Technology-based methods for the assessment of fine and gross motor skill in children: A systematic overview of available solutions and future steps for effective in-field use

Clark, CCT, Bisi, MC, Duncan, MJ & Stagni, R

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Review article: Technology-Based Methods for the Assessment of Fine and Gross Motor Skill in Children: A Systematic Overview of Available Solutions and Future Steps for Effective In-Field Use

Running heading: Technology Assessed Motor Skill

Abstract

We sought to provide researchers and practitioners with a holistic overview of technology-based methods for the assessment of fine and gross motor skill in children**.** We conducted a search of electronic databases using Web of Science, PubMed, and Google Scholar, including studies published up to March 2020, that assessed fine and/or gross motor skills, and utilised technological assessment of varying study design. A total of 739 papers were initially retrieved, and after title/abstract screening, removal of duplicates, and full-text screening, 47 were included. Results suggest that motor skills can be quantitatively estimated using objective methods based on wearable- and/or laboratory-based technology, for typically developing (TD) and non-TD children. Fine motor skill assessment solutions were; force transducers, instrumented tablets and pens, surface electromyography, and optoelectronic systems. Gross motor skill assessment solutions were; inertial measurements units, optoelectronic systems, baropodometric mats, and force platforms. This review provides a guide in identifying and evaluating the plethora of available technological solutions to motor skill assessment. Although promising, there is still need of large-scale studies to validate these approaches in terms of accuracy, repeatability, and usability, where interdisciplinary collaborations between researchers and practitioners and transparent reporting practices should be advocated

Key words

Motor Skill; Technology; Children; Motor Competence; Emerging

1. Introduction

Studies examining the importance of motor skills related to health, sports performance, academic achievement, and cognition in children have accelerated over the preceding decades [1]. Within the plethora of studies examining motor skills there are a substantial range/number of different methods that have been employed in the assessment of both fine and gross motor skill in typically (i.e. no known impediment to motor development) and non-typically (i.e. motorically or cognitively impaired) developing children. Quantitative and reliable assessment of such skills is a cornerstone of advancing the scientific understanding of the benefit of having '*good'* motor skills. However, recent work [2] has suggested a need for clarity on what type of method for assessing motor skills should be used, in which situation, and for what purpose. Bardid et al [2] recently provided a comprehensive and holistic review of motor competence assessments and their practicality. This review [2] is useful for practitioners who currently use well-established process (i.e. measures that provide performers, practitioners and researchers with qualitative information about how a motor skill is completed) and product (i.e. measures are quantitative and indicate the outcome of the movement, such as, throwing speed, number of success catches) measures of motor skills and highlights the relevance of emerging technologies in providing quantitative, potentially more analytic, and reliable assessment of motor skills. On the other hand, it does not provide a complete overview of the available methodological technology-based methods that have been proposed in the literature. In their conclusions, authors suggested the integration of motion devices and observation methods to provide a more holistic assessment of children's motor competence; however, in order to achieve this, first, there is a need to identify, assess, and present the possible technology-based solutions reported in the literature. Following the proliferation of technology in recent years, and its integration into all aspects of life, there is a currently distinct dearth of a technologically specific review of the evidence base, with only evidence specific to physical activity measurement, and not motor skills [3].

Typically, the assessment of motor skills has involved observation and scoring of various motor tasks by a trained assessor, such as those used in the various iterations of the test of gross motor development (TGMD), which provides both process and product inferences. For instance, where process measures yield the quality of the movement observed in the TGMD [4]; alternatively, product type measures, which provide an indication of the outcome of the motor skill, include distance jumped, or the time taken to sprint 10m. When acquisition of a child's fine motor skill is the aim; graphomotor assessment or bi-manual prehension, i.e., picking up and moving objects [5–9], remains standard practice. Technological solutions based on human movement analysis methods can support motor skills assessment providing objective quantitative measures of what is traditionally assessed visually (e.g. automatic assessment of a test) and/or, can be integrated, exploiting innovative analytical approaches, providing new insights and a more holistic assessment of children's motor competence. For example, Sacko et al. [13] and Duncan et al. [14] have examined the utility of accelerometers to accurately quantify the energy expenditure associated with specific fundamental movement skills. Whilst additional work has showcased the ability of pervasive technology to automatically assess motor skills, and compared outcomes to human assessors [12,15]. For instance, Barnes et al [15] demonstrated good agreement between observer and magnetometry derived fine and gross motor scores, yielding correlation coefficients of ~0.7. Whilst Bisi et al [12] showed that automatic assessment of the TGMD-2, compared to observer assessment, yielded an agreement of 87% on average across an entire cohort for each skill, when using IMU's. Moreover, traditional modes of analysis are being enhanced or combined with novel analytical approaches to quantification, such as harmonic ratios, short-term Lyapunov exponents, multiscale entropy, and recurrence quantification analysis [10,11], in turn, proffering hitherto unseen insight into the minutiae of motor skills.

Despite the increasing scientific interest in children's motor skills as applied to clinical health and motor development, in addition to the increasing prevalence of systematic reviews related to motor skill during childhood [2,16], there has been no systematic review which amalgamates the extant literature relating to the technological assessment of fine and/or gross motor skills. Given the variegated emerging technologies and analytics that are being used to quantify and qualify motor skills, and the potential for critical information relating to movement to be drawn from advanced analysis of quantitative methods, we sought to evaluate whether evidence was present in the available literature to support the choice of technology-based approach for, routinely used, quantitative motor skills assessment. By reviewing the available proposed solutions of emerging technologies for the assessment of fine and gross motor skills in children, this work aims at providing a detailed methodological overview of currently proposed technology-based possibilities, with the final aim of supporting future research and possible in-field use and validation.

2. Methods

2.1 Literature search

For the purpose of this review, a computerised search was conducted using the following databases: Web of Science, PubMed and Scopus, thus providing access to a wide range of studies, and in line with standard databases used in this field. Systematic reviews aim to identify, evaluate, and summarize the findings of all relevant individual studies, making the available evidence more accessible to decision makers and key stakeholders [63]. Whereas, a scoping review is a form of knowledge synthesis that addresses an exploratory research question aimed at mapping key concepts, types of evidence, and gaps in research related to a defined area or field by systematically searching, selecting, and synthesizing existing knowledge [64]. The review aimed to identify research studies using technology-based methods to assess motor skills in children published from database inception until March 2020. A combination of the following key words, Medical Subject Heading (MeSH) terms, and Boolean logic operators were used to locate studies for review; motor competence OR movement competence OR motor development OR fundamental movement skill* AND biomechanic* OR markerless OR accelerom* OR inertial sensor* OR IMU* OR wearable sensor* OR wearable technolog* OR kinematic* OR quantitative development AND children OR developing population. The "*" symbol was used as a wildcard operator to specify any number of characters, used at the end of a root word, and allows searches for variable endings of a root word. To replicate this same search criterion the search strings were adapted to the specific characteristics of each database. The exact strings used for the three databases are detailed in **supplementary file 1**.

Figure 1 shows the results of the literature search and article selection process.

****FIGURE 1 HERE****

Multiple searches were then made in each of the selected databases and additional hand searches for relevant references and citations linked to the primary studies obtained during literature search. Such that, of the finally included studies, the reference lists were inspected to check for any papers not already identified.

2.2 Inclusion/exclusion criteria

The articles to be included in the review had to satisfy the following criteria: (i) investigation of technology-based solutions for the assessment of gross and or fine motor skill in children (e.g. IMU, multi-dimensional kinematics and kinetics, accelerometers, magnetometers, gyroscopes, graphomotor tools, force transducers), (ii) clear purpose of the application of technology for supporting quantitative motor skill assessment, (iii) full scientific papers in English language.

A wide range of study types were eligible for the review, including typically and non-typically developing children, observational and interventional studies, as well as validation and calibration studies (including lab-based studies).

Technical reports, review articles, non-human based studies, or studies which did not measure motor skills were excluded and not considered further.

All titles and abstracts and all full-text assessments were conducted independently, in triplicate, and decisions to accept or reject a paper were agreed between the authors by way of cooperative triangulation. This process meant that each assessment was conducted, checked, and confirmed by three authors

2.3 *Quality assessment*

As predefined quality assessment tool was found to be appropriate for the current study, a proprietary set of 13 questions were selected to evaluate quality of each work and to identify possible methodological gaps. The selected questions were:

1. Are the research objectives clearly stated?
2. Is the design of the study clearly described?
3. Were participant characteristics adequately described?
4. Was sample size used justified?
5. Was equipment and set up clearly described?
6. Were movement tasks clearly defined?
7. Were the analytical techniques clearly described?
8. Were appropriate statistical analysis methods used?
9. Were the main findings of the study clearly described?
10. Were key findings supported by the results?
11. Were limitations of the study clearly described?
12. Were key findings supported by other literature?
13. Were conclusions drawn from the study clearly stated?

For evaluation purposes, possible scores were: 2 = Yes; 1 = Limited detail; 0 = No.

2.4. Data extraction

A customised data extraction form was developed. The data extraction themes were selected to give an exhaustive overview of each article for analysis. Data extraction themes included the following comprehensive tabular headings: type of study, Country, target population, presence of control group, population characteristics, sample size, type of analysis, type of motor skill, tasks analysed, process vs product outcomes, instrumentation, reference assessment, measurement system, portability, cost, time, data processing, data entry and reduction, and data output. In order to support readers in the identification of available solutions for specific purposes, extracted data were organized with respect to motor skills that can be assessed when evaluating motor competence and with respect to laboratory based or wearable technology. In particular, they will be presented in three main sections: i) assessment of fine motor skills (Table 1a and b); ii) assessment of gross motor skills using wearable devices (Table 2a and b); iii) assessment of gross motor skills in laboratory (Table 3a and b).

3. Results and Discussion

****Insert tables 1 (a and b), 2 (a and b), and 3 (a and b)****

3.1 Quality of the studies:

Overall quality of the studies was good with an average score of 21 out of a maximum of 26 (range 13-26). Critical issues resulted from questions number 4, scoring 0 in 42 studies over 45, and question 11, with an average score of 1. Complete evaluation tables are reported in the supplementary tables 1 a, b, and c, for fine motor, gross motor – wearable-based, and gross motor – laboratory based, respectively.

3.2 Fine motor skills

Eight out of 17 (47%) studies were conducted in neurologically or motor-impaired (non-typically developing (TD)) children, 9 out of 17 (53%) studies were conducted in TD children. Age range of participants in eligible studies was 5-to-18y, whilst sample sizes varied from 8-to-209 (Table 1a and 1b).

3.2.1 Non-typically developing children

In non-TD children; reaching, writing and block stacking tasks were used to assess fine motor skill. Instrumentation of these tasks was conducted following classic guidelines, i.e., no novel or adapted assessments. Specifically, writing tablets and pressure sensitive drawing/writing utensils were used. However, measurement of fine motor skill was achieved by employing a mixture of classic and novel techniques, which will subsequently be discussed.

Classic assessment approaches

Butler et al [17] assessed the kinematics of the upper limb in children with cerebral palsy (CP) using the Reach and Grasp Cycle, which included six sequential tasks: reach, grasp cylinder, transport to mouth, transport back to table, release cylinder, and return to initial position. In the same population, Chau et al [18] assessed grip and normal forces during handwriting. Both Butler et al [17] and Chau et al [18] included TD and non-TD participants, yielding clinically useful comparisons, although Chau et al relied upon a small, convenience sample. Formica et al [19] sought to quantitatively assess the shoulder motor behaviour in children with hemiplegia during pointing tasks. Relatedly, Kuhtz-Bushbeck et al [20] evaluated motor behaviour in children after traumatic brain injury with quantitative instrumented measures of gait and of functional hand movements, which included reaching and grasping. Colucini et al [21] employed kinematic analyses in an effort to discern the functional fine motor differences, in the form of grasping and moving blocks, between adults and children, with and without hemiplegic CP. The former studies [17–21] all utilised participants with, relatively, severe motor impairments; however, in the process of reviewing the literature base, it was evident that a few studies focussed on developmental or dystonia related impairments. Smits-Engelsman et al [22] and Chang et al [23], respectively, investigated hand-writing efficiency in children with Developmental Coordination Disorder (DCD), and both groups independently reported fine-motor skill was diminished, compared to TD controls. Finally, Casselato et al [24] investigated kinematic characteristics of unconstrained movements of the upper limb, reaching and writing, suggesting that a linear relationship between severity of dystonia, and reduced velocity, loss of muscular activation focalization, impairment of rest-movement modulation, and impaired hand-writing movement.

Novel approaches

Among fine motor control studies included in this review, none incorporated novel assessment approaches, and maintained the use of classic/traditional assessment. Notwithstanding, whilst assessments were not novel, many studies incorporated analytically advanced techniques to classify or score non-TD participants (which is discussed in the following section), such as 3D kinematics [17,19,21, 24] and digitized handwriting assessment tools [18,22,23].

Classification strategy/statistics

Butler et al [17], Formica et al [19], and Colucini et al [21] used 3D kinematics to capture and classify all fine motor movements, whilst Casselato [24] also utilised 3D kinematics, concurrently with surface electromyography (EMG). In all four cases, and as expected, TD children outperformed non-TD counterparts across tasks including whole arm movements, pointing, grip strength and numerous hand-specific actions; moreover, it was asserted that each of the assessments could be used to supplement clinical measurement programmes. Across the four studies utilising 3D kinematics [17, 19, 21, 24], the set-up and specification varied, with each study utilising a different recording frequency (20, 60, 100 and 120Hz) and camera allocation (6 and 8 cameras) (Table 1a). Despite the varying operational set-up, Butler [17]; Formica [19]; Colucini [21] and Casselato [24] all suggested, potential, clinical efficacy in their approach, particularly with reference to speed, velocity and torque parameters. Smits-Engelsman et al [22] and Chang et al [23] utilised a digitized writing tablet, whilst, similar in function, Chau et al [18] utilised a force transducing tablet, which can discern force applied to a more sensitive degree than a digitized tablet. All three studies utilising some form of hand-writing assessment noted TD children outperformed non-TD counterparts in terms of time to completion and pressure distribution. Interestingly, both English and Chinese language was assessed, and despite ethnic diversity, comparable results were attained between studies such that discrimination between TD and non-TD children could be made. All three studies [18,22,23] utilised a different operational set-up, although all exploited a liquid crystal display, with recording frequencies varying between 94, 200 or 206Hz. Promisingly, all three hand-writing assessment studies noted easy set-up, minimal data entry, and automated algorithmic assessment and output. Kuhtz-Bushbeck [20] utilised a clinical assessment tool, which consisted of a neurologist assessing each participant visually, concomitant to kinematic evaluation. This approach represented a large time and personnel burden, moreover, there was a distinct lack of clarity with regards to the kinematic assessment. Thus, it is infeasible to suggest this as a technological solution, but does highlight that when employing technology-assisted approaches, absolute clarity and transparency is of utmost importance.

General discussion

The non-TD populations used to assess fine motor skill varied from relatively mild motor impairments, to severe, acquired or genetic, neurological impairments, thus, making direct comparisons between such participants impractical. Colucini [21], in a robust experimental protocol, utilised adults and children, with and without hemiplegic CP, and asserted that, in children, the on-going maturation process of the central nervous system confounds our ability to discern ‘normal’ fine motor skill; but could, at least, distinguish between TD and non-TD children. Evidently, in non-TD populations, the assessment of fine motor skill has been more related to functionality, rather than its application to sporting or physically active movements. Most studies asserted a certain degree of clinical utility in their findings, however, such assertions are questionable; four studies utilised 3D kinematics ([17][19][21][24]), which is a time, space and resource consumptive technology, which is not conducive to effective clinical practice. However, in the studies employing hand-writing assessment [18,22,23], the technological solution represents relatively low financial burden. Furthermore, whilst not explicitly reported, Chang et al [23] highlight that digitized handwriting assessment took less time than a standard clinician assessment, and thus, likely represents a useful technological solution, that could be easily incorporated clinically and sub-clinically. The type of fine motor skill investigated varied by severity of motor impairment in the participants. In those with a greater degree of impairment, the focus was on whole arm or joint movement towards the performance of a basic fine motor task, such as pointing. In those with a developmentally related motor impairment (DCD), the focus was centred on graphomotor skill, such as writing, drawing, and grasping. Across all included studies, the application of novel technologies aided in the assessment of fine motor skill, and clearly represents an excellent opportunity to advance to our understanding of growth and development, in TD and non-TD children alike; however, to establish clinical utility in non-TD children, such technological solutions must be refined, both in terms of monetary and time requirements, with considerations made for end-users, such as clinicians, and transparency in the methods employed.

3.2.2 Typically developing children

In TD children; writing, drawing and box opening were used to assess fine motor skill. Concordant to non-TD children related studies, instrumentation consisted of classic guidelines, with no novel or adapted assessments. Specifically, writing tablets were the most preponderant tool used. With respect to measurement of fine motor skills, pressure sensitive pens and tablets, in addition to stereophotogrammetry or motion capture was employed.

Classic assessment approaches

Six of the studies included in this review focussed, broadly, on fine motor skill in the form of graphomotor assessment [5–7,25–27] using some form of digitizing writing tablet. Rosenblum et al [6] were the only group to utilise a comparison or control group (proficient vs non-proficient writers). The tasks involved in this group of studies involved writing and copying shapes, letters and numbers, sequentially or randomly. The remaining 3 studies that investigated fine motor skill in TD children all utilised a test involving grasping and moving an item [8,9,28]. Blank et al [28] investigated children, aged 3, 4, 5, and 6-years, and sought to explicate the development of grip strength. Mason et al [8] assessed bi-manual prehension through moving cylindrical objects in young (4-6y) and older (7-10y) children. Finally, Rudisch et al [9], in a similar protocol to Blank et al [28], utilised a sample of children with a range of ages, from 5-to-16-years, and tracked the speed and efficiency with which participants opened boxes.

Novel approaches

Among fine motor control studies included in this review (Table 1b), none incorporated novel assessment approaches, and maintained the use of classic/traditional assessment. Notwithstanding, whilst assessments were not novel, many studies incorporated analytically advanced techniques to classify or score TD participants (which is discussed in the following section).

Classification strategy/statistics

Rueckregel et al [5]; Rosenblum et al [6]; Ren et al [7]; Waterman et al [25]; Duval et al [26] and Lin et al [27] all utilised a digitized writing tablet. The recording frequency of the devices used ranged from 60 to 200Hz, with a reported spatial resolution of 0.05 mm. Across all digitized tablet studies, protocols were complete within 30 minutes, required minimal set-up, and yielded detailed information regarding speed, automation, and pressure distribution. Of all the tablet-based studies, most recorded time-domain features (as noted above). Ren et al [7], on the other hand, utilised Dynamic Time Warping (DTW) to assess pen tip trajectories, associated with maturation, demonstrating that spatio-temporal parameters can be attained with relative ease. Blank et al [28] utilised a force transducer with combined tri-axial accelerometer, where grip forces (by a uni-axial force transducer) and inertial forces (tangential forces, calculated from the measurements by accelerometers within the object) were recorded. The authors reported that the device represented an inexpensive tool, which could be operationalised and collect data within one-minute, with similar portability to a classic hand-held dynamometer. Mason et al [8] utilised stereophotogrammetry, where light-emitting diodes were affixed to each hand, and subsequently tracked during grasping. Whilst robust outputs were attained, including velocities and timing, this approach is confined to a laboratory environment. Comparably, Rudisch et al [9] utilised a bi-manual approach, where an electromagnetic system was applicated to each hand. In this application, hand position and orientation were attainable, and permitted the discerning of subtle, age-related differences within 10 minutes. However, the electromagnetic system was not portable, which could be considered a limitation to its in-field use, and would hinder the ability of practitioners to integrate this assessment, more readily, into practice.

General discussion

As compared to studies assessing non-TD children, those that focussed on TD children were able to recruit comparably large sample sizes (non-TD highest: 33 vs. TD highest: 187), which permits greater generalizability in the findings. In studies examining TD children, there was, aside from Rosenblum et al [6], an absence of any form of control or comparator group, with studies utilising cross-sectional designs. One of the most preponderant hurdles to the uptake of the aforementioned technological solutions, is portability. All of the approaches were, reportedly, low in cost, however, only the digitized writing tablets represent a robust, transportable tool, and, indeed, are accompanied with less set-up time, and less-time to output. All of the included studies were able to ascertain more detailed, nuanced variables than traditional, manual scoring techniques, and yielded good insight, especially in how fine motor skill develops across ages. The broad range of childhood ages examined represents a distinct strength of the evidence base. Notwithstanding, however, all of the included studies were cross-sectional, and despite utilising diverse age ranges, truly longitudinal studies are warranted to confirm the veracity of age-mediated differences in fine motor skill.

3.2.3 Summary of fine motor control and technological benefits

The results of the studies reviewed in this section supports the use of wearable sensors for the assessment of fine motor control development in TD and non-TD children. Both classic and novel approaches for the assessment of fine motor performance highlighted distinct differences in non-TD vs. TD children, particularly related to outcome measures. Notwithstanding, it is evident that now ubiquitous sensors permit the automated, quantitative, and expedited assessment of fine motor skill. For all fine-motor control-based studies, there were no tangible reports for monetary cost. In studies that focussed non-TD children, there were no reports of associated time. Whilst for studies in TD children, most did not report any usable information for time, with only the following exceptions, and even in cases where time was reported, the standardisation of reporting was not uniform. Accordingly, Blank et al [28] and Rudisch et al [9] reported a time acquisition of 1-minute and <10 minutes, respectively, whilst Rueckriegel et al [5] and Rosenblum et al [6] reported that assessments took 30 minutes and 25 minutes, respectively.

3.3 Gross motor skills – Wearable based assessment

Three-of-13 (23%) studies were conducted in neurologically or motor-impaired (non-TD) children [29–31], 10 out of 13 (77%) of studies were conducted in TD children [10–12,15,32–37] (Table 2a and 2b). The age range of participants in eligible studies was 2-to-15y, whilst sample sizes varied from 14 to 112.

3.3.1 Non-typically developing children

Two studies focused on children with developmental coordination disorder (DCD) (or Attention Deficit Hyperactivity Disorder and DCD) [30,31], 1 on children with Down, and Prader-Willi, syndromes [29]. All 3 studies included a control group of age-matched TD participants and sample size per group was less than 20. The 2 studies focusing on DCD, included 9-year-old participants, while in [29], the age range was 2 to 11 years. Specifically, testing for group differences between non-TD and TD group in the estimated parameters was the most frequent approach. Two studies [1,2] analysed gait to assess locomotor skill. One study [31] a series of tasks (right and left leg stance, rhythmic and beat on legs, jumping jacks, etc.) to assess gross motor skill in a broader perspective. Number and placement of sensors differed in the three studies: one study utilized only one sensor on the trunk [30], one four sensors (on sternum, trunk and shanks) [29] and one 12 sensors (on upper and lower trunk, upper and lower arms, upper and lower legs and feet) [31]. Measurements of motor skill were achieved by employing a mixture of classic and novel biomechanical approaches, which will subsequently be discussed. In general, no study reported specific information regarding time required for data-acquisition, -entry and -elaboration with sensors and no study made raw data and/or algorithms available as open-sources.

Classic assessment approaches

Classic quantitative measures of motor performance were included in all the 3 studies. These measures were used to quantify objectively some outcome features of motor performance (e.g. variability, speed) aiming at highlighting differences between groups. Root Mean Square (RMS, or normalized root mean square, nRMS) of the acceleration vector was considered in all the studies, but direct comparison of results is not possible due to the different tasks analysed and different sensor locations [38]. Belluscio et al [29], using a sensor placed on the pelvis, showed that non-TD children had higher nRMS accelerations in the mediolateral direction during gait, while no difference was found in RMS of trunk acceleration between DCD and TD children in any direction during treadmill walking [30]. Ricci et al [31] showed that DCD patients had lower RMS values at the thigh than TD peers during frog jumping.

Assessment of gait spatiotemporal parameters (walking speed, stride frequency, and stride length) was included in one study [29], highlighting significant differences between non-TD and TD in normalized stride length and normalized stride frequency. Ricci et al [31], by analysing 9 motor tasks, included a series of quantitative measures (depending on the task of interest) aiming at quantifying task temporal parameters, duration, counting of correct events, sway area and jerk, and found significant differences between non-TD and TD in some of the monitored parameters.

Novel approaches

Novel approaches using wearable sensors aimed at characterizing motor control performance characteristics, i.e. quantifying aspects related to dynamic stability, symmetry, complexity etc. [29,30]; the novel metrics used to this purpose were meant i) to highlight differences between non-TD and TD children [29,30], and ii) to provide interpretative information on which aspects of motor control performance are related to these metrics. Belluscio et al [29], applied the attenuation coefficient (characterizing the attenuation/amplification of the accelerations from the lower to the upper level) [39] and the improved harmonic ratio at pelvis acceleration vector (a measure of gait symmetry)[40] and found that non-TD children attenuate less than TD children and show a less symmetric gait. Speedsberg et al [30] calculated short-term local dynamic stability from measures of orthogonal trunk accelerations [41], a method that aims at quantifying the body's resilience to small perturbations naturally inherent during walking. As hypothesized in the work, DCD children showed general reduced local dynamic stability and the proposed metrics (short-term Lyapunov exponent) showed good power of discrimination between DCD and TD.

Classification strategy/statistics

In order to evaluate the applicability/performance of the proposed methodology, all the 3 studies assessed eventual significant differences in the quantified parameters between the non-TD and the TD groups. In addition, Belluscio et al [29] evaluated the relationship between each estimated parameter and a clinical scale (GMFM-88) using Pearson correlation coefficients; while Speedsberg [30] applied receiver operating characteristic curve (ROC) analysis to evaluate the discriminative power of short term local dynamic stability in differentiating children with DCD and TD.

General discussion

The number of sensors utilised in the above mentioned studies was; 1 on the sternum in [30], 4 (on both legs, pelvis and sternum) in [29], and 12 (frontal upper and lower trunk, upper and lower arms, upper and lower legs and feet) in [31]. Clearly, this aspect influences the ease of setup and cost, whilst from the low number of studies' it is not possible to conclude if one approach is better than another. Among the quantitative proposed measures, the novel approaches, in addition to yielding promising results, have several advantages; for instance, they required only pelvis/trunk acceleration data, thereby minimizing time for technical setup, data entry and reduction. However, it is important to point out that these metrics have some technical requirements (e.g. minimum number of available strides [42]) and include many parameters that require adequate set-up before being used.

3.3.2 Typically developing children

Most of the studies (8-of-10) focused on children older than 5 years [10–12,15,32,35–37]. Among these, 1 focused on a single age group (11year old children) [15], while the others divided children in age groups (age range 6-10), or according to task developmental levels. Two studies included children of different ages (from 2 to 12 years [33,34], from 7 to 12 years [37]) classifying them according to the development level of the specific task/s. Overall, sample sizes ranged between 14 to 80 TD children, whilst correlation of quantitative measures with age/stage of development was the most frequent analytical approach. Different tasks were used to assess gross motor skill; some studies focused on one specific task (gait, running, hopping, jumping, throwing) [10,11,32–36] and others on a series of tasks (Dragon Challenge V2.0 [15], gait and tandem gait [11,11,32], TGMD-2 locomotor sub-test [12], seven skills from TGMD-3 [37]). Only 3 studies included object-control skills [15,35,37] while the others addressed mainly locomotor competences. Measurements of motor skill were achieved by employing a mixture of classic and novel biomechanical approaches, which will subsequently be discussed. One study reported information regarding time required data processing with sensors (a reduction of time for scoring TGMD-2 locomotor subtest from 2-to-15 minutes per participant [12]), highlighting the advantages of automatic versus standard assessment, while the others did not provide such information. Furthermore, only 1 study provided a free, open-source, database of collected data [11].

Classic assessment approaches

Most of the studies that included classic biomechanical measures, quantified actual and/or normalized time, kinematic, and variability parameters of the analysed task, respectively [11,33–36]. These parameters were assessed using algorithms in both time- and frequency domains. Temporal parameters included cycle duration, phase duration (e.g. stance) and task frequency/cadence, whilst kinematic parameters included peak-to-peak acceleration, maximum peak of acceleration, root mean square of the acceleration vector, velocity/angular velocity at some relevant task instant (e.g. take-off), and estimation of the forward trunk angle. Masci et al [34] also included the estimation of vertical stiffness during running using a spring-mass model [43]. Variability of many of the above-mentioned parameters were also assessed (e.g. using standard deviation), for instance, one study [33] assessed intra individual variability using Coefficient of Multiple Correlation. In [12] and [37], classic approaches of frequency and time domain analysis were used for scoring automatically the TGMD-2 locomotor subtest and seven motor skills of the TGMD-3, respectively. However, given these works sought to replicate standard test assessment, and not to provide novel biomechanical results, the type of analysis can primarily be considered classic (that is, based on standard biomechanical analysis).

Novel approaches

Novel approaches for the assessment of motor competence/development in TD included non-linear methods of human movement [10,11,32] (similarly to novel approaches presented in non-TD) and multi-dimensional analysis of similarity measures between participants [15]. In three studies [10,11,32], nonlinear methods were applied with the aim of characterizing motor control performance as a whole (e.g. harmonic ratio, short-term Lyapunov exponents, multiscale entropy, and recurrence quantification analysis). Multiscale entropy and recurrence quantification analysis were applied on trunk acceleration data during gait and tandem gait, and were found to be related with age maturation [11,32] and tandem walking competence [10]. These measures allowed highlighting the concurrent development of automaticity (in gait) and manifested motor complexity (in tandem gait) in TD school-children [11]. Barnes et al [15] proposed an innovative approach applied to wrist magnetometer data collected during a series of selected gross motor tasks (Dragon Challenge 2.0). They used dynamic time warping of the magnetometer time series data for pairs of children whilst pairwise comparison across the whole cohort produced a similarity matrix of all child-to-child correlations. By using multi-dimensional analysis of similarity measures between participants rather than direct parameterisation of the physiological data, patterns of physical motion were quantifiable, allowing objective and robust profiling of relative function across participant groups. The authors suggested that the accuracy and resolution shown can be improved by expanding the data set to include orthogonal axes, higher sampling rates, different measurement variables (e.g. acceleration signal in addition to magnetometer time series data) and multiple sensor positions (e.g. ankle in addition to wrist).

Classification strategy/statistics

To evaluate the performance of the proposed methodology, four main strategies were used: i) age effect analysis on the evaluated metrics or evaluation of differences among age groups [10,11,32]; ii) correlation with task developmental levels [10,33–36]; iii) replication of standard assessment [12,37]; iv) profiling of relative function across participant groups compared to standardize assessment [15]. Approaches i) and ii) were applied on single tasks or on a pair of tasks (gait and tandem gait); whilst approaches iii) and iv) were used to assess TGMD-2 locomotor subtest [12], seven motor skills of the TGMD-3 [37] and Dragon Challenge V2.0 [15], respectively.

General discussion

The number of sensors utilised in the mentioned studies ranged from 1 to 5. In 8 studies out of 10, a sensor was positioned on the lower trunk [10–12,32–36]; among these, 5 used this as the sole sensor for the analysis [10,32–34,36]. Sensors were affixed at the wrist in the studies that included object control tasks [15,35,37], and in those requiring the evaluation of arm movement [12,37]. The number of sensors influences ease of the setup and cost; clearly, the possibility of assessment via only one sensor would enhance widespread applicability. As previously discussed, regarding studies on non-TD children, among the quantitative proposed measures, novel approaches, in addition to yielding promising results, have the advantages of requiring only one sensor (on the trunk or on the wrist), thus minimizing time for technical setup, data entry and reduction. No general conclusion can be drawn on discriminant capacity and/or accuracy of the proposed methods, as some studies do not provide this information, and others [12,15,33–37] analyse different tasks, and compare the results with different reference assessment (e.g. standard analysis or developmental level) using different statistical descriptors.

3.3.3 Summary of gross motor control and technological benefits of wearable-based assessment

The overarching results of the studies in this section support the use of wearable sensors for the assessment of gross motor control and/or development in TD and non-TD children. In general, both classic and novel approaches for the assessment of motor performance highlighted differences in non-TD versus TD children, and age/competence related differences in TD population. Depending on the goal of the approach, proposed setup required different number of sensors, leading to different cost, time for technical setup and data analysis. In general, when aiming at replicating standard visual assessment, a higher number of sensors is required in order to allow implementing instrumented versions of classic motor competence tests (or measures that are directly correlated). On the other hand, novel approaches aiming at characterizing motor control performance as a whole, have the advantage of using a lower number of sensors (one or two). However, it is important to point out that these novel metrics are typically more complex to implement and to analyse, requiring a full understanding of the analytical technique for a proper use and providing results that are not directly associable to a standard visual assessment. All the retrieved studies were of exploratory design, and predominantly cross-sectional, including a limited sample size, from different countries. For time duration, only Barnes et al [15], Belluscio et al [29], and Bisi et al [12] reported time taken for analyses, amounting to 2.5 minutes, <2 minutes, and 2 minutes, respectively. However, there were no tangible reports for monetary cost reported

3.4 Gross motor skills – Laboratory assessment

A variety of instrumental devices were used for the experimental assessment of gross motor competence in laboratory conditions (Table 3a and 3b). Eleven-of-17 studies (65%) exploited stereophotogrammetry for the assessment of 3D segmental kinematics [44–54], of these, one [45] integrated a split-belt treadmill instrumented with force plates and Virtual Reality environment, 6 (35%) utilized at least two force plates [44,46,48,50,53,54] for the measurement of ground reaction forces, and one utilized an accelerometer [47] for trunk acceleration. One-of-15 studies [55] exploited only a force platform to measure ground reaction force, integrated with standard video recordings; three (18%) [56–58] used a basographic mat (Gaitrite®, CIR Systems, PA, USA) to assess spatio-temporal parameters, and two (12%) [59,60] used marker-less video-based kinematic analysis (Kinect®, Microsoft, USA). Eight out of 17 (47%) studies analysed neurologically- or motor-impaired children. The age range of participants was 2 to 15 years, with sample sizes varying from 15 to 407. All but two of the studies addressing non-TD children [46,57] included a control group in the analysis, whilst the remaining 9 studies (53%) analysed TD children [52,55,56,59,60] aged 2 to 15 years, with sample sizes varying from 7 to 360.

3.4.1 Non-typically developing children

Eight out of 17 studies (47%) analysed pathological conditions associated with alterations of gross motor performance: 4 (23%) in cerebral palsy [46,49,51,54]; 2 (12%) in DCD [48,57]; 1 (6%) in autism spectrum disorder [45]; and 1 (6%) in a general motor impaired population, including cerebral palsy, general orthopaedic and neurologic conditions, and neuropathic toe-walkers [44]. The age of the participants ranged from 6 to 17 years, with a sample size ranging from 14 to 26 subjects in all studies but Böhm at al. [46] and Baker et al. [44], who included 280 and 407 children with different motor alterations, respectively. Of the 8 studies, 6 [44,45,49,51,54,57] included a control group of aged-matched TD participants, testing the difference in the addressed parameters between the two groups. Only two studies did not include a control group, in such cases, Böhm at al. [46] sought to identify predictors associated with the ability to run in CP children; whilst Morrison et al. [57] sought to analyse gait spatio-temporal parameters in children with DCD. Gait was analysed in 5 studies [44,45,49,51,57], running in 3 [46,48,53], whilst only one study [45] included a motor competence scale (MABC-2) in the assessment.

Classic assessment approaches

All studies applied classic motion analysis approach to characterise the competence of the analysed children in either walking, running, or sit-to-stand, estimating, firstly, spatio-temporal parameters: cadence, stride-, step- swing-time, step-, and stride-length were estimated to characterize both gait [45,57] and running [46,48,53] performance; whole and percent phase duration for sit-to-stand [54]. Second, joint kinematics and kinetics: progression speed, joint angles and range of motion, ground reaction forces, and joint moments were exploited to characterize and evaluate motor performance [45,48,49,51,53,54]. Or third, comprehensive quantitative motor performance indexes: Gait Deviation Index, Gait Profile Score, and Gillette Gait index were analyzed by Baker et al. [44]; Gait Coordination Index by Chen et al. [49] and Gross Motor Function Coordination System by [54].

Novel approaches

No novel approach was presented for the characterization of gross motor competence of non-TD children in laboratory conditions.

Classification strategy/statistics

All studies included a control group and analysed the difference in selected variables between the non-TD and TD groups. Böhm at al. [46] assessed the correlation of the flying phase, as an indicator of running competence, with one leg balance, muscle weakness, and muscle spasticity. Morrison et al. [57] analysed the symmetry and repeatability characteristics of space-time parameters in DCD children as indicators of their reliability.

3.4.2 Typically developing children

Out of 9 studies, 3 focused on children older than 4 years of age [50,52,59], 2 focussed on children older than 7-years [47,56], whilst 1 focussed on children older than 9-years [60]. Younger children were analysed by Getchell et al. [55], with age ranging from 4-to-8 years, by Mapaisansin et al.[54], with age ranging from 4-to-12 years, and Guffey et al. [55], from 2-to-5 years; 2 studies [54,59] included also adults in the analysed sample, in addition to typically developing children: Mapaisansin et al. [54] 19 young adults aged 22,41±1,98 years; Bonnechere et al. [59] 40 adults aged 37±14 years, and 22 elderly aged 74±6 years. Sample sizes of typically developing children were variable, ranging from 7 [61] up to 360 subjects [56]. Different motor skills were assessed across the included studies; walking was analysed in 4 studies [47,52,56,58], including both forwards and backwards in [52], jumping and hopping in 3 studies [55,56,60], turning in one [50], balance in 1 [58], sit-to-stand in 1 [54],and, throwing, jogging and running in 1 [47]. Only 1 study [59] focused on a gamified assessment of gross and object control, i.e. participants aimed to clean virtual mud from a screen using hands, trunk and legs to control motion. The correlation of the quantitative measures was calculated with age/stage of development or with motor competence for the specific skill (i.e. hopping, paediatric balance, vertical jump) [55,58,60]. Measurements of motor skill were achieved by employing both classic and novel biomechanical approaches.

Classic assessment approaches

Most studies exploited classic quantitative motion analysis approaches to instrument the assessment of the selected motor task, quantifying space time parameters (i.e. step, stride, leap, hop length and time, sit-to-stand whole and relative phase duration) [54,56,58] and/or segmental kinematics [50,52,54] (i.e. joint angles and/or range of motion) and/or kinetics [50,54] (i.e. ground reaction forces, joint moments). All data processing was performed in the time domain, whilst only 1 study [58] exploited principal component analysis for data reduction of gait spatio-temporal parameters.

Novel approaches

Three studies [52,56,57] used quantification approaches that can be considered novel with respect to classic laboratory motion analysis. Two studies [59,60] adopted a novel instrumentation, exploiting a Kinect® platform for marker-less tracking of segmental kinematics. In particular, Bonnechere et al. [59] used the marker-less tracking (i.e. Kinect®) to assess a physical therapy exercise (i.e. clean a screen from the virtual mud) designed to train a variety of motor schemes (i.e. joint control, stretching, balance and postural control); they evaluated the performance (i.e. process) as related to the time required to clean the screen from the virtual mud (i.e. product). Sgrò et al. [60] exploited the same marker-less platform to instrument vertical jump, verifying the possibility to classify correctly jump motor competence in the analysed subjects. Getchell et al. [55] exploited a force platform, a classic instrumentation in quantitative motion analysis, with a novel approach, proposing body stiffness estimated during hopping as a quantification of hopping motor competence.

Classification strategy/statistics

Only three studies compared the performance of the proposed quantitative assessment to that of an existing motor competence scale (i.e. hopping developmental level assessed by an expert trainer [55], paediatric balance scale [58], process evaluation of vertical jump based on Western Australia Teacher Resources [60]). The remaining studies related the quantified variables to age/developmental stage to serve as a quantitative descriptor of motor competence in the addressed TD population.

General discussion

Studies exploiting laboratory quantitative motion analysis methods for the quantification of motor competence in non-TD and TD children exploited a variety of instrumental devices, aiming to characterize the level of motor competence in specific populations of non-TD and TD children. Most of the studies (all seven for non-TD [46,49,51,54] and five [54,56,58] out of eight for TD children) exploited a traditional motion analysis approach, aiming to relate traditional quantitative descriptors of motion to age and/or motor competence, or to identify alterations with respect to a control group. The proposal of novel approaches using laboratory instrumentation was limited, whilst none of the identified studies aiming to quantify motor competence in laboratory conditions, addressed the characterization of gross motor competence as a whole, but rather addressed the quantitative characterization of one specific motor skill. Nevertheless, the instrumental quantification always demonstrated its effectiveness in differentiating the level of motor competence in the target population. No study reported specific information regarding time required for data-acquisition, -entry and -elaboration, and no study made raw data and/or algorithms available as open-source.

3.4.3 Summary of gross motor control and technological benefits

Based on the included literature, the use of laboratory measurement instrumentation for the quantification of gross motor competence demonstrated its effectiveness, although limited to specific motor skills. The quantitative methods permitted the characterization and/or differentiation of TD and non-TD populations, and to rank different stages of competence in TD children, although to reiterate, this was limited to specific motor skills. Evidently, more comprehensive characterization approaches are still missing. All the retrieved studies were preliminary and explorative, either cross-sectional or case-control, over relatively limited sample of subjects, from different countries. Although providing promising results using technological solutions for the assessment of specific motor skills, no study provided a systematic characterization of the technology-based approach over a significant sample of subjects, thus not allowing generalization. Moreover, there were no tangible reports for time or monetary cost reported.

4 Conclusions and recommendations

The current literature base highlights that several quantitative technology-based methods for the assessment of children’s fine and gross motor skills. Promising preliminary results suggest the efficacy and advantages of emerging technologies for the reliable assessment of fine and gross motor skills have been confirmed, both for TD and non-TD children, in and outside the laboratory; however, the preliminary nature of these studies fails to provide conclusive information regarding the reliability of these technology-based approaches, as well as failing to provide clear indications regarding the related expected operator independency, costs and time expenditure reduction. These limitations do not allow to provide clear suggestions to practitioners for in-field application. Further advanced methodological studies addressing the characterization of accuracy, repeatability, operator independency, costs, and time consumption, as well as meta-analyses are necessary for defining which tailored effective solution for assessing motor skills should be preferred, in which situation, and for what purpose. Notwithstanding, however, the available evidence is not requisite for meta-analytical assessment, at this point.

Considering this, the authors’ strongly advocate that researchers and practitioners continue expanding this field of research, and delineate such evidence in a transparent manner. Thus, we highlight the following key issues, essential for achieving a widespread, efficient, ecological, and reliable use of technology-based motor competence assessment:

i) Technology choice should depend on the final goal of the end-user. In order to maximise translation and usability, research should seek to employ the minimal number of sensors, cameras, and/or tools, that achieves optimal and clinically-useful results.

ii) Authors are encouraged to provide information regarding the time required for data-acquisition, -entry and –processing, in order to allow possible users to compare different approaches in terms of (in-field) applicability.

iii) Performance, reliability and constraints of the proposed methods should always remain a strong focus. Future research should aim at evaluating them also in response to interventions, to elucidate whether such novel outputs can be positively (or negatively) impacted, and likewise, to detect change and normative values over time, through the course of motor development.

iv) Data sharing and open source code/software is encouraged to support research and collaboration activities in this emerging field, promoting its in-field application. Moreover, such practices would enhance essential inter-disciplinary collaborations (e.g. between sport and exercise scientists, computer scientists and engineers).

5. Ethics declarations

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5.2 Conflict of interest

All authors declare that they have no conflicts of interests in relation to this review.

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Table 1a. Data extraction results. Fine motor skills, non-typically developing children.

REF	ANALYSED POPULATION										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Butler EE, Ladd AL, Louie SA, Lamont LE, Wong W, Rose J [17]	CP	TD	25 TD children and adolescents (11M-14 F, ages 5–18 years, mean age 11.0 4.1 years). 2CP (moderate, left-sided spastic hemiplegic CP, 2 F, ages 14 and 15 years)	Case-control; USA	Reach and Grasp Cycle.	//	8 camera optoelectronic motion analysis system (Motion Analysis Corporation), Fs=60Hz.	lab	joint kinematics for eight primary motions of the trunk and dominant arm (trunk flexion–extension, trunk axial rotation, shoulder elevation, shoulder internal–external rotation, elbow flexion–extension, forearm pronation–supination, wrist flexion–extension, and wrist ulnar–radial deviation) represented as function of task cycle (1-100%). 12Hz low pass filtering.	markers kinematics.Nine segments model (ISB recommendations): trunk, right-left shoulder girdle, right-left upper arm, right-left forearm, right-left had.	The children with CP demonstrated reduced elbow extension, increased wrist flexion and trunk motion, with an increased tendency to actively externally rotate the shoulder and supinate the forearm during T1 compared to the TD children.
Casellato C, Zorzi G, Pedrocchi A, Ferrigno G, Nardocci N [24]	genetic dystonia	TD	15 children with genetic dystionia syndromes (11M-4F, age range 8-18 y, mean 14y, + specific description of diagnosisi, medications, DBS etc) and 9 age-matched TD children	Exploratory; Italy	reaching (15 trials) / writing (4 trials of "8s"). Self-paced	Burke-Fahn-Marsden Dystonia Rating scale (severity, upper limb severity and disability)	motion capture system (20Hz) and EMG (1000 Hz) integrated and syncronized.	lab	Kinematics: (1) reaching: finger path curvature, finger velocity and its peak, symmetry between acceleration and deceleration phases, precision. (2) writing: smoothness of trajectory. EMG data: (1) reaching: RMS of activation, muscular activity focalization, tonic activation during rest; (2) writing: RMS of activation.kinematic: time domain. EMG. Low pass filtering at 5Hz, algorithms in time domain for parameter identification.	marker kinematics: positioned on upper limb segments (upper arm, lower arm, forearm, forefinger/pen). Bipolar EMG from 6 muscles: anterior deltoid, posterior deltoid, brachial biceps, brachial triceps, wrist-fingers flexor, wrist-fingers extension.	During reaching, the distinguishing factors of dystonic movement were reduced velocity, loss of muscular activation focalization, and impairment of rest-movement modulation. Muscular parameters were able to linearly discriminate the different levels of severity.

Chang SH, Yu NY [23]	handwriting difficulties and DCD (HWD-DCD); handwriting difficulties and no DCD (HWD-nDCD)	TD	33 HWD-DCD (18M 15F, 7y5mo±8mo); 39 HWD-nDCD (22M-17F, 6y11mo±6mo); 22 nonHDW (12M-10F, 6y10mo±8mo)		writing. 1) 'automated handwriting ': Write Chinese Characters 40 times. 2) control of handwriting movement: Write 2 simple characters followed by 3 complex characters.	MABC, VMI, parent report questionnaire (DCDQ), teacher-rating questionnaire (Chinese Handwriting Evaluation Questionnaire)	digitizing tablet + wireless pen with a force-sensitive tip (1024 levels). FS=200Hz, spatial accuracy 0.015cm. Pen size and weight similar to a typical pen ued by the children.	portable	1) Counting of number of peaks for stroke movement. 2) mean stroke velocity and axial pen force of each stroke. + number of changes in velocity direction (level of automation); Time constant (characterization of the automation process); Mean stroke velocity; Mean axial pen force. time domain. Non-parametric kernel estimate (cut-off F=15Hz).	position of the pen tip; axial pen force.	The attainment of automated handwriting was markedly slower in children with handwriting deficits and DCD, who used a faster stroke velocity to write simple characters (1.22 times those without handwriting deficits), but when writing complex characters, their stroke velocity and pen force were lower (0.85 and 0.89 times those without handwriting deficits, respectively)
Chau T, Ji J, Tam C, Schwellnus H [18]	CP with documented fine motor difficulties	TD	6 TD (4M-2F, all right handed, age 6.7±0.6y), 6 CP (4M-2F, 5 left-handed, age 8.3±1.6y)	Exploratory ; Canada	Writing: copying two lines of text on the tablet with the instrumented writing utensil, using their dominant unaffected hand.	for the CP children: Beery-Buktenica Developmental test of VMI, Quest Dissociated Movement subtest, Quest Grasp subtest.	pressure-sensitive liquid crystal display (LCD) writing surface, a desktop computer and an instrumented writing utensil + (optional) height-adjustable table whithin which the writing surface may be embedded. FS=94Hz.	partially portable	Total grip force and normal force profiles, Average grip force distribution. Other quantitative measures: Grip height, Maximum grip force, In air time, Contact time, Movement time, Stroke duration, Stroke length, N° of strokes, Disfluency, Average x-/y-/ tangential velocity, average coherence, Median Normal force, Peak normal force. time and spatial domain.	kinematics and kinetics. Barrel pressure distribution, Normal force, horizontal and vertical tip position,	The instrumentation revealed nontrivial correlations between normal and grip forces (0.55 +/- 0.16), a temporal delay between normal and grip forces (97.7 +/- 16 ms), and a consistent grip-to-normal force ratio (4.3 +/- 1.5), across all participants. Grip force distributions agreed intuitively with qualitative observations of individual grasps of the writing utensil. Further, 5 new parameters derived from grip force measures statistically differentiated between able-bodied children and those with hemiplegic CP.

Coluccini M, Maini ES, Martelloni C, Sgandurra G, Cioni G [21]	motor disabilities	TD and healthy adults	10 children with motor disabilities: 5 spastic hemiplegia (HCP) (median age 11.0 years), 5 with dyskinetic movement disorders (MD) (median age 11.6 years). Control group: 5 healthy children (HC) (median age 11.0 years), 5 healthy adults (HA) (median age 22.0 years)	Exploratory ; Italy	Picking bloks from an initial position, transporting them toward the target position and dropping them into the box (at self-selected and at dominant speed; with dominant/unaffected and with non dominant/affected limb)	scores of the dominant and non-dominant limb (BFMDRS UL) as well as the total score (BFMDRS)	an optoelectronic motion analysis system(BTS) equipped with eight infrared cameras operating at 100 fps	lab	Total task duration; Duration of the transport phase; Duration of the reaching phase; Duration of the grasping phase; Duration of the releasing phase. angular range of motion was estimated as maximum angular deviation both during the reaching and the transport phase. SVDPA was applied to the linear acceleration of the end-effect (marker on the wrist). coefficient of periodicity of acceleration. time and spatial domain. Statistical approach.	marker kinematics.	kinematic analysis may add valuable information to understand the developmental process in healthy children and to differentiate distinct levels of impairment in children with neurological disorders.
Formica D, Petrarca M, Rossi S, Zollo L, Guglielmelli E, Cappa P [19]	hemiplegia	//	8 children (mean age 9.6 ± 2.7 (SD) years; age range from 6 to 14 years);	Exploratory ; Italy	pointing/saggital plane movement	//	optoelectronic system equipped with six cameras set at a sampling rate of 120 images per second (Vicon 512, Oxford Metrics, UK).	lab	speed, velocity, torque. in-built kinematic software	arm kinematics	the presence of a different control strategy for fast movements in particular during lowering phase. Results suggest that motor control is not able to optimize Jerk and Torque-change cost functions in the same way when controls the two arms, suggesting that children with hemiplegia do not actively control MA lowering fast movements, in order to take advantage of the passive inertial body properties, rather than to attempt its optimal control.

Kuhtz-Buschbeck JP, Stolze H, Gölge M, Ritz A [20]	traumatic brain injury	TD	20 with traumatic brain injury -9.5 +- 2.5, 20 TD children - 9.6+- 2.6	Case-control; Germany	13m walking gait, grasping	neurologist assessment	K-ABC test, visual clinical assesment, unspecified kinematics	portable	K-ABC score, cadence, velocity, stride characteristics. time domain	Quantitative measures included 10 spatiotemporal gait parameters and 6 variables describing reaching and grasping. Qualitative scores of gait and upperlimb movements were also obtained.	Gait velocity and step and stride lengths were significantly smaller in children after TBI than in control subjects (Mann-Whitney U test, P<.05). Reach-to-grasp movements of the TBI children were characterized by a significantly longer reaction time (Mann-Whitney U test, P<.05) and movement duration, reduced velocity, and coordination deficits
Smits-Engelsman BC, Wilson PH, Westenberg Y, Duysens J [22]	DCD+LD	TD	32 children, 16M 16F, mean 11.3y range 9-12y, 25% left handed (reference value for dutch primary school population 15%)	Exploratory; The Netherlands	draw straight line segments between two targes 2.5 cm apart (3 different target sizes 0.22, 0.44, 0.88 cm) in discrete and cyclic aiming	MABC	electronic pen (wacom ud 12-18 206Hz+oasis sw) leaving no trace on the writing table	portable	DCD/LD and controls displayd conventional trade off between target size and average movement time; but DCD-LD movement errors were minimal on discrete task and significantly more in the cyclic. DCD/LD rely more on feedback during movement execution and have difficulty switching to a FFD or openloop strategy. data filtered at 10.3hz, time and trajectory parameters (errors)	straight-line segment drawing accuracy	Overall, the two groups did not differ in response time, nor did they respond differently according to Fitts' Law. Both groups displayed a conventional trade-off between Target Size and average Movement Time. However, while movement errors for children with DCD/LD were minimal on the discrete task, they made significantly more errors on the cyclic task.

Table 1b. Data extraction results. Fine motor skills, typically developing children.

REF	ANALYSED POPULATION										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Blank R, Breitenbach A, Nitschke M, Heizer W, Letzgus S, Hermsdörfer J [28]	TD	adults	134 TD children: 23 three-, 44 four-, 39 five- and 28 six-yearold (69 girls: mean age 60 months, SD 12 months; 65 boys: mean age 61 months, SD 12 months; total range: 37–83 months); 16 adults (mean age 29 years, SD 11 months, 9 females, 7 males)	Cross-sectional; Germany	repetitive vertical arm movements at different frequencies with a hand-held object (dominant hand). (Moving a lightweight object up and down at increasing rates from 0.5 Hz up to individual maximal arm movement rates (>2.5 Hz))	//	The object contained a force sensor and three accelerometers in the x-, y- and z-directions (range ±70 m/s2). The force sensor only measured grip forces perpendicular to the grip surfaces and was mounted near the object's centre of gravity, as were the acceleration sensors. After amplification (DC) and AD conversion (500 Hz, 12-bit resolution), the signals were analysed on an IBM-compatible PC.	portable	1) smoothness of arm movements within each movement frequency category (signal-to-noise ratio), 2) Temporal parameters (phase lag between grip and load force, fine temporal coordination), 3) Combined (temporal and force) parameter: fine coordination. grip force modulation and force economy. frequency and time domain algorithms	Grip forces (by a uni-axial force transducer) and inertial forces (tangential forces, calculated from the measurements by accelerometers within the object).	during cyclic movements with hand-held loads, temporal control is well established at the age of 4 years whereas the fine gain control needs a longer time to develop.
Duval T, Rémi C, Plamondon R, Vaillant J, O'Reilly C [26]	TD	//	seven 3-4year old children, seven 4-5 year old children, nine 5-6 year old children	Exploratory; Guadeloupe	graphomotor	//	digitiizng tablet	portable	length, duration, speed. sigma-lognormal, and classical modelling	spatio-temporal features	The ability to perform graphomotor activities depends on kindergarten grades. More importantly, this study shows which performance criteria, from sophisticated neuromotor modeling as well as more classical kinematic parameters, can differentiate children of different school grades

Lin Q, Luo J, Wu Z, Shen F, Sun Z [27]	TD	//	40 TD: 8 in grade 1 (6 years old), 8 in grade 2 (7–8 years old, mean age 7.6 years, SD 0.5 years), 8 in grade 3 (9 years old), 8 in grade 4 (9–11 years old, mean age 10.1 years, SD 0.8 years), 8 in grade 5 (11–12 years old, mean age 11.6 years, SD 0.5 years).	Cross-sectional; China	drawing	//	force-tablet connected to computer	portable	cumulative trace length, vector length of straight line and vertical diameter of circle were determined. Drawing duration, mean drawing velocity, and number of peaks in stroke velocity profile (NPV) were derived. normalized force angle regulation (NFR) and variation of fine motor control (VFC). time domain	spatial parameters, kinematic parameters.	The maturation and automation of fine motor ability were reflected by increased drawing velocity, reduced drawing duration, NPV and NFR, with decreased VFC in circles drawing task. Grade and task main effects as well as significant correlations between age and parameters suggest that factors such as schooling, age and task should be considered in the assessment of fine motor skills.
Mason AH, Bruyn JL, Lazarus JA [8]	TD	//	right hand preference in writing, divided in 2 groups: young (n=16-1discarded as outlier; 10F 6M; age 4-6 mean 4.5) older (n=15, 8f 7m, age 7-10 mean 8.7)	Cross-sectional; USA	reach to grasp movement unimanual and bimanual cilindrical objects of same and different sizes	Proposes the anaysis of bi-manual prehension as a behavioural paradigm to study motor development	Motion capture system (Visualeyezer, Phoenix Technologies Incorporated, Burnaby, British Columbia, 200Hz), light emitting diodes in both hands: distal portion of the thumbnail, distal porion of the index finger, styloid procss of the wrist	Lab	younger children have a mode sequential patten, duration of the task decrases with maturation. 7Hz LP filter, time domain to analyse duration, aperture (ditance between markers) velocities, interlimb timing, comparison of differences between the two groups in different conditions (1-2 hands, small-large cilinder)	trajectories of the active markers	While average kinematic results indicated that children in the 4-6 and 7-10 age range performed bimanual movements similarly to each other, spatio-temporal coupling measures indicated that the younger children performed the bimanual movements in a more sequential (serial) fashion. Kinematic results also indicated that the cost of the increase in task complexity normally seen in adults when grasping two targets bimanually compared to a single target unimanually are not consistently present for children. Instead, the cost associated with increases in task complexity appear to be mediated by whether the bimanual task imposes significantly greater demands on attentional processes.

Ren T, Li F, Luo JF, Wu Z [7]	TD	//	5 groups divided er grade: 9m 12f 7.4+-0.4y; 11m 9f 8.4+-0.4y; 9m 11f 9.5+-0.3y; 9m 10f 10.7+-0.3y; 9m 8f 11.8+-0.5y		hand writing: letters a, carattere cinese, firma	//	Wacom tablet 133Hz 0.01mm	portable	Dynamic time warping	trajectory of pen tip	Data analysis revealed a more consistent writing ability for higher grade children not only in the writing products but also in the velocity profile of the pen movements. Significant correlations between grade and parameters suggest that measures extracted by DTW are effective in examining typical development of handwriting in children
Rosenblum S, Parush S, Weiss PL [6]	non-proficient writers	proficient hand-writers	50 proficient and 50 non-proficient writers	Cross-sectional; Israel	The tasks analyzed included copying seven different single letters from the computer screen, copying four different words, writing two 22-character long sentences (one familiar and one unknown), and copying a 100-character–long paragraph.	Teachers' Questionnaire for Handwriting Proficiency (Rosenblum, Jessel, Adi-Japha, Parush, & Weiss, 1997) completed by their classroom teachers.	A4 size lined paper affixed to the surface of a WACOM (407 X 417 X 36.3 mm) x–y digitizing tablet using a wireless electronic pen with pressure sensitive tip (model UP 401).	portable	Time domain	total time, "on paper" time, "in air" time, mean writing speed.	Non-proficient handwriters required significantly more time to perform handwriting tasks [$F(4,91) = 14.83$, $p < .0001$]; their "in air" time, was especially longer as compared to the proficient handwriters [$F(4,91) = 13.63$, $p < .0001$]. Their handwriting speed was slower [$F(4,91) = 5.99$, $p < .0002$], and they wrote fewer characters per minute ($F(4,91) = 14.63$, $p < .0001$).

Rudisch J, Butler J, Izadi H, Birtles D, Green D [9]	TD	//	14M 14F, rang 5-16y, 8.3+-2.3y, 78% right handed, 3 age groups: 5-6 (7m 8f), 7-9(3m 10f), 10-16(4m 5f)	Cross-sectional; UK	bimanual box opening task (divided in unimanual tasks)	//	1 sensor per hand electromagnetic system(Polemus, 120hz)	partially portable	differences in spatiotemporal parameters associated to maturation and neurological development. filtering 15hz, spatiotemporal parametrs	hand position and orientation	Results show qualitative changes in spatiotemporal sequencing between the young and older children which typically marks a phase of distinct reduction of growth and myelination of the Corpus Callosum (CC). Results show qualitative changes in spatiotemporal sequencing between the young and older children, which coincides with distinct changes in the growth rate and myelination of the CC.
Rueckriegel SM, Blankenburg F, Burghardt R, Ehrlich S, Henze G, Mergl R, Hernáiz Driever P [5]	TD	//	187 TD children and adolescents between the ages of 6–18 years	Cross-sectional; Germany	several writing and drawing (circles, sentences, letters 'a' lower case)	Edinburgh Handedness Inventory and several questions about gross and fine motor practice.	pen equipped with a sensor + Task sheets fixed under the transparent overlay of a digitizing graphic tablet (WACOM IV). (sampling rate of 200 Hz and a spatial resolution of 0.05 mm)	portable	(a) Speed: Frequency (F) of strokes and arithmetic mean of stroke peak velocity (SPV). (b) Automation: Number of changes of y-axis velocity (NCV) from acceleration to deceleration and vice versa, i.e. number of y-axis velocity maxima and minima, per stroke.(c) Variability: Variation coefficient of stroke peak velocity (VARPV) and stroke duration (VARD). (d) Writing and drawing pressure (P).	Position and pressure of the pen	progression of kinematic parameters for each movement domain of the handwriting and circle drawing tasks correlated significantly with age (Pearson's correlation, $p<0.003$). Speed, automation and pressure increased with age, whereas variability decreased. Nonlinear regressions revealed maturation of hand movements at a certain age. Age of completed maturation depended on the task complexity (drawing circles vs. handwriting) and kinematic parameters. In the speed and automation domains, handwriting movements finish maturing later than circle drawing. Male subjects drew circles at significantly higher speeds than female subjects. Fine motor practice and laterality of handedness did not influence kinematic parameters. A repeated measure ANOVA confirmed the significant interdependency between age and complexity level for speed and automation ($p<0.001$).

Waterman AH, Giles OT, Havelka J, Ali S, Culmer PR, Wilkie RM, Mon-Williams M [25]	British and Kuwaiti adults and primary school children	//	48 British adults (21m 27f, 18-23y 20.4+-1.2y; 4 lefthanded); 50 British children (27. 23f, 5.3-6.2y 5.7+-0.3y; 8 left handed); 21 Kuwaiti adults (8m 13f, 21-45y 29+-6.1y; 3 lefthanded); 90 Kuwaiti children (45m 45f, 5.6-6-8y 6.0+-0.3y, 7 lefthanded)	Cross-sectional; UK/Kuwait	8 trials, each trial requiring the participant to trace a shape apeered on the screen using the stylus provided; direction givn by indication of starting and ending point	//	taglet PC (Toshiba Portege M700-13P, screen 260x163mm, 1.280x800 pixel, 32 bit colour, 60Hz refresh rate) in landscape position in front of the subject	portable	tracing error lower in adults than children; authors state that for adults tracing errors were significantly larger in their non preferrec direction , but difference very small. For children the difference is more subtle. only referred specialised sw to compare drawn line and reference path; resuts analysed usign a Bayesian Estimation technique to relate each error score to age, nationality and tracing direction.	spatial parameters	The Kuwaitis were better when moving their arm leftward while the British showed the opposite bias. Bayesian analysis techniques showed that while children were worse than adults, they also showed asymmetries-with the asymmetry magnitude related to accuracy levels.

Table 2a. Data extraction results. Gross motor skills – Wearable based assessment, non-typically developing children.

REF	ANALYSED POPULATION										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Belluscio, V.; Bergamini, E.; Salatino, G.; Marro, T.; Gentili, P.; Iosa, M.; Morelli, D.; Vannozzi, G. [29]	Children with Down (DS) and Prader-Willi syndromes (PWS)	TD (Control Group, CG)	38 (15DS, 11PWS, 12CGG). 15 DS (9F-6M; BMI range: 15.2–24.0 kg/m2, age range: 2.8–11.7 years); 11 PWS (4F.7M; BMI range: 12.9–32.4 kg/m2, age range: 2.7–10.1 years); 12 CG (6F-6M; BMI range: 11.3–23.6 kg/m2, age range: 3.7–11.0 years)	Case-control, exploratory; Italy	Gait (10m, 3 repetitions, self-selected speed, target at eye level at the end of the walkway).	GMFM-88 total score + GMFM-88 dimension E (locomotion). (+GMFCS and QI)	4 IMUs (Opals, APDM Inc., USA) located at pelvis, sternum, both distal tibiae levels with Velcro straps. Fs=128 Hz.	portable	20Hz low pass filtering. Algorithms implemented in both frequency and time domain. Data output: average walking speed, average stride length, and stride frequency (normalized according to Hof [Ref]), normalized Root Mean Square of acc, Attenuation Coefficient between Pelvis and Sternum and Improved Harmonic Ratio for each acceleration component.	Lower limb ML angular velocity for spatiotemporal parameters. Upper body 3D acceleration (sternum and pelvis) for stability parameters	Children with DS and PWS exhibit reduced gait symmetry and higher accelerations at pelvis level than CG. While these accelerations are attenuated by about 40% at sternum level in CG and DS, PWS children display significant smaller attenuations, thus reporting reduced gait stability. Significant correlations were found between the estimated parameters and the GMFM-88 scale when considering the whole PWS and DS group and the PWS group alone.
Ricci M, Terribili M, Giannini F, Errico V, Pallotti A, Galasso C, Tomasello L, Sias S, Saggio G [31]	ADHD/ DCD	TD	37 (17DCD/ADHD, 20TD). 17 DCD/ADHD (5F-12M, 8.5+-1.25y, classified according to DSM-V), 20 TD (5F-15M, 9+-0.95y)	Case-control, exploratory; Italy	List of tasks: right and left leg stance, rhytmic and beat on legs, rhytmic hands pronosupination, jumping jacks, split jumping, walk on heels, frog jump, rhytmic	DCDQ	12 IMUs (Movit G1, Captiks Srl, Italy) on frontal upper and lower trunk, upper and lower arms, upper and lower legs and feet. Fs= 200Hz, quaternions from Kalman, network data transmission rate 50 Hz.	portable	Time domain analysis and Kalman filtering to estimate sensor orientation. Data output: several parameters for the evaluation of global coordination, maintainence of balance, recovery of balance, hands and feet coordination, depending on the analyzed task (number of correct repetitions, sway area, AP/ML flexion, Duration, Jerk, Jumping time, mean velocity, RMS, rotation, Stance-, Stride-, Swing-, Tapping-time).	3D acceleration and angular velocities of each sensor.	Some measured motor parameters in some specific tasks showed significant differences ADHD/DCD patients from the healthy subjects.

					toe beat on floor, rhytmic toe tapping heels.						
Speedtsberg MB, Christensen SB, Stenum J, Kallemose T, Bencke J, Curtis DJ, Jensen BR [30]	DCD	TD	18 (8DCD, 10TD). 8 DCD (6F -2M, 8.8 ± 1.5y, 139.5 ± 8.1cm, 33.6 ± 7.3 kg); 10 TD (7F-3M, 9.1 ± 1.4y,141.1 ± 3.0cm, 33.7 ± 1.8 kg).	Case-control, exploratory; Denmark	Walking on a treadmill for 4 minutes.	MABC-2	1 accelerometer (MQ16, MarqMedical, Denmark) on sternum + treadmill. Fs=256 Hz	lab (treadmill)	Time domain analysis. Data output: short term local dynamic stability, root mean square and relative root mean square of the three trunk acceleration components (VT, ML and AP direction). Root mean square and relative root mean square as a measure of variability.	3D trunk acceleration components.	Children with DCD have general reduced local dynamic stability and that the short term Lyapunov exponent has good power of discrimination between DCD and TD.

Table 2b. Data extraction results. Gross motor skills – Wearable based assessment, typically developing children.

REF	ANALYSED POPULATION										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Barnes, Claire M.; Clark, Cain C. T.; Rees, Paul; Stratton, Gareth; Summers, Huw D. [15]	TD	na	55 TD children. (33 F-22 M, 11 ± 0.5 y, 1.45 ± 0.06 m, 40.4 ± 9.4 kg, BMI 19 ± 3.5 kg · m2)	cross-sectional, validation; UK	Dragon Challenge V1.0 (stability, locomotor and object control components of FMS): balance bench; Core agility; Wobble Spot; Overarm Throw; Basketball Dribble; Catch; Jumping Patterns; T-Agility; Sprint	stadard Dragon Challenge assesment	2 custom built MEMS including a triaxial accelerometer and a magnetometer. Mounted on wrist (posterior wrist joint) and right ankle (lateral mallowlar prominence of fibula) with velcro straps. Fs=40Hz. In this study, focus ONLY on wrist mounted MEMS.	portable	Dynamic time warping of the magnetometer time series data for pairs of children. Pairwise comparison across the whole cohort produced a similarity matrix of all child to child correlations. Data output: 'performance sphere' in with children sit on concentric shells of increasing radius as performance deteriorates.	Wrist-worn magnetometer trace for the radial direction (from elbow to wrist)	Sensor score showed good agreement with standard scoring. Multi-dimensional analysis of similarity measures between participants can quantify complex and varied patterns of physical motion, allowing objective and robust profiling of relative function across participant groups.
Bisi MC, Pacini Panebianco G, Polman R, Stagni R. [12]	TD	na	45 TD children. 3 age groups. 6year old children (4F-11M, 6 ± 0y, 1.20 ± 0.03m, 23 ± 3 kg), 8 year old children(7F-8M, 8 ± 0y, 1.31 ± 0.07cm, 29 ± 6kg), 10	Corss-sectional, Validation; Italy	TGMD-2 locomotor subtest (run, gallop, hop, leap, horizontal jump, slide).	TGMD-2 standard assessment	5 IMUs (Opals, APDM Inc., USA) positioned on wrists, ankles and lower trunk. Fs=128Hz. Video reconding (frontal and sagittal plane, GoProHero 4, GoPro Inc. USA, and Canon Legria FS20, Canon Europe).	portable	Algorithms implemented in both frequency and time domain to replicate TGMD-2 criteria. Data output: automatic TGMD-2 locomotor subtest scoring.	3D accelerations, 3D angular velocities, magnetic field orientation of forearms, legs and lower trunk.	The automatic scoring based on sensors showed excellent agreement with standard scoring, with a reduction of time for scoring from 15 to 2 min per participant. Results support the use of IMUs for MC assessment,supporting objectively evaluator decisions and reducing time requirement for the evaluation of large groups.

			year old children (6F, 9M, 10 ± 0y, 1.43 ± 0.08m, 38 ± 6kg).								
Bisi MC, Stagni R [32]	TD	young adults (reference)	105 participants (among which 75 children). 6year old children (7F-8M, 6 ± 0y, 1.20 ± 0.04m, 22 ± 3 kg), 7 year old children(7F-8M, 7 ± 0y, 1.28 ± 0.05m, 30 ± 5kg), 8 year old children (8F-7M, 8 ± 0y, 1.31 ± 0.07m, 29 ± 6kg), 9 year old children(8F-7M, 9 ± 0y, 1.38 ± 0.06cm, 34 ± 6kg), 10 year old children (7F-8M, 10 ± 0y, 1.43 ± 0.08m, 38 ± 6kg), 15 year old adolescents (7F-8M, 15 ± 0y, 1.70 ± 0.07m, 62 ± 11kg), 25 year old adults (7F-8M, 25 ± 1y,	Cross-sectional, exploratory; Italy	Natural walking, NW, and tandem walking, TW (self-selected speed, back and forth on a 10m long tapeline).	heathly adults complexity as reference	2 IMUs (Opals, APDM Inc., USA) positioned on lower trunk and on the right leg. Fs=128Hz.	portable	Algorithms for nonlinear analysis: Multiscale entropy (MSE). Data output: motor complexity during gait, tandem gait and ratio between the complexity manifested during the two tasks.	Trunk 3D acceleration components, ML angular velocity of the lower leg.	MSE increased significantly with age in TW and decreased in NW on the sagittal plane. Assuming the development of complexity in TW as reference, MSE in NW showed a reduction to half of the complexity of TW with maturation on the sagittal plane. Results indicate MSE as sensitive to differences in performance due to maturation and to expected changes in complexity related to the specific performed task.

			1.72 ± 0.09m, 65 ± 11kg).								
Bisi, M.C., Tamburini, P., Panebianco, G.P., Stagni, R. [10]	TD	na	80 TD children. 6year old children (8F-8M, 1.19 ± 0.04m, 23 ± 2 kg), 7 year old children(8F-8M, 7 ± 0y, 1.27 ± 0.05m, 29 ± 5kg), 8 year old children(8F-8M, 1.29 ± 0.07m, 29 ± 5kg), 9 year old children(8F-8M, 1.38 ± 0.06m, 34 ± 6kg), 10 year old children (8F-8M, 1.40 ± 0.05cm, 37 ± 5kg)	Cross-sectional, exploratory; Italy	Natural walking, NW, and tandem walking, TW (self-selected speed, back and forth on a 15m long tapeline).	Standard assessment of tandem walking performance (number of correct consecutive steps)	1 IMU (Opals, APDM Inc., USA) positioned on lower trunk (L5 level). Fs=128Hz.	portable	Algorithms for nonlinear analysis: Multiscale entropy (MSE) and Recurrence quantification analysis (RQA). Data output: postural and movement complexity of gait (recurrence quantification analysis and multiscale entropy) during natural walking and tandem gait.	Trunk 3D acceleration components.	RQA and MSE allowed highlighting age-related changes in both postural control of the trunk and motor complexity, while classic standard assessment of TW resulted uniformly distributed in the different age groups. Results suggest this quantitative approach as relevant when assessing the motor development in schoolchildren and complementary to standard clinical tests.

Bisi, M.C., Tamburini, P., Stagni, R. [11]	TD	young adults (reference)	112 participants (among which 80 children). Schoolchildren presented in Bisi, Tamburini, Panebianco Stagni. 15 year old adolescents (8F-8M, 15 ± 0y, 1.68 ± 0.09m, 60 ± 13kg), 25 year old adults (8F-8M, 25 ± 1y, 1.71 ± 0.09m, 64 ± 11kg).	Cross-sectional, exploratory; Italy	Natural walking, NW, and tandem walking, TW (self-selected speed, back and forth on a 15m long tapeline).	healthy adults performance as reference	3 IMUs (Opals, APDM, USA) positioned on lower trunk and on the shanks (above lateral malleolus). Fs=128Hz.	portable	Algorithms in time and frequency domain, both for linear and nonlinear analysis. Data output: Age-reference data for natural walking and tandem walking of gait temporal parameters (double support-, stance-, stride-time), their variability (standard deviation of temporal parameters), nonlinear measures (pattern regularity through recurrence quantification analysis, motor complexity through multiscale entropy). Database of IMU raw data avaiable as supplementary files.	Trunk 3D acceleration components, ML angular velocity of the lower legs.	Age effect was shown on temporal parameters, their variability, multiscale entropy and recurrence quantification analysis. These parameters were selected for monitoring locomotor development and presented on an ad-hoc designed polar plot showing age-group reference bands.Graphic results outline locomotor differences with maturation at first glance. The patterns in NW and TW allow to characterize specific aspects of locomotor maturation, to evaluate in which area changes occur and towards which direction, depending on the task. The novel database containing participants' raw collected data is made available as additional result of the present study.
Grimpampi E, Masci I, Pesce C, Vannozzi G [35]	TD	na	58 TD children (divided according to throwing developmental level, DLTC). 12 DLTC1 (9F-2M, 6 ± 1.78y), 30 DLTC2 (28F-12M, 8 ± 1.91y), 16 DLTC3 (1F-15M, 8 ± 1.06y)	Cross-sectional, validation; Italy	Overarm throwing (Instruction: "Throw the ball hard at the wall". Tennis ball. Wall at 6 m distance).	Video analysis of the tasks by trained operator using developmental sequences of the trunk action, to categorise the participants into three levels, according to the Developmental Levels of the Trunk	3 IMU (Opal, APDM Inc., USA) on the following landmarks: near the wrist of the right forearm, the anterior central surface of the thorax and lower lumbar spine. Fs = 128 Hz.	portable	Low pass filtered signals (25Hz). Task phases identified based on trunk and wrist angular velocities. Data Output : (i) cocking phase duration (ii) duration of the peak-to-peak ωv; (iii) acceleration phase duration; (iv) duration of minimum ωv from initial acceleration; (v) duration of minimum ωv from final acceleration. Kinematic parameters for each phase of the trial were: (vi) maximum trunk ωv during the acceleration phase; (vii) maximum pelvis ωv during the acceleration phase; (viii) peak-to-peak of the trunk ωv between the cocking and acceleration phase ; (ix) maximum trunk antero-	Trunk and pelvis 3D acceleration and angular velocities. Wrist angular velocity for task segmentation.	Trunk and pelvis angular velocities and time durations before the ball release showed increasing/decreasing trends with increasing developmental level. Significant differences between developmental level pairs were observed for selected biomechanical parameters. The results support the suitability and feasibility of objective developmental measures in ecological learning contexts, suggesting their potential supportiveness to motor learning experiences in educational and youth sports training settings.

						Compone nt			posterior linear acceleration during the post ball release phase. Range of movement of pitch (ROMPitch) and yaw (ROMYaw) during acceleration and cocking phase, respectively.		
Lander N, Nahavandi D, Mohamed S, Essiet I, Barnett LM [37]	TD	na	14 children (5F-9M, age range 7-12years, age mean 9.64years, 1.384 ± 0.104m, 31.6 ± 5.4 kg)	Cross-sectional, validation; Australia	Seven TGMD-3 skills: 4 locomotor (jump, hop, skip and side step) and 3 object control (catch, throw and kick).	TGMD-3 standard assessment	17 IMU sensors (XSENS MVN Awinda wireless motion capture suit, Fs=60Hz) and video recording were used for initial signal processing. Proposed new method identifies 4 sensors (wrists and ankles) to be more feasible for field assessment.	portable	XSENS MVN Awinda wireless motion capture suit (17 IMU) to construct a human model in the virtual environment to determine relative movement and positions of limbs in space (required steps: anthropometric measurements and calibration processes). Manual coding of tests to review and code each motor skill performances for all participant trials, based on videos and on motion capture data. Feature extraction of the acceleration data of 4 sensors to be closely aligned in determining performance in the algorithm developed.	Raw acceleration data from 4 sensors (wrists and angles, Fs=50hz).	Using signal processing-based methods via four sensors was a reliable and feasible way to assess seven motor skills in children. This approach means monitoring and assessment of children's skills can be objective, which will potentially reduce the time involved in motor skill assessment and analysis for research, clinical, sport and education purposes.

Masci I, Vannozzi G, Getchell N, Cappozzo A. [33]	TD	na	40 TD children (divided according to hopping developmental level, DLLA). 10 DLLA1 (4.6 ± 0.9y, 19.7 ± 1.8kg, leg length 0.53 ± 0.04m), 10 DLLA2 (4.7 ± 1.10y, 20.2 ± 2.8kg, leg length 0.6 ± 0.06), 10 DLLA3 (7.3 ± 2.9y, 26.7 ± 9.7kg, leg lenth 0.63 ± 0.09m) 10 DLLA4 (10.4 ± 1.9y, 37.7 ± 6.8kg, leg length 0.73 ± 0.07m)	Cross-sectional, validation; Usa	Hopping over distance from one cone to the other (5 m long pathway maked with cones at the ends; preferred speed).	video analysis of the hops by trained operator using developmental sequences to categorize the participants in 4 levels, according to DLLA	1IMU (Freesense, Sensorize s.r.l., Italy, 1 3D acc + 2 2D gyros) on lower trunk . Fs=100Hz. Video reconding (Sony DCR-TRV 360, Sony Electronics Inc)	portable	Algorithms in time domain. Data outputs: temporal parametes (intervals, duration and cadence) of the hops, normalised according to Hof [ref]; peak to peak difference of each acceleration component over each hop cycle; intra variability of acceleration during stance; CMC of accleration along each axis; one way ANOVA to identify the variable/s discriminatig DLLA.	Lower trunk 3D acceleration and 2D angular velocities	The important variables discriminating between DLLAs are Peak to Peak acceleration in AP and single hop Cycle Duration. The discri minant model was able to predict the membership to the extreme groups, DLLA1 and DLLA4, with an accuracy of 80% and 90%, respectively. Conversely, the samemodel lowered its performance in classifying children to DLLA2 and DLLA3 (40% and 50% of accuracy, respectively). Results indicated that some time and kinematic parameters changed with some developmental levels. Since inertial sensors were suitable in describing hopping performance and sensitive to developmental changes, this technology is promising as an in-field and user-independent motor development assessment tool.
Masci, I., Vannozzi, G., Bergamini, E., Pesce, C., Getchell, N., Cappozzo, A. [34]	TD	na	54 TD children (divided according to running developmental level, DLLA). 9 DLLA1 (2.2 ± 0.3y, 13-4 ± 1kg, leg length 0.37 ± 0.03m), 15 DLLA2 (2.8 ± 0.7y, 14.2 ± 1.9kg, leg length 0.45 ± 0.04), 15 DLLA3 (5.6 ± 1.8y, 21.8 ± 5.1kg, leg lenth 0.6 ± 0.07m) 15 DLLA4 (7.8 ± 2.2y, 31.9 ± 10.6kg, leg	Cross-sectional, validation; Usa	Running at maximum speed along a 15m path.	video analysis of running by trained operator using developmental sequence for arms action to categorize the participants in 4 levels, according to DLAA	1IMU (Freesense, Sensorize, s.r.l. Italy, 1 3D acc + 2 2D gyros) on lower trunk. Fs=100Hz. Video reconding (Sony DCR-TRV 360, Sony Electronics Inc)	portable	Low pass filtered signals (15 Hz for the cephalo-caudal component (CC) and 25 Hz for the other two components). Algorithms in time-frequency domain. CC frequency analysis using a hamming window L/6 (L signal lenght) to have the maximum frequency per instant, allowing to identify three running phases (increasing steady and decreasing acceleration). Data output: step frequency from FF of CC; RMS of 3 components of acc and angular velocites; Stance duration, max peak of acceleration; vertical stiffness. Step Frequency	Lower trunk 3D acceleration and 2D angular velocities	Normalized Step frequency was sensitive to transition DLAA1-2 e DLAA2-3. The findings showed that different sets of temporal and kinematic parameters are able to tap all steps of the transitional process in running skill described through qualitative observation and can be prospectively used for applied diagnostic and sport training purposes.

			length 0.62 ± 0.12m)						and Stance Duration normalized according to Hof [62].		
Sgrò, F., Mango, P., Pignato, S., Schembri, R., Licari, D., Lipoma, M. [36]	td	na	64 TD children (29F-35M, 9.17±0.97 y, 1.51±0.85m, 36.34±10.08kg, leg length: 0.72±0.04m)	Cross-sectional, validation; Italy	Standing long jump (Instruction: "You have to jump forward as long as you can").	classified by rater observator in 3 levels according to western australian teachers resourches	1 IMUs (Opal, APDM Inc., USA) back lower trunk (l4-l5). Fs=128Hz.	portable	Low pass filtered signals (acc, 20hz), angular velocities (15Hz). Data Output : propulsion time, flight time, linear and angular velocity at takeoff, the maximum peak of acceleration in anteroposterior and vertical directions, and the forward angle of the trunk at takeoff. Temporal and velocity parameters were also estimated in a nondimensional form according to Hof [62]. Temporal and kinematic parameters were then used for multivariate analysis.	Lower trunk 3D acceleration and angular velocities	Primary predictors for developmental group discrimination were maximum peak acceleration in the vertical and anteroposterior directions, respectively, and normalized preparation time. These outcomes represent significant steps toward improving the assessment of Standing Long Jump rate of development in childhood and supporting physical education.

Table 3a. Data extraction results. Gross motor skills – Laboratory assessment, non-typically developing children.

REF	ANALYSED POPULATION										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Baker R, McGinley JL, Schwartz MH, Beynon S, Rozumalski A, Graham HK, Tirosh O. [44]	cerebral palsy/general orthopaedic conditions/other neurological conditions/five were idiopathic toe walkers	TD	407 children (12±3y, BMI 20±5kg/m2): 271 had cerebral palsy, 88 had general orthopaedic conditions (such as Perthes disease, slipped upper femoral epiphysis and rotational malalignment), 43 had other neurological conditions (such as spina bifida, hereditary spastic paraplegia and acquired brain injuries) and five were idiopathic toe walkers. 38 TD children as control group (11±3y, BMI 19±5kg/m2)	Case-control validation; Australia	three left and right gait cycles	Gillette Functional Assessment Questionnaire (FAQ), Gross Motor Function Classification System (GMFCS), Gait Deviation Index (GDI), and Gillette Gait Index (GGI)	Vicon 512 or X system. Plug-in-Gait model. 2 force plates (Amti).	lab-based	Data output: body segment kinematics (plug-in-gait model) and force platform data	3D kinematics (plug-in-gait model of lower extremities) and 3D gound reaction forces.	GDI and GPS are alternative and closely related measures. The GDI has prior art and is particularly useful in applications arising out of feature analysis such as cluster analysis or subject matching. The GPS will be easier to calculate for new models where a large reference dataset is not available and in association with applications using the MAP.
Biffi E, Costantini C, Ceccarelli SB, Cesareo A, Marzocchi GM,Nobile	Children with Autism Spectrum Disorder (ASD)	TD	15 ASD: 14M-1F, 9.81±1.57y; 16TD: 15M-1F; 10.01±1.30Y.	Case-control exploratory; Italy	Habituation period: 6 min gait placing one foot on each separate belt. Test:	MABC-2 (+ IQ and DCDQ)	GRAIL system (dual belt tradmill that integrates 16-channel force plates, Fs=1000Hz). Motion-catpure system (Vicon, 10 optoelectronic	lab-based	kinematic data low pass filtered (6Hz). Custom software developed in Matlab for parameter estimation (time domain) and statistical analysis.Data output: Spatio-temporal	3D kinematics of 25 markers - Human Body Model (Van der Bogert 2013)	At baseline, children with ASD had reduced ankle flexion moment, greater hip flexion at the initial contact, and greater pelvic anteversion. After the discrete gait perturbation, variations of peak of knee extension significantly differed between groups and correlated with the severity of autistic core

M, Molteni M, Crippa A [45]					20-step trial recorded as baseline (T0). Then 20 trials with discrete gait perturbation (after a random number of steps, a single perturbation was applied to the dominant side at toe-off using split-belt acceleration). Single steps around perturbation were recorder. At the end, 20 steps were recorded as a post-perturbation trial (T1).		cameras, fs=100Hz, + 3 videocameras). VR environment projected on a 180° cylindrical projection screen with optic flow synchronized to tradmill speed. 25-marker Human Body Model (Van der Bogert 2013)		parameters: stance period, step length, walking speed. Joint kinematics and kinetics (ankle, knee and hip): peak flexion moments, flexion at IC, range of motion in flexion and peak of extention. Pelvic tilt at IC and its mean value during cycle.		symptoms. Throughout perturbation trials, more than 60% of parameters showed reliable adaptation with a decay rate comparable between groups. Overall, findings depicted gait peculiarities in children with ASD, including both kinetic and kinematic features; a motor adaptation comparable to their TD peers, even though with an atypical pattern; and a motor adaptation rate comparable to TD children but involving different aspects of locomotion. The platform showed its usability with children with ASD and its reliability in the definition of paradigms for the study of motor learning while doing complex tasks, such as gait.
Böhm H, Wanner P, Rethwilm R, Döderlein L [46]	Cerebral palsy	//	280 children: age range 6-17y, GMFCS level II	Cross-sectional exploratory; Germany	running barefoot	postural control (single leg balance test and vertical single leg jumps); muscle weakness and muscle	8 camera Vicon-MX system. Plug-in-Gait model of lower extremities. 2 force plates (Amti).	lab-based	time-domain. Identification of gait events (touch down, take-off). Data Out-put: presence of floating phase	3D kinematics (plug-in-gait model of lower extremities) and 3D gound reaction forces.	The ability to run was significantly higher in unilateral (67%) than in bilateral (55%) affected patients. Significant differences between runners and non-runners were found for spasticity, BMI and postural control, but not for muscle strength. Lower M. rectus femoris spasticity, higher m gastrocnemius spasticity and enhanced postural control appear to be the best predictors for being able to run.

						spasticity.					
Chappell A, Gibson N, Williams G, Allison GT, Morris S [53]	Cerebral Palsy	TD	40 CP children (25 M, 15 F; age 12y ± 11m; 19 unilateral, 21 bilateral; GMFCS 25 level I, 15 level II). 22 TD children (15 M, 7 F; age 10y ± 2m)	Case-control exploratory; Australia	running	The Gross Motor Function Classification System (GMFCS)	8-camera motion capture system at 250 Hz (Vicon T- series, Oxford Metrics, UK); 3 in-ground force platforms in series at 1000Hz (AMTI, Watertown, MA)	lab-based	normalised running speed (velocity of the pelvis divided by height), hip and ankle power (A2 peak ankle power generation, H3 peak hip flexor power generation in swing) to characterize propulsion strategy (PS = A2/(A2 + H3))	3D kinematics and 3D ground reaction forces (Vicon Nexus 2.5,Vicon Motion Systems, Oxford, UK)	Maximum speed, A2 and PS were significantly less in children with CP GMFCS level I than in TD children and significantly less in children in GMFCS level II than level I. For children with CP, A2 and PS were significantly smaller in affected legs than non-affected legs. In affected legs, H3 was significantly larger in children in GMFCS level II than GMFCS level I but not different between TD children and children in GFMCS level II. The contribution of ankle plantarflexor power to forward propulsion in running is reduced in young people with CP and is related to GMFCS level. This deficit appears to be compensated in part by increased hip flexor power generation but limits maximum sprinting speed.
Chen L, Wang J, Gao L, Hassan E, Li H, Li S, Liao F [49]	Cerebral Palsy	TD	26 CP children (age, 6.75 ± 2.27 yrs; height, 1.13 ± 0.15 m; weight, 18.3 ± 4.52 kg) and 50 TD children (age 6.89 ± 2.43 yrs; height 1.26 ± 0.21 m; weight, 29.6 ± 8.72 kg [mean ± SD])	Case control exploratory; China	10-m walking	The Gross Motor Function Classification System (GMFCS)	kinematics -OptoTrak 3020 motion analysis system (Northern Digital Inc, Waterloo, Canada) with a sample rate of 100 Hz	lab-based	software Visual3D was used to analyze the recorded gait data in the time domain. Comparison of output data was performed within and betweem TD and CP children. Output data: joint angles.	3D kinematics	GCI in children with CP post-rehabilitation was significantly higher than that in the children with typical development (P G 0.05) but significantly lower than that in children with CP prerehabilitation (P G 0.05). There are significant differences in GCI for children with CP prerehabilitation between level I, level II, and level III (P G 0.05). The results of intraclass correlation coefficients (90.8) indicated that the obtained GCIs were reliable.

Chia LC, Licari MK, Guelfi KJ, Reid SL. [48]	DCD	TD	14 DCD (9.5 ± 1 yr); 14 TD controls (9.6 ± 1 yr)	Case control exploratory ; Australia	running at a velocity of 2.44 ± 0.25 m/s along a 15 m track	//	12-camera Vicon MX system and AMTI force plate.	lab-based	Kinematic and inverse dynamic calculations were performed in Vicon Nexus using the UWA lower body model	3D kinematics (plug-in-gait model of lower extremities) and 3D gound reaction forces.	Although features of the kinematic and kinetic trajectories were similar between groups, DCD group displayed decreased peak knee extension compared with TD group prior to initial foot contact. Furthermore, DCD group displayed increased variability in sagittal plane kinematics at the hip and ankle during toe off compared with TD group. Kinetic analysis revealed that children with DCD displayed significantly reduced knee extensor moments during the stance phase of the running cycle. Consequently, peak knee power absorption and ankle power generation was significantly lower in the DCD group.Furthermore, there was a trend for children with DCD to have shorter strides and a longer stance period than the TDcontrols.
Farmer SE, Pearce G, Stewart C [51]	Cerebra l Palsy	TD	20 CP children: mean age 9.9 years (aged 4–14 years), height 89.5–150 cm, weight 12.4–54.5 kg. 20 TD children: mean age 10.1 years (aged 6–15 years), height of 115–168 cm, weight of 17.2–62.7 kg	Case-control exploratory study; UK	gait	//	Vicon kinematic system (Vicon Motion Systems Ltd., Oxford, UK).	lab-based	walking speed, maximum, minimum and range of motion (ROM) values at the hip and knee during the gait cycle	3D kinematics	Children with cerebral palsy had reduced ROM and walked more slowly than normal children. There are significant differences between TD and cerebralpalsy coordination phases with marginally greater significance for most component parameters; the exception beingin-phase flexion.
Morrison SC, Ferrari J, Smillie S. [57]	DCD	//	20 children: age 6-11 years	Cross-sectional exploratory study; UK	walking	//	Baropodometric mat (GaitRite)	lab-based	Data output: variability of space-time parameter	Gait-time parameters of gait	Intraclass correlation coefficient values attained in this study ranged from 0.24 to 0.73, with good reliability achieved for one parameter (cadence), and moderate reliability for step length, stride length, and double support duration.

Table 3b. Data extraction results. Gross motor skills – Laboratory assessment, typically developing children.

REF	**ANALYSED POPULATION**										
	target population	**presence of control group**	**Sample size and population characteristics**	**Study details (type and location)**	**analyzed task/s**	**reference assessment**	**measurement system**	**portable/ lab-based**	**data processing and computational approach + data outputs**	**measured variable/s**	**main findings**
Bonnechère B, Sholukha V, Omelina L, Van Vooren M, Jansen B, Van Sint Jan S [59]	TD	//	81 healthy subjects: 19 TD children (5 to 15 years old, 10 ± 3y), 40 adults (18 to 65 years old, 37 ± 14y), 22 elderly subjects (60 to 88 y, 74 ± 6years old)	Cross-sectional exploratory ; Belgium	serious game (SG) targeting gross- and object control: clean the screen covered by virtual mud using a cloth controlled with hands, trunk and legs alternatively. 3 repetitions were perfomed per modality.	//	Kinect sensor	lab-based	For each body part (lower limbs, upper limbs, trunk): 1) Time required to clean 90% of the screen (global performance). 2) Accuracy of the motion assessd by computing the number of times that the subject is placing the cloth in the same position on the screen. were calculated to quantify the level of development of motor control.	Segmental kinematics as estimated by Kinect model	ANOVA tests showed statistically significant differences between the three groups for duration (53 ± 15, 27 ± 10 and 119 ± 30 s for children, adults and elderly subjects respectively) and accuracy (87 ± 5, 89 ± 10 and 70 ± 8% for children, adults and elderly subjects respectively). The slopes of the curves that approximated the evolution of the performance over various ages are coherent with previous studies about motor control development and physiological decline.

Clark C, Barnes C, Holton M, Summers H, Stratton G [47]	TD	//	11 children: 10±0.8y, 1.41±0.07m, 33.4±8.6kg, body mass index; 16.4±3.1 kg.m2)	Cross-sectional validation; UK	throwing, walking, jogging, running	quantitative analysis of FMS	Vicon three-dimensional kinematics; accelerometer	lab-based	Integrated acceleration; segmental kinematic evaluation in Vicon Nexus	internal/external rotation of shoulder, gait speed, joitn angles, acceleration	Maximum shoulder external rotation and maximum shoulder internal rotation velocity, mediolateral centre of mass range and centre of mass coefficient of variation, maximum stride angle in the jog and walk and maximum sprint stride angle and maximum shoulder internal rotation velocity were significantly correlated. Maximum sprint stride angle and maximum internal rotation velocity were significantly correlated to overall integrated acceleration. Overall integrated acceleration was comparable between participants, whereas three-dimensional variables varied by up to 65%. Although overall integrated acceleration was comparable between participants, three-dimensional variables were much more varied. Indicating that although overall activity may be correspondent, the characteristics of a child's movement may be highly varied.
Dixon PC, Stebbins J, Theologis T, Zavatsky AB [50]	TD	//	54 TD children (characteristics not provided)	Cross-sectiona exploratory ; UK	walking straight and 90° turning task (left and right)	//	12-camera Vicon MX system(Vicon,Oxford, UK, Plug-in Gait + Oxford Foot Model set-up). Two force plates (Advanced Mechanical Technology,Inc.,Watertown,USA) collected GRF data at 1000Hz	lab-based	Filtering of marker trajectories; calulation of net internal joint oments and powers via inverse dynamics in Nexus; Identification of gait features in the time domain	Markers trajectoris for segmental 3D kinematics calculation; Ground reaction force as measured by force platform	Directions were reversed and magnitudes decreased during the approach phase. Step turns showed reduced ankle powergeneration, while spin turns showed largeTZ. Both strategies required large knee and hip coronal and transverse plane moments during swing. These kinetic differences highlight adaptations required to maintain stability and reorient the body towards the new walking direction during turning. From a clinical perspective, turning gait may better reveal weaknesses and motor control deficits than straight walking in pathological populations, such as children with cerebral palsy.

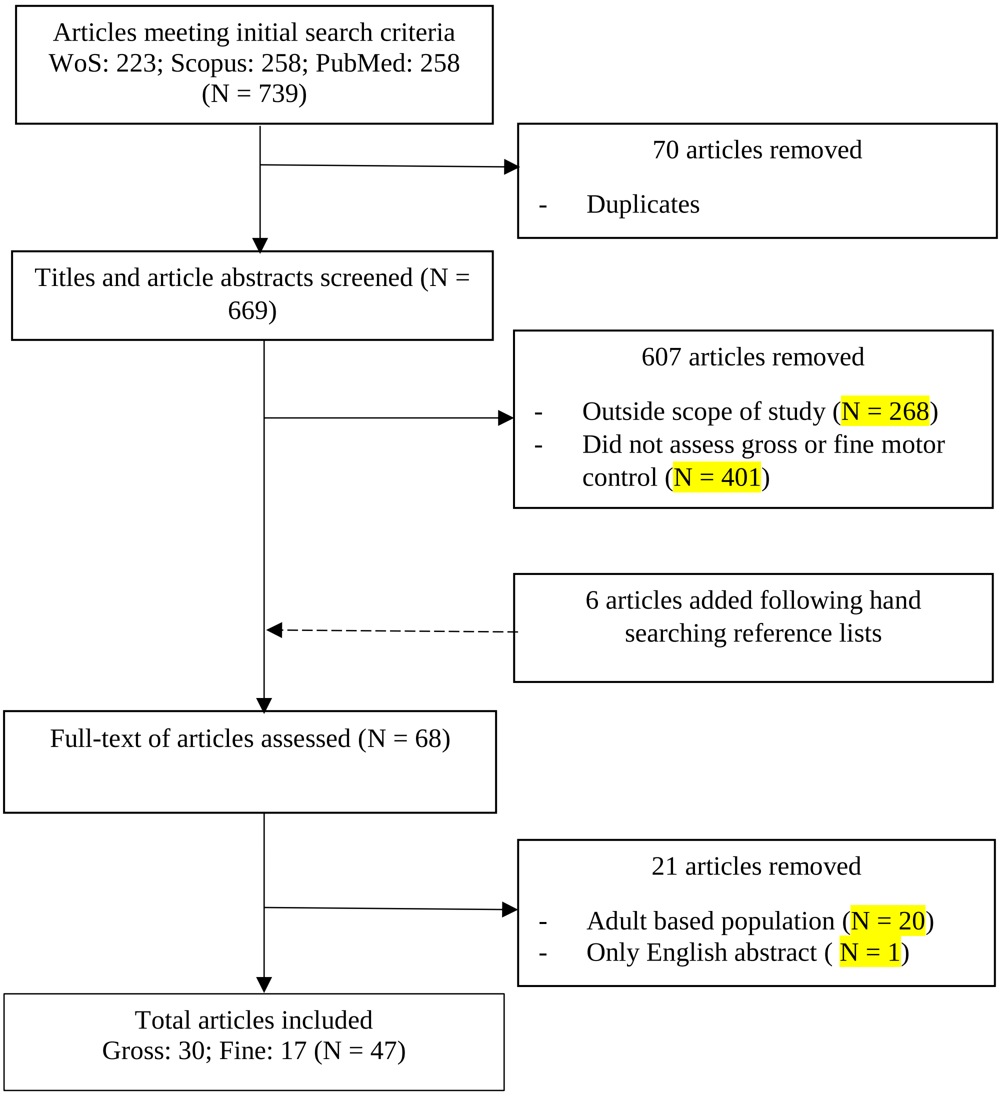
Getchell N, Roberton MA [55]	TD	//	7 children: 5females, 2males; 4-8y (6.1+-1.2y)	Cross-sectional validation; USA	hopping straight along a 4.8m path	hopping developmental level assessed by expert trainer (level 2 and 3)	Kistler 40x60 force platform platform, fs 833Hz + Milliken camera recording movement in the sagittal plane	lab-based	Smoothing of vertical ground reaction force; planar coordinates in the sagittal plane digitized from video data; marker on the hip assumed as centre of gravity; calculation of whole body stiffness as slope of vertical force versus centre of gravity displacement	Ground reaction forces; video recording of sagittal motion	Both instantaneous and estimated average whole body stiffness showed dramatic reductions between developmental Levels 2 and 3. It was proposed that stiffness may be a key parameter controlled by the central nervous system as children hop. Children at early developmental levels set this parameter too high.
Guffey K, Regier M, Mancinelli C, Pergami P [58]	TD	//	84 children: 2.0–4.9 years	Cross-sectional validation; USA	gait and balance in standing posture	Paediatric balance scale	Baropodometric mat (GaitRite)	lab-based	principal component analysis of spatio-temporal parameters	step and stride length, velocity, cadence, step time, cycle time, stance time, swing time, single support time, and double support time	Comparison of spatiotemporal parameter means between age groups showed trends associated with motor development similar to the ones described in the literature such as decreased cadence and increased step/stride length with increasing age. However, no significant differences in normalized spatiotemporal parameters were found between age groups. Age, leg length, cadence, step/stride length, step/stance time, and single/double support time showed significant correlation with balance scores. When the parameters were grouped into spatial, temporal, and age-related components using principal components analysis and included in a multiple regression model, they significantly predicted 51% of the balance score variance. Age-related components most strongly predicted balance outcomes.

Holm I, Tveter AT, Fredriksen PM, Vøllestad N. [56]	TD	//	360 girls and boys between 7 and 12 years (age, height and weight for each year of age and divided per male and females). 7yo: 36M, 7.5±0.3years, 128.3±4.4cm, 26.8±2.8kg; 16F 7.5±0.2years 128.9±5.5cm 28.2±4.2kg 8yo: 27M, 8.5±0.2years, 133.7±4.7cm, 30.6±4.8kg; 21F 8.6±0.1years 131.7±5.4cm 29.4±4.1kg 9yo: 31M, 9.3±0.3years, 138.1±6.2cm, 32.9±5.3kg; 38F 9.3±0.2years 137.3±6.4cm 31.9±5.5kg 10yo: 29M, 10.4±0.3years 142.7±6.6cm 35.9±5.5kg; 39F 10.3±0.2years 142.4±4.8cm 36.5±5.1kg 11yo: 25M, 11.6±0.2years 149.3±7.0cm 41.2±6.2kg; 28F 11.4±0.2years 148.7±6.5cm	Cross-sectonal validation; Norway	walking at four different speeds and hopping on either leg with as long serial jumps as possible across the whole walkway.	normative quantitative performance data for evaluating motor competence both in healthy and diseased children	Baropodometric mat (GaitRite)	lab-based	Gait and Hopping spatio-temporal parameters	WALKING: Step length (cm) Normalized step length (step length/height) Cadence (step/min) Base of support (cm) Toe in/out (°). HOPPING: Hop length (cm) Normalized hop length (hop length/height) both for Best and Controlateral leg.	here was an increase in absolute step length of 15% from 7 to 12 years of age. However, for normalized step length there was no increase. The total increase in absolute and normalized hop length from 7 to 12 years was 64% and 36%, respectively. Multiple regression analysis displayed a significant increase for absolute and normalized hopping length with age. While step length only showed a small increase from 7 to 12 years of age, hop length showed significant increase both in absolute and normalized values. The variability, however, was large, indicating that a normative sample of hop length measurements includes a wide range of values for each age group.

			39.1±5.8kg 12yo: 33M, 12.3±0.3years 153.0±6.2cm 43.4±7.3kg; 37F 12.4±0.3years 157.9±7.2cm 47.2±10.4kg								
Mapaisansin P, Suriyaamarit D, Boonyong S [54]	TD	//	58 children: 18 aged 4-6 yrs (5.8 ± 0.9y, 9M and 9F, 18R and 0L dominant leg, 28.53 ± 3.28 Kg, 112.41 ± 7.10 cm), 20 aged 7-9 yrs (8.56 ± 0.73 y, 10M and 10F, 19R and 1L dominant leg, 26.50 ± 4.66 Kg, 126.95 ± 4.78 cm), 20 aged 10-12 yrs (11.66 ± 0.70 y, 10M and 10F, 19R and 1L dominant leg, 39.47 ± 8.57 Kg, 146.01 ± 9.67 cm); 19 young adults (22.41 ± 1.98 y, 10M and 9F, 19R and 0L dominant leg, 56.42 ± 5.36 Kg, 165.80 ± 6.78 cm)	Cross-sectional exploratory; Thailand	Sit to stand (STS) with adjustable bench (height set at 100% of the participant's lower leg length, and the seat depth at 25% of the participant's thigh length)	//	8 camera (Raptor E, sampling rate 120Hz) stereophotogrammetric system (Motion Analysis Corporation, Santa Rosa, CA) and 2 force platforms (Bertec Corp., Columbus, OH, sampling rate 1200 Hz)	lab-based	Tempotal segmentation of the task: phase I, flexion; phase II, load transfer; phase III, extension; phase IV, stabilization. Five-segment model (foot, shank, thigh, pelvis, and trunk) to calculate trunk and pelvis angles absolute angleswith respect to the vertical directon, and trunk-pelvis, hip, knee, and ankle relative angles. Joint moments normalised with respect to body weight. Data were analysed with respect to age and heigth.	whole task and phase in percentage of task duration; segment and joint angle values at each phase transition point; joint moment peaks at the beginning of phase II normalised with respect to body weight.	Children aged 4–6 years (or 1.0–1.20 m height) took less time to accomplish STS movement than adults (or 1.60–1.80 m height). Children aged 4–9 years performed STS movement by using more trunk and hip flexion and anterior pelvic tilt, but less knee flexion and ankle dorsiflexion than children aged 10–12 years and adults. At the final standing position, children aged 4–12 years exhibited more knee extension and more ankle plantar flexion than adults. In addition, children aged 4–12 years had more peak trunk-pelvic extension and less peak knee extension moments than adults. Different strategies to achieve the STS task were found among children aged 4–12 years in terms of total movement time, joint angle, and joint moments. Adult-like kinematic and kinetic STS patterns were not seen in children up to 12 years old.

Meyns P, Desloovere K, Molenaers G, Swinnen SP, Duysens J [52]	TD	4 aduls (2m, 2f; 29.86+-6.22y; 68.85+-6.21kg; 1.74+-0.06m)	24 children: 12m, 12f; 9.4+-2.16 y; 31.72+-8.64 kg; 1.38+-0.14 m	Cross-sectional exploratory; Italy	walking at preferred speed alon a 10m path BW and FW	comparison with angles of FW gait of a nomal adult person	Streophotogrammatry (Vicon (100Hz) + PlugInGait)	lab-based	right and left, upper and lower arm, leg and feet angles with respect to the vertical axis in the sagittal plane; angles in FW and BW where correlated (pearson) with FW gait angles of normal aduults; timimng and angular velocity	Segmental kinetatics in the sagittal plane, temporal paramters; velocity	Upper and lower limb kinematics of FW correlated highly to revBW kinematics in children, which appears to be consistent with the proposal that control of FW and BW may be similar. In addition, age was found to mildly alter lower limb kinematic patterns. In contrast, interlimb coordination was similar across all children, but was different compared to adults, measured for comparison. It is concluded that development plays a role in the fine-tuning of neural control of FW and BW.
Sgrò F, Nicolosi S, Schembri R, Pavone M, Lipoma M [57]	TD	//	41 children, age ranging from 9 to 12 years: 11.3+-1y, 1.49+-0.9m, 43.18+-12.09kg,ll 0.6+-0.32m, bmi 19,21+-4.59	Cross-sectional validation; Italy	vertical jump in development and consolidation	reference observational process evaluation based on western australian teachers resources	Kinect (sampling 30hz, resolution 0.35m)	lab-based	Correlation of COM kinematics and temporal analysis with task competence	COM trajectoy	Multivariate analysis of variance (MANOVA) and discriminant analysis verified that the height of the jump and the flight height predict the primary differences in jumping skill developmental levels, and the Kinect-based assessment discriminates these levels.

Figure 1


Articles meeting initial search criteria
WoS: 223; Scopus: 258; PubMed: 258
(N = 739)
70 articles removed
- Duplicates
Titles and article abstracts screened (N = 669)
607 articles removed
- Outside scope of study (N = 268)
- Did not assess gross or fine motor control (N = 401)
6 articles added following hand searching reference lists
Full-text of articles assessed (N = 68)
21 articles removed
- Adult based population (N = 20)
- Only English abstract (N = 1)
Total articles included
Gross: 30; Fine: 17 (N = 47)

Supplementary files

Supplementary Table 1a. Quality assessment, fine motor skills

Refs	*Article*	*Quality assessment item*													
		1	2	3	4	5	6	7	8	9	10	11	12	13	Total
		Fine motor skills, non-typically developing children													
[17]	Butler et al	1	2	2	0	1	2	2	2	2	1	1	2	2	20
[24]	Casellato et al	2	2	1	0	1	2	2	2	2	2	2	2	2	22
[23]	Chang et al	2	2	2	0	2	1	2	2	1	2	2	1	2	21
[18]	Chau et al	2	2	2	0	2	2	2	2	2	2	2	0	2	22
[21]	Coluccini et al	2	2	1	0	1	1	2	2	2	2	0	2	1	18
[19]	Formica et al	2	2	2	0	1	1	1	2	2	2	0	2	2	19
[20]	Kuhtz-Buschbeck et al	2	2	2	0	1	1	1	2	2	2	1	2	2	20
[22]	Smits-Engelsman et al	2	2	2	0	1	2	2	2	2	2	0	2	2	21
	Average	1,87	2	1,75	0	1,25	1,5	1,75	2	1,87	1,87	1	1,62	1,87	20
		Fine motor skills, typically developing children													
[28]	Blank et al	1	2	2	0	2	1	2	2	2	2	0	2	2	20
[26]	Duval et al	2	1	0	0	1	2	2	2	2	2	0	2	2	18
[27]	Lin et al	2	2	2	0	1	2	2	2	2	2	0	2	2	21
[8]	Mason et al	2	1	1	0	2	1	2	2	2	2	0	2	2	19
[7]	Ren et al	2	2	2	0	1	1	2	2	2	2	0	2	2	20
[6]	Rosenblum et al	2	1	1	0	2	1	1	2	2	2	0	2	2	18
[9]	Rudisch et al	2	2	2	0	1	1	2	2	2	2	2	2	2	22
[5]	Rueckriegel et al	2	2	1	0	2	1	1	2	2	2	2	2	2	21
[25]	Waterman et al	1	2	2	0	1	2	2	2	2	2	0	2	2	20
	Average	1,78	1,67	1,44	0	1,44	1,33	1,78	2	2	2	0,44	2	2	20

Supplementary Table 1b. Quality assessment, gross motor skills -Wearable based assessment

Refs	*Article*	*Quality assessment item*													
		1	2	3	4	5	6	7	8	9	10	11	12	13	Total
		Gross motor skills - wearable based assessment, non-typically developing children													
[29]	Belluscio V, et al	2	2	2	0	2	2	2	2	2	2	2	1	2	23
[31]	Ricci M, et al	1	1	1	0	2	2	2	1	1	2	0	0	1	14
[30]	Speedsberg MB, et al	2	2	2	0	2	2	2	2	2	2	2	0	2	22
	Average	1,67	1,67	1,67	0	2	2	2	1,67	1,67	2	1,33	0,33	1,67	20
		Gross motor skills - wearable based assessment, typically developing children													
[15]	Barnes CM, et al	2	2	2	0	2	2	2	2	2	2	0	0	2	20
[12]	Bisi MC, et al	2	2	2	0	2	2	2	2	2	2	1	0	2	21
[32]	Bisi MC, Stagni R	2	2	2	0	2	1	2	2	2	2	0	1	2	20
[10]	Bisi MC, et al	2	2	2	0	2	1	2	2	2	2	0	1	2	21
[11]	Bisi MC, et al	2	2	2	0	2	2	2	2	2	2	2	1	2	23
[35]	Grimpampi E, et al	2	2	1	0	2	2	2	2	2	2	1	1	2	21
[37]	Lander N, et al	2	2	2	0	2	2	2	2	2	2	1	1	2	21
[33]	Masci I, et al	2	2	2	2	2	2	2	2	2	2	2	1	2	25
[34]	Masci I, et al	2	2	2	0	2	2	2	2	2	2	1	0	2	20
[36]	Sgrò F, et al	2	2	2	0	2	2	2	2	2	2	2	2	2	24
	Average	2	2	1,9	0,2	2	1,8	2	2	2	2	1	0,8	2	22

Supplementary Table 1c. Quality assessment, gross motor skills -Laboratory assessment

Refs	*Article*	*Quality assessment item*													
		1	2	3	4	5	6	7	8	9	10	11	12	13	Total
		Gross motor skills – Laboratory assessment, non-typically developing children													
[44]	Baker R, et al.	2	2	2	0	1	1	1	1	2	2	1	0	2	17
[45]	Biffi E, et al.	2	2	2	0	2	2	2	1	2	2	2	1	2	22
[46]	Böhm H, et al.	1	2	2	0	2	2	2	1	2	1	2	1	2	20
[53]	Chappell A, et al.	2	2	2	0	2	1	2	2	2	2	2	2	2	23
[49]	Chen L, et al.	2	1	1	0	1	2	2	2	2	1	2	1	2	19
[48]	Chia LC, et al.	1	2	2	0	2	2	2	1	2	1	1	1	2	19
[51]	Farmer SE, et al.	0	1	1	0	1	2	2	1	2	2	0	1	1	10
[57]	Morrison SC, et al.	2	2	2	0	2	2	2	2	2	1	2	1	2	22
	Average	1,50	1,75	1,75	0	1,62	1,75	1,87	1,37	2	1,50	1,50	1	1,87	19
		Gross motor skills – Laboratory assessment, typically developing children													
[59]	Bonnechère B, et al.	2	1	1	0	1	1	1	1	2	1	1	0	1	13
[47]	Clark C, et al.	2	2	2	0	2	2	1	1	2	2	2	1	2	21
[50]	Dixon PC, et al.	1	2	0	0	2	2	2	2	2	2	2	1	2	20
[55]	Getchell N,Roberton MA	2	2	1	0	2	2	2	1	2	1	0	2	2	19
[58]	Guffey K, et al.	2	2	2	0	2	2	2	2	2	2	2	1	2	23
[56]	Holm I, et al.	2	2	2	0	2	2	2	2	2	2	0	2	1	21
[54]	Mapaisansin P, et al.	1	2	2	2	2	2	2	2	2	2	0	1	2	22
[52]	Meyns P, et al.	2	2	2	0	2	2	2	2	2	1	2	2	2	23
[60]	Sgrò F, et al.	2	2	2	2	2	2	2	2	2	2	2	2	2	26
	Average	1,78	1,89	1,56	0,44	1,89	1,89	1,78	1,67	2	1,67	1,22	1,33	1,78	20,89