomotor performances associated to age maturation.

FIGURE 2 HERE

ii) Sex (Males vs Females);

In NW, male participants showed lower stdStride ([25th, 0.03, median, 0.06, 75th, 0.07]), DETap (([25th, 53.4, median, 64.0, 75th, 76.4]) and AvgLap (([25th, 6.3, median, 6.9, 75th, 7.9]) than girls ([stdStrid, ([25th, 0.05, median, 0.06, 75th, 0.09], DETap ([25th, 66.3, median, 71.6, 75th, 83.1], AvgLap (([25th, 6.8, median, 7.4, 75th, 9.0]), while no significant differences was found in TW between the two groups. Figure 3 shows polar plots describing differences in locomotor performances for male and female participants. From the Figure, it can be seen that in TW, despite median values between groups are similar, female participants have a lower inter-subject variability.

FIGURE 3 HERE

iii) Level of motor competence (upper quartile versus lower quartile);

When analysing locomotor performance indices with respect to TMC assessment, in NW no statistical differences were found between children in the upper or lower quartile of TMC assessment. Details of participants in the upper and lower quartiles according to TMC assessment are shown in Table 2.

TABLE 2 HERE

In TW, significant differences were found on most of the parameters: less competent children showed significantly higher stdStride, higher DS duration, stance duration, nStrideT, higher recurrence parameters and lower SEN values in ML and AP directions. 25th-, median and 75th percentiles for the parameters showing significant differences are shown in Table 3.

TABLE 3 HERE

FIGURE 4 HERE

iv) Children with a DCDQ score below threshold versus children with no indications of DCD;

Five children (2F/3M) resulted with an indication or a suspect of DCD according to DCDQ [29]. Median age was 80 months (min 74, max 97 months). Figure 5 shows NW and TW polar plots for the 5 children, superimposed to the reference band of the corresponding age group.

FIGURE 5 HERE

Discussion.

Motor control regulates human motion, operating in synergy with the musculoskeletal system in determining joint kinematics and loading to effectively perform a given motor task, continuously adapting to external constraints. Its key role ascertained, its quantitative characterization as related to motor function for specific subjects or populations during the execution of daily living activities is still missing.

Recently, a cluster of indexes has been proposed for the purpose, showing promising preliminary results [18,23]. The selected indexes are derived from metrics analysing the dynamic structure of kinematics signals measured during the execution of specific motor tasks, and have been related to specific characteristics of the underlying motor control (e.g. automaticity, complexity) [4,20,30].

The present research work aimed to test the performance of this cluster of metrics in characterizing motor control from kinematics measured using wearable sensors. The selected testing population were healthy school children aged 6 to 8 years (I and II grade, primary school), serving as reference for the expected maturation of motor control with age and motor experience. The selected tasks were NW and TW, as suitable to highlight maturation in control automaticity and complexity, respectively, in line with previous literature [18,20].

Despite the small 24 month age range considered in the present study, results showed a significant decrease in variability, and an increase in automaticity (in NW) and complexity (in TW) with increasing age, in agreement with previous literature [18,23]. While only small significant differences has been highlighted in NW between male and female participants, reported results allow some preliminary inferences regarding the two groups: female, as a group, result more homogenous, showing, in TW, lower dispersion of the polar band in many parameters (see Figure 3), indicating a lower inter-subject variability as compared to the male group. Moreover, the parametric characterisation depicted in the polar plots of female participants tends to show a more mature pattern than the one of males when compared to age reference polar bands present in the literature [23]. Given the relatively small sample of subjects analysed in the present study, and the focused population of Italian children attending the same primary school, these results cannot be generalized to other populations of children; on the other hand, they support the use of this tool for the characterization of potential sex differences in motor control performance.

Interestingly, the trend of motor development associated to age maturation resulted even more evident when comparing the less competent children with the more competent ones, as identified according to TMC assessment. Less competent children, according to TMC, showed a motor performance, according to proposed metrics, comparable to that of younger/less experienced ones, and more competent ones to that of older/more experienced children. When aiming at characterizing a specific population or a single child, it is thus possible to relate the proposed metrics and polar plots to an ‘age equivalent’ one in order to understand if possible delays in motor development are present and in which area (variability, motor complexity etc.).

Finally, the examples of specific children with indication of DCD (see Figure 5) show how the locomotor control performance of a participant can be quantitatively characterized and compared to age reference bands. The analysis of a singular curve with respect to the corresponding age reference band allows i) understanding in which area the child shows a possible motor delay; ii) understanding which components of motor control are mostly affected (e.g. ineffective peripheral realization of a movement, immature control of centre of mass progression, insufficient automaticity etc.) and iii) supporting the definition of effective focused interventions. Ideally, if a child shows a TW complexity (SEN) lower than expected, he/she should be encouraged to explore different movements and strategies in order to enrich his/her ability to adapt and develop effective motor solutions; on the other hand, if NW variability is too high (or complexity is too high), training with task repetitions should be encourage in order to improve automaticity.

A possible limitation of the present study is that children with indication of DCD were identified based on DCDQ, a questionnaire parents fill in, and no gold standard assessment specifically designed for evaluating the motor performance of DCD children was available (e.g. MABC-2 [31]). DCD is recognised as a heterogeneous condition with different functional manifestations [32] and, in order to investigate specifically this developmental disorder by means of the proposed cluster of metrics, a novel study including patients with diagnosed DCD together with their clinical assessment is necessary.

Future developments must extend the use of the proposed metrics to the characterization of larger groups of children, possibly from different schools, socio-economic backgrounds, and countries, to then possibly proceed to their exploitation in interventional studies, in order to evaluate intervention effectiveness and/or support their definition.

In summary, the proposed cluster of parameters allowed to describe the expected trend and changes in the analysed population with respect to age and motor competence, and to differentiate subject with specific motor control alterations (below DCDQ threshold) in a population without significant biomechanical differences. These results, from a large sample of subjects with a small age range, support the suitability of the proposed cluster of parameters to characterize motor control underlying the execution of a specific task (e.g. NW and TW) in different populations (e.g. different age, different level of motor competence) as well as in specific subjects (e.g. DCD).

In addition to analyzing motor development and alteration in children and adults, the proposed method could effectively support the in-silico analysis of the effect of specific motor control alterations on the biomechanics of motion, allowing to quantitatively characterize, using specific parameters, the motor control behavior associated to a specific dynamic structure of motion.

Conflicts of Interest: None.

Funding: None.

Ethical Approval: The Bioethical Committee (Comitato di Bioetica) of the University of Bologna approved this study (25/05/2016).

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HUMAN MOTOR CONTROL: IS A SUBJECT-SPECIFIC QUANTITATIVE ASSESSMENT OF ITS MULTIPLE CHARACTERISTICS POSSIBLE? A DEMONSTRATIVE APPLICATION ON CHILDREN MOTOR DEVELOPMENT

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Highlights

- **Motor control determines motor performance in synergy with musculoskeletal system**
- **A parametric method for subject-specific assessment of motor control is tested**
- **Testing was performed on 86 primary school children from I and II grade**
- **Proposed parameter cluster effectively characterised motor competence**

Human motor control: is a subject-specific quantitative assessment of its multiple characteristics possible? A demonstrative application on children motor development

Abstract.

In synergy with the musculoskeletal system, motor control is responsible of motor performance, determining joint kinematics and kinetics as related to task and environmental constraints.

Multiple metrics have been proposed to quantify motor control from kinematic measures of motion, each index quantifying a different specific aspect, but the characterization of motor control as related to a specific subject or population during the execution of a specific task is still missing.

In the present work, the performance of a novel approach for quantitative parametrization of motor control is tested over 86 primary school children: 36 I grade, 50 II grade; 40 females, 46 males. Children were assessed performing natural and tandem gait using 3 inertial measurement units, and gait variability, regularity and complexity indexes were calculated from gait temporal parameters and trunk acceleration. Standard Test of Motor Competence and Developmental Coordination Disorder Questionnaire were used to assess reference motor competence.

The proposed set of parameters allowed to discriminate the level of motor competence as related to age and standardised scales, while differences related to sex resulted negligible.

The proposed method can effectively integrate musculoskeletal dynamic models, allowing the parametric characterization of motor control of specific subjects and/or populations.

Keywords: motor assessment, motor control, dynamics of gait, motor development, motor parameters, wearable sensors

Introduction

Motor control is the regulation of movement in organisms provided of a nervous system; it regulates balance and dynamic stability, and allows to correctly perform activities of daily living [1]. Its performance depends on the ability to implement both anticipatory control and continuous adaptation to constraints.

Considering a daily living activity as '*simple*' as walking, properly functioning motor control provides us with anticipatory activation patterns for bipedal motion and the concurrent stabilization of the trunk and head, as well as the continuous adaptation in response to external perturbations (e.g. uneven surface, obstacles, visual or auditory disturbances) [2]. The integrity of the musculoskeletal system is necessary, but not sufficient to guarantee a proper biomechanical function, as it results evident considering a toddler [3] (i.e. immature motor control) or stroke patients [4] (i.e. motor control altered by pathology): in both cases motor function is hindered by lacking motor control with an appropriate musculoskeletal system.

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Materials & Methods

Study subjects

Eighty-six children attending the first and second year of the primary school were included in the study (Table1): 36 children (18 females (F)/18 males (M)) attending the first year of primary school (Grade1, age range 73-85 months), 50 children (22F/28M) attending the second year (Grade2, age range 85-97 months). All children had no known developmental delay and no musculoskeletal pathology. Children were excluded from the study if they had any severe visual or hearing impairment, used aids (except for glasses), had cochlear implantations, or when there was a lack of cooperation.

TABLE 1 HERE

The Bioethical Committee of the authors' institution approved this study (25/05/2016), and informed consent was obtained from the participant' parents.

Experimental setup

The assessment was performed in schools, in a well-lit and ventilated room with adequate heat and sound. 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. Areas with "wobbling" soft tissues (fat or muscles) and areas close to joints were avoided to minimize soft tissue artifact, in agreement with the 'Guidelines for Magnetic and Inertial Measurement Unit Use' [16]. Figure 1 shows Sensor positioning and axis orientation.

FIGURE 1 HERE

For the applied sensors, accelerometer and gyroscope noise were 0.0012 m/s2/√Hz and 0.05 deg/s/√Hz, respectively, while sensors dimensions were 48.4 × 36.1 × 13.4 mm (L × W × H), weight <22grams (with battery).

Inertial sensor data were recorded at 128Hz, synchronized and wirelessly streamed from the three sensors to the computer using "Robust Synchronized Stream Mode' (Opal, APDM, USA). Data were buffered on the sensors to prevent data loss in the case of interruption of the wireless connection.

Data were collected while participants performed the following two tasks:

- NW back and forth along a 15 m corridor;
- TW along a 15m long tapeline on the floor.

Different path lengths for the two tasks were selected in order to obtain comparable number of strides per task (NW strides are theoretically more than double in length than TW strides). Participants were asked to perform NW and TW at self-selected speed in order not to influence the spontaneous control of gait [22].

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 [18].

As reference for the assessment of children motor development, they were asked to complete the Test of Motor Competence (TMC) [24], which is a product based test including two gross (heel to toe walking and walking/running in slopes) and two fine (placing bricks and building bricks) motor tasks. TMC standard assessment (time duration of execution) was recorded, higher duration is associated to lower motor competence. In addition, parents were asked to complete the Developmental Coordination Disorder Questionnaire (DCDQ) [25].

Data analysis

Collected raw data were consistent and relative movements between sensors and segments negligible given i) sensor positioning in agreement with the 'Guidelines for Magnetic and Inertial Measurement Unit Use' [16] and ii) the 'not explosive' nature of NW and TW [16]. NW and TW tasks were analysed as described by Bisi and Stagni [23]. Foot contacts and foot offs were identified from shank angular velocity around the ML axis applying the algorithm proposed by Salarian t al. [23,26]. The first two and the last two strides of each trial and, for NW, U-turns were excluded, to avoid transitions, and initiation and termination patterns [23]. For all participants 14 strides were analysed, being the maximum number of non interrupted tandem strides identifiable for all subjects.

Parameters quantifying NW and TW timing and their variability were calculated starting from the identified foot contacts and foot offs. Recurrence and complexity measures [18,23] were calculated on trunk acceleration components to quantify specific aspects of motor control (i.e. regularity, automaticity, complexity).

The extracted parameters were represented in polar plots organised in the following four sectors, representing different areas of motor control performance:

1) Temporal parameters:
    - Normalized Stride time (nStrideT, scaled according to Hof [27])
    - Stance time (StanceT, expressed in % of stride time)
    - Double Support time (DS, expressed in % of stride time)
2) Variability:
    - standard deviation of stride time (stdStrideT)
    - standard deviation of StanceT (stdStance)
    - standard deviation of DS (stdDS).
3) Motor complexity:
    - Sample Entropy on the three trunk acceleration components ($\tau=6$) (SENv, SENml and SENap) [20,28].
4) Pattern regularity:
    - Recurrence Quantification Analysis (RQA) parameters: Recurrence rate (RR), determinism (DET) and averaged diagonal line length (AvgL) for antero-posterior (AP) and medio-lateral (ML) trunk acceleration components [18,19].

For comparability purposes, results were normalized to the 2nd and 98th percentiles obtained in [23], which included participants aged 6-25 years.

Participants were the grouped and analysed based on:

i) Age (Grade1 versus Grade2 children);
ii) Sex (Males versus Females);
iii) Level of motor competence (upper quartile versus lower quartile, *i.e.* 21 children scoring the highest TMC values, lower competence, versus 21 with the lowest one, higher competence).

Finally, iv) Children with a DCDQ score below threshold (age adjusted) for Indication of, or Suspect for, DCD versus children with no indications of DCD [29] were analysed based on the proposed parameters for motor control characterization.

For each group 25th, median and 75th percentiles of the estimated parameters were calculated; a Kruskal-Wallis test with minimum level of significance of 5% was performed to highlight differences for each parameter between groups in the two tasks.

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

Results.

Statistical analysis and polar plot representation, allowed to quantitatively identify specific differences related to age, sex, and level of motor competence in the target population. Moreover, specific alterations could be identified in the parameters of children with indication/suspect of DCD.

Polar plots resulting for each comparison (i to iv) are reported: sectors represent temporal parameters (nStrideT, Stance and DS), temporal parameter variability (stdStride, stdStance and stdDS), motor complexity (SENap, SENml and SENv) and pattern regularity (RRml, DETml, AvgLml, RRap, DETap and AvgLap).

i) Age (Grade1 vs Grade2 children)

In NW, complexity on the vertical axis SENv, and nStrideT resulted significantly reduced in Grade2 children (SENv, [25th, 1.02, median, 1.13, 75th, 1.35], nStrideT [25th, 3.06, median, 3.25, 75th, 3.56]) with respect to the Grade1 group (SENv, [25th, 1.10, median, 1.27, 75th, 1.39], nStrideT [25th, 3.20, median, 3.40, 75th, 3.74]).

In TW, only DETap resulted significantly lower in Grade2 children (DETap, [25th, 72.1, median, 80.9, 75th, 85.9]) when compared to the Grade1 (DETap, [25th, 79.8, median, 83.8, 75th, 87.6]). Figure 2 shows polar plots describing differences in locomotor performances associated to age maturation.

FIGURE 2 HERE

ii) Sex (Males vs Females);

In NW, male participants showed lower stdStride ([25th, 0.03, median, 0.06, 75th, 0.07]), DETap (([25th, 53.4, median, 64.0, 75th, 76.4]) and AvgLap (([25th, 6.3, median, 6.9, 75th, 7.9]) than girls ([stdStrid, ([25th, 0.05, median, 0.06, 75th, 0.09], DETap ([25th, 66.3, median, 71.6, 75th, 83.1], AvgLap (([25th, 6.8, median, 7.4, 75th, 9.0]), while no significant differences was found in TW between the two groups. Figure 3 shows polar plots describing differences in locomotor performances for male and female participants. From the Figure, it can be seen that in TW, despite median values between groups are similar, female participants have a lower inter-subject variability.

FIGURE 3 HERE

iii) Level of motor competence (upper quartile versus lower quartile);

When analysing locomotor performance indices with respect to TMC assessment, in NW no statistical differences were found between children in the upper or lower quartile of TMC assessment. Details of participants in the upper and lower quartiles according to TMC assessment are shown in Table 2.

TABLE 2 HERE

In TW, significant differences were found on most of the parameters: less competent children showed significantly higher stdStride, higher DS duration, stance duration, nStrideT, higher recurrence parameters and lower SEN values in ML and AP directions. 25th-, median and 75th percentiles for the parameters showing significant differences are shown in Table 3.

TABLE 3 HERE

FIGURE 4 HERE

iv) Children with a DCDQ score below threshold versus children with no indications of DCD;

Five children (2F/3M) resulted with an indication or a suspect of DCD according to DCDQ [29]. Median age was 80 months (min 74, max 97 months). Figure 5 shows NW and TW polar plots for the 5 children, superimposed to the reference band of the corresponding age group.

FIGURE 5 HERE

Discussion.

Motor control regulates human motion, operating in synergy with the musculoskeletal system in determining joint kinematics and loading to effectively perform a given motor task, continuously adapting to external constraints. Its key role ascertained, its quantitative characterization as related to motor function for specific subjects or populations during the execution of daily living activities is still missing.

Recently, a cluster of indexes has been proposed for the purpose, showing promising preliminary results [18,23]. The selected indexes are derived from metrics analysing the dynamic structure of kinematics signals measured during the execution of specific motor tasks, and have been related to specific characteristics of the underlying motor control (e.g. automaticity, complexity) [4,20,30].

The present research work aimed to test the performance of this cluster of metrics in characterizing motor control from kinematics measured using wearable sensors. The selected testing population were healthy school children aged 6 to 8 years (I and II grade, primary school), serving as reference for the expected maturation of motor control with age and motor experience. The selected tasks were NW and TW, as suitable to highlight maturation in control automaticity and complexity, respectively, in line with previous literature [18,20].

Despite the small 24 month age range considered in the present study, results showed a significant decrease in variability, and an increase in automaticity (in NW) and complexity (in TW) with increasing age, in agreement with previous literature [18,23]. While only small significant differences has been highlighted in NW between male and female participants, reported results allow some preliminary inferences regarding the two groups: female, as a group, result more homogenous, showing, in TW, lower dispersion of the polar band in many parameters (see Figure 3), indicating a lower inter-subject variability as compared to the male group. Moreover, the parametric characterisation depicted in the polar plots of female participants tends to show a more mature pattern than the one of males when compared to age reference polar bands present in the literature [23]. Given the relatively small sample of subjects analysed in the present study, and the focused population of Italian children attending the same primary school, these results cannot be generalized to other populations of children; on the other hand, they support the use of this tool for the characterization of potential sex differences in motor control performance.

Interestingly, the trend of motor development associated to age maturation resulted even more evident when comparing the less competent children with the more competent ones, as identified according to TMC assessment. Less competent children, according to TMC, showed a motor performance, according to proposed metrics, comparable to that of younger/less experienced ones, and more competent ones to that of older/more experienced children. When aiming at characterizing a specific population or a single child, it is thus possible to relate the proposed metrics and polar plots to an 'age equivalent' one in order to understand if possible delays in motor development are present and in which area (variability, motor complexity etc.).

Finally, the examples of specific children with indication of DCD (see Figure 5) show how the locomotor control performance of a participant can be quantitatively characterized and compared to age reference bands. The analysis of a singular curve with respect to the corresponding age reference band allows i) understanding in which area the child shows a possible motor delay; ii) understanding which components of motor control are mostly affected (e.g. ineffective peripheral realization of a movement, immature control of centre of mass progression, insufficient automaticity etc.) and iii) supporting the definition of effective focused interventions. Ideally, if a child shows a TW complexity (SEN) lower than expected, he/she should be encouraged to explore different movements and strategies in order to enrich his/her ability to adapt and develop effective motor solutions; on the other hand, if NW variability is too high (or complexity is too high), training with task repetitions should be encourage in order to improve automaticity.

A possible limitation of the present study is that children with indication of DCD were identified based on DCDQ, a questionnaire parents fill in, and no gold standard assessment specifically designed for evaluating the motor performance of DCD children was available (e.g. MABC-2 [31]). DCD is recognised as a heterogeneous condition with different functional manifestations [32] and, in order to investigate specifically this developmental disorder by means of the proposed cluster of metrics, a novel study including patients with diagnosed DCD together with their clinical assessment is necessary.

Future developments must extend the use of the proposed metrics to the characterization of larger groups of children, possibly from different schools, socio-economic backgrounds, and countries, to then possibly proceed to their exploitation in interventional studies, in order to evaluate intervention effectiveness and/or support their definition.

In summary, the proposed cluster of parameters allowed to describe the expected trend and changes in the analysed population with respect to age and motor competence, and to differentiate subject with specific motor control alterations (below DCDQ threshold) in a population without significant biomechanical differences. These results, from a large sample of subjects with a small age range, support the suitability of the proposed cluster of parameters to characterize motor control underlying the execution of a specific task (e.g. NW and TW) in different populations (e.g. different age, different level of motor competence) as well as in specific subjects (e.g. DCD).

In addition to analyzing motor development and alteration in children and adults, the proposed method could effectively support the in-silico analysis of the effect of specific motor control alterations on the biomechanics of motion, allowing to quantitatively characterize, using specific parameters, the motor control behavior associated to a specific dynamic structure of motion.

Conflicts of Interest: None.

Funding: None.

Ethical Approval: The Bioethical Committee (Comitato di Bioetica) of the University of Bologna approved this study (25/05/2016).

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Figure 1

Fig.1. Inertial sensor positions (lower trunk and shanks) and axis orientations. Boxes indicate the signals analysed per each sensor (trunk: 3D acceleration components; shanks: angular velocity around the ML axis).

Figure 2

Fig.2. Polar bands for NW and TW for Grade1 and Grade2 children, respectively. Asterisks indicate significant differences ($p<0.05$) between groups when performing the same task (NW or TW).

Figure 3

Fig.3. Polar bands for NW and TW for male and female children, respectively. Asterisks indicate significant differences ($p<0.05$) between groups when performing the same task (NW or TW).

Figure 4

Fig.4. Polar bands for NW and TW for the 21 less competent and the 21 more competent children according to TMC assessment (upper and lower quartiles). Asterisks indicate significant differences ($p<0.05$) between groups when performing the same task (NW or TW).

Figure 5

Fig.5. Polar lines for NW and TW for the children resulting with an indication of DCD according to DCDQ. Age matched reference polar bands in light grey.

Figure 1

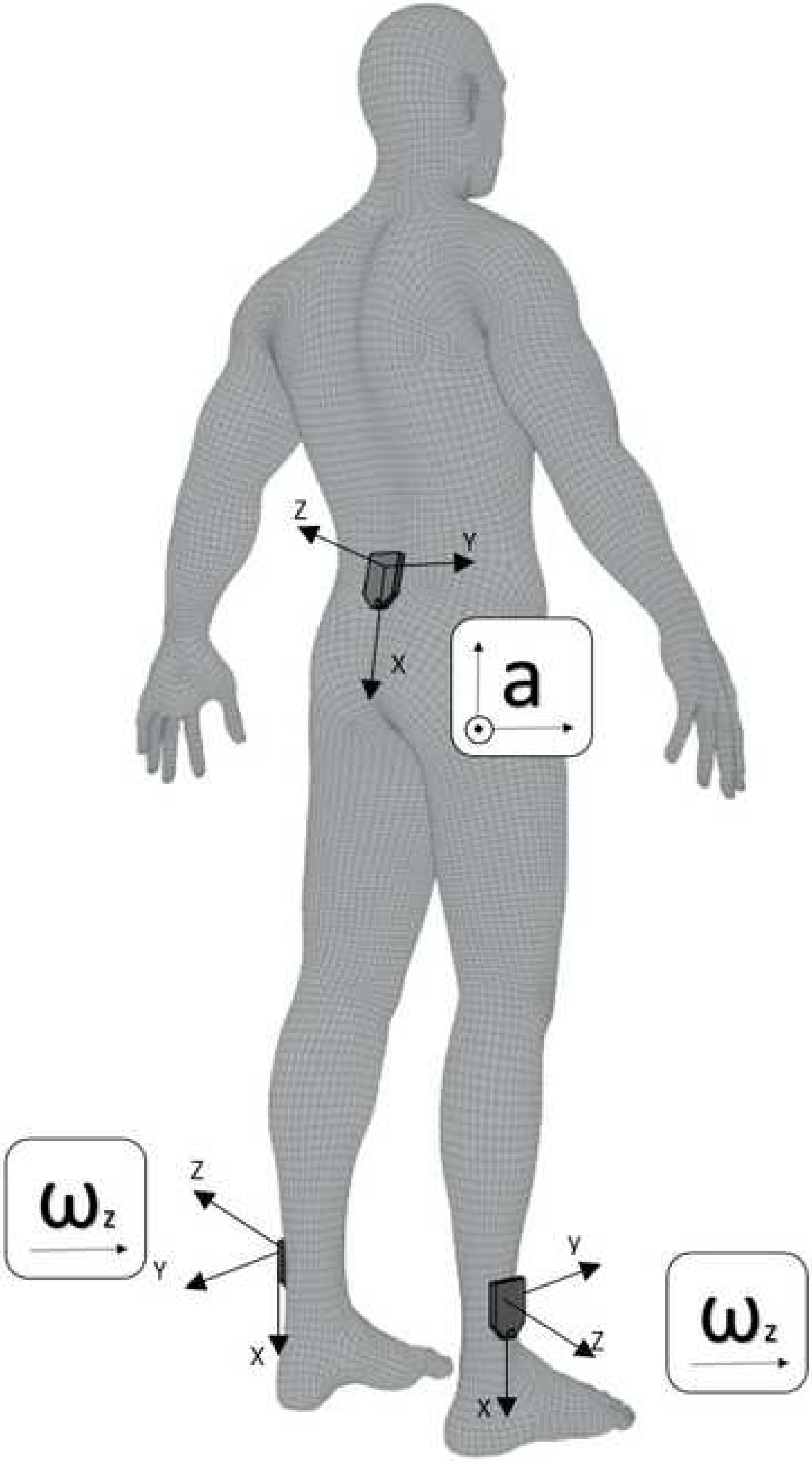
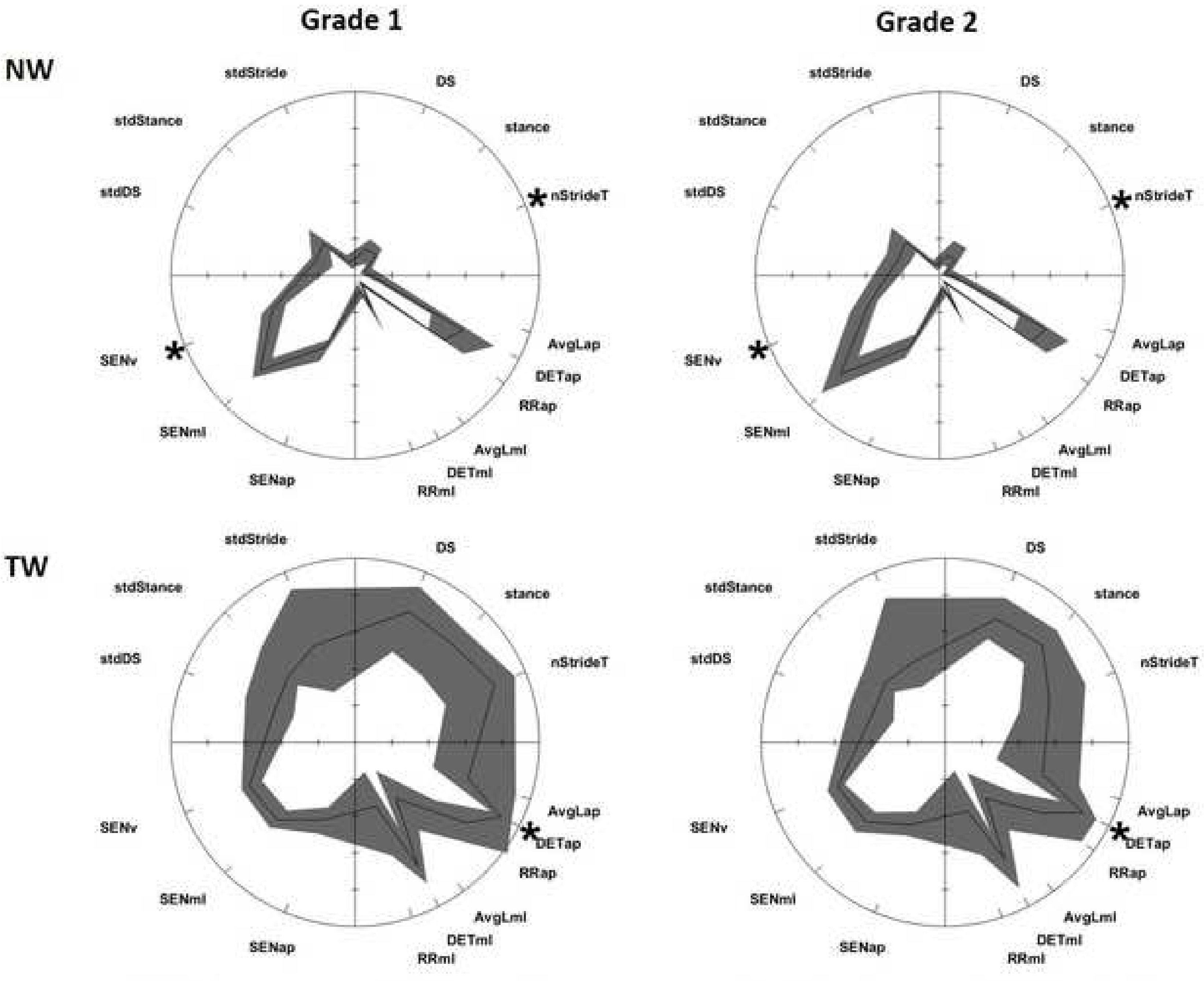
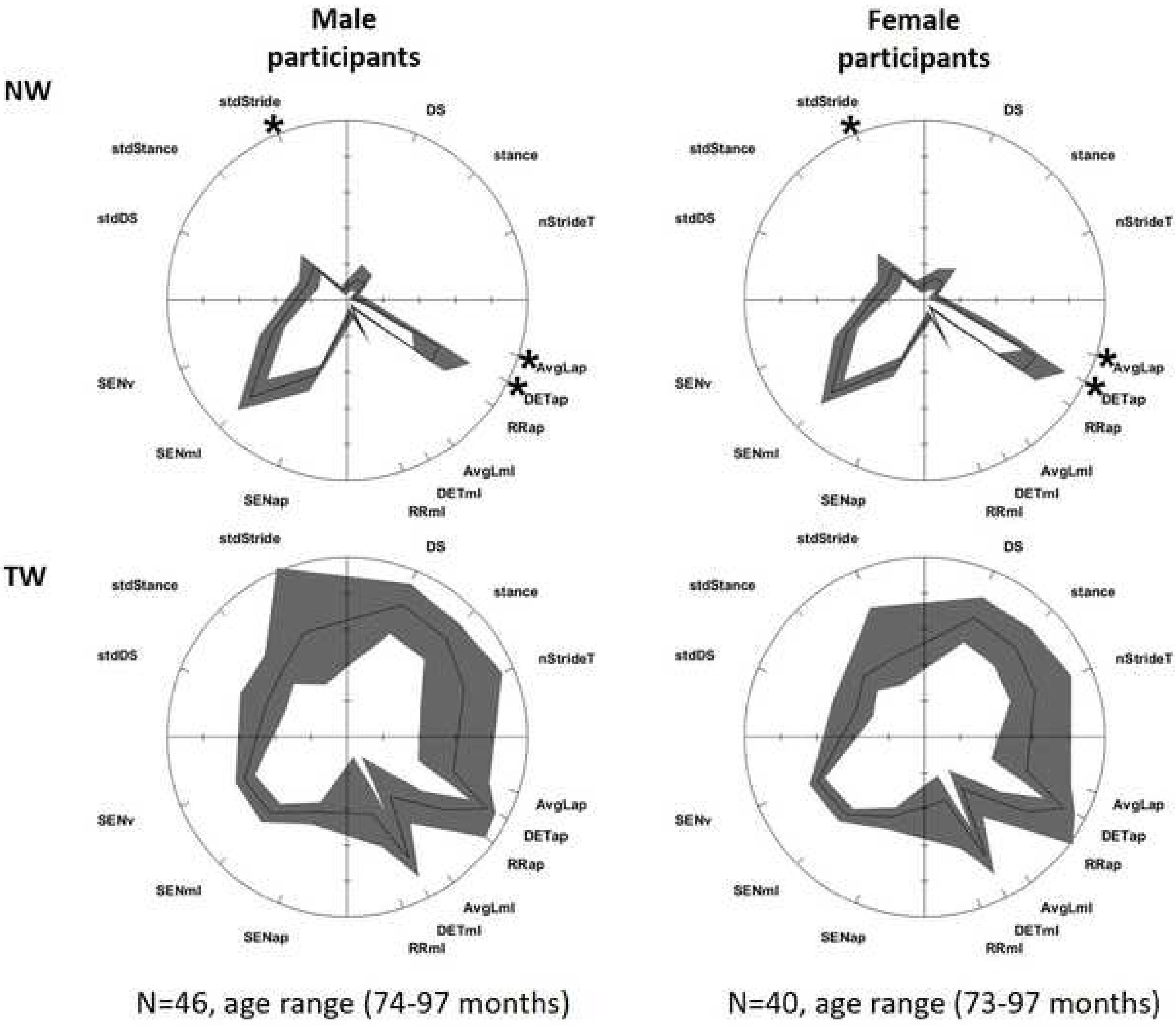


Figure 2



N=36, age range 73-85 months

N=50, age range 85-97 months



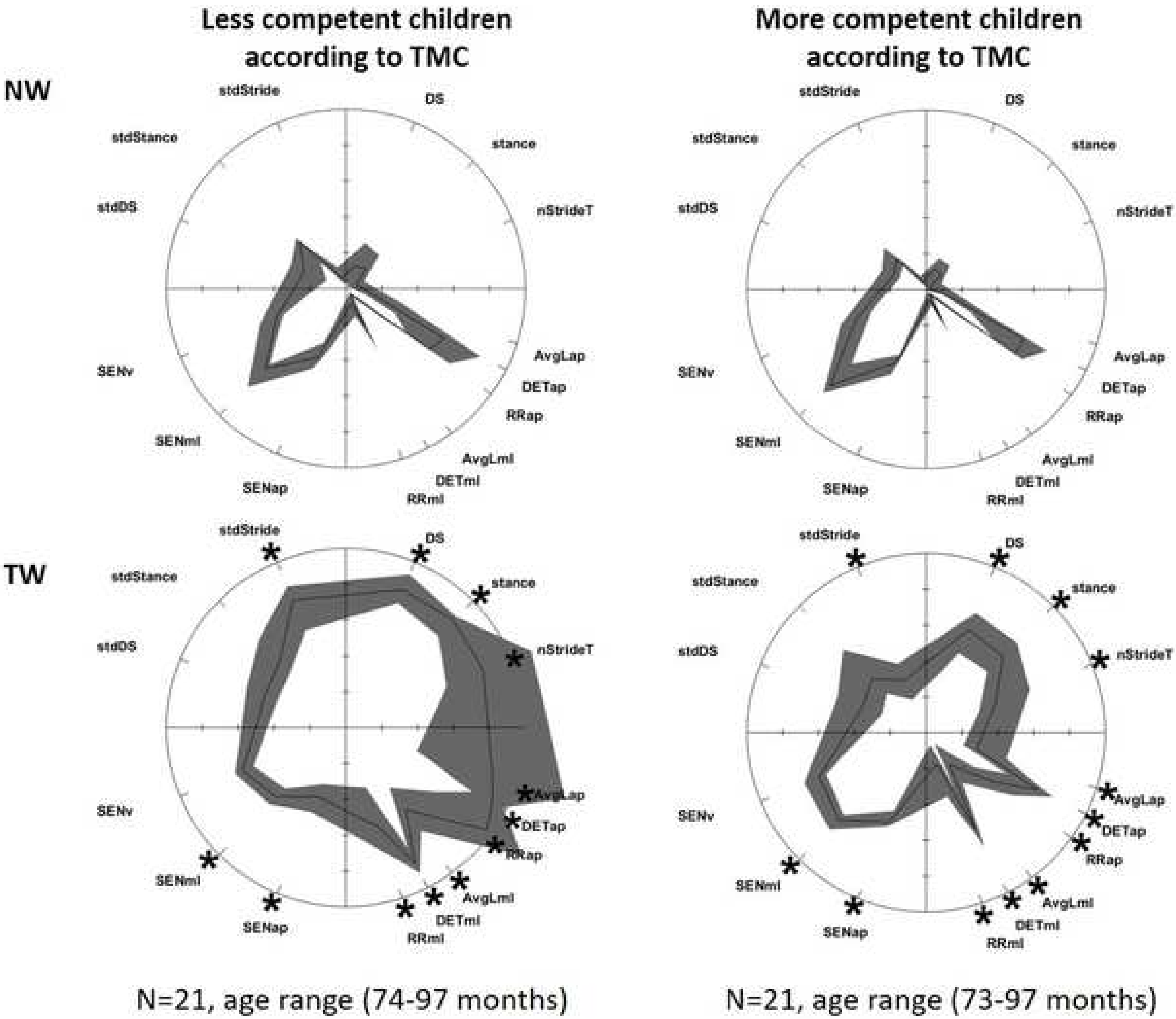
Male participants

Female participants

N=46, age range (74-97 months)

N=40, age range (73-97 months)

Figure 4


Less competent children according to TMC
More competent children according to TMC
NW
TW
stdStride
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DETap
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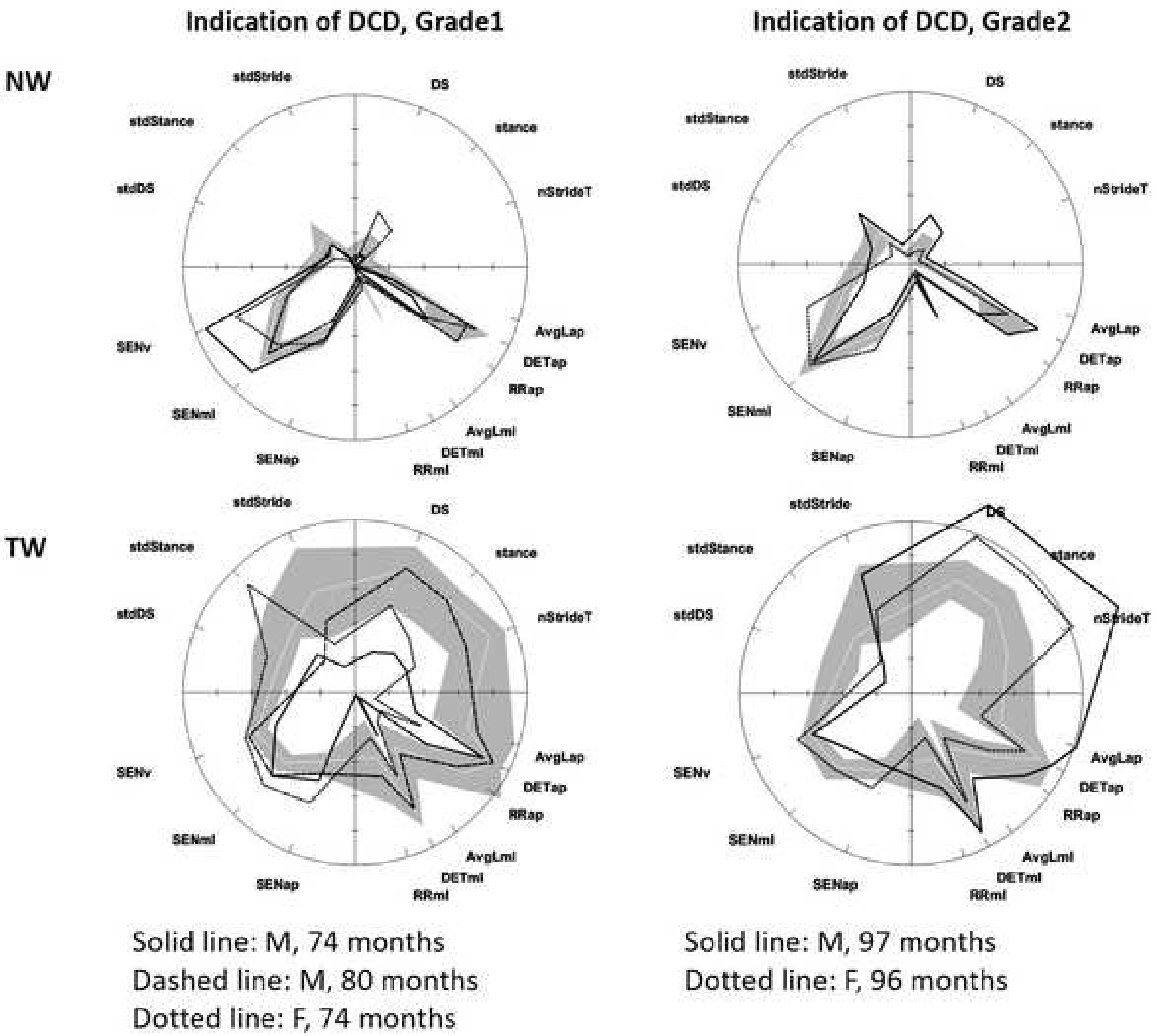
RRml
SENap
SENml
SENv
stdDS
stdStance
*
N=21, age range (74-97 months)
N=21, age range (73-97 months)

Figure 5


Indication of DCD, Grade1
Indication of DCD, Grade2
NW
TW
stdStride
DS
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nStrideT
AvgLap
DETap
RRap
AvgLml
DETml
RRml
SENap
SENml
SENv
stdDS
stdStance
Solid line: M, 74 months
Dashed line: M, 80 months
Dotted line: F, 74 months
Solid line: M, 97 months
Dotted line: F, 96 months

Table 1.

	Grade1			Grade2		
	tot	**male**	**female**	**tot**	**male**	**female**
n	36	18	18	50	28	22
age (months)	78 (73-85)	78 (74-85)	79 (73-85)	91.5 (85-97)	91 (85-97)	92.5 (86-97)
height (m)	1.21 (1.08-1.30)	1.25 (1.11-1.30)	1.21 (1.08-1.30)	1.28 (1.16-1.40)	1.27 (1.16-1.38)	1.28 (1.19-1.40)
body mass (kg)	26.1 (19.5 - 38.0)	27.4 (19.5 - 38.0)	25.5 (19.6 - 33.0)	28.2 (19.7 - 41.0)	28.5 (19.7 - 38.0)	28 (20.8 - 41.0)

Table 1. Details of age groups participating in the study. Age, height and body mass represented as median (min-max).

Table 2.

	Less competent children according to TMC	**More competent children according to TMC**
M/F	9F/12M	8F/13M
age (months)	84 (74-97)	93 (73-97)
height (m)	1.23 (1.08-1.37)	1.27 (1.13-1.40)
body mass (kg)	28.0 (19.5 - 38.0)	28.0 (22.0- 41.0)

Table 2. Details of age groups participating in the study. Age, height and body mass represented as median (min-max).

Table 3

	Less competent children according to TMC			More competent children according to TMC		
	25th	median	75th	25th	median	75th
stdStride	0.38	0.50	0.55	0.14	0.22	0.28
DS %	47.35	51.30	55.92	33.78	40.91	45.84
Stance %	73.06	76.29	76.97	66.71	69.96	72.76
nStrideT	7.58	9.28	11.47	5.40	6.16	7.74
AvgLap	9.24	13.49	17.61	7.33	8.05	9.74
DETap	77.31	85.43	89.42	59.78	72.13	77.56
RRap	14.36	18.64	21.48	11.03	12.61	14.22
AvgLml	9.19	10.66	12.10	5.96	7.35	8.52
DETml	75.54	81.39	85.03	50.27	66.16	72.88
RRml	11.30	14.02	15.91	8.00	9.34	11.61
SENap	0.97	1.13	1.31	1.24	1.37	1.43
SENml	1.25	1.39	1.50	1.59	1.68	1.83

Table 3. 25th, median and 75th values of the performance parameter showing significant differences during TW between children in the upper or lower quartile of TMC assessment.