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Wearable-based electronics to objectively support diagnosis of motor impairments in school-aged children

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ABSTRACT

Developmental coordination disorder (DCD) and attention-deficit hyperactivity disorder (ADHD) are neuro-developmental disorders, starting in childhood, which can affect the planning of movements and the coordination.

We investigated how and in which measure a system based on wearable inertial measurement units (IMUs) can provide an objective support to the diagnosis of motor impairments in school-aged children.

The IMUs measured linear and rotational movements of 37 schoolchildren, 7–10yo, 17 patients and 20 control subjects, during the execution of motor exercises, performed under medical and psychiatric supervision, to assess different aspects of the motor coordination.

The measured motor parameters showed a high degree of significance in discriminating the ADHD/DCD patients from the healthy subjects, pointing out which motor tasks are worth focusing on. So, medical doctors have a novel key lecture to state a diagnosis, gaining in objectivity with respect to the standard procedures which mainly involve subjective human judgment.

Differently to other works, we propose a novel approach in terms of number of used IMUs and of performed motor tasks. Moreover, we demonstrate the meaningful parameters to be considered as more discriminant in supporting the medical diagnosis.

1. Introduction

The human motor control is the way the neuromuscular system activates/coordinates muscles/limbs to perform motor skills. For some school-aged children, this control does not refine over time as it is expected to do, so are diagnosed with developmental coordination disorder (DCD) and/or attention-deficit hyperactivity disorder (ADHD).

Children with DCD act with poor coordination, poor postural control and/or fine or gross motor clumsiness, without achieving age-appropriate activities of daily living, such as walking, playing catch, etc. (Smits-engelsman, 2011).

Children with ADHD can be predominantly hyperactive or inattentive or a combined type (American Psychiatric Association, 2013). The hyperactivity results in inability to control impulses, leading to squirm, fidget, or bounce when sitting. Studies investigating ADHD referred impaired motor skills in terms of poor coordination and poor gross and fine motor functioning (Bart et al., 2010).

DCD results 6% in prevalence worldwide (Smits-engelsman, 2011); ADHD is different among countries, but averages 5% in prevalence (Sayal et al., 2017).

Interestingly, DCD and ADHD are frequently combined, their comorbidity as high as 50% (Buderath et al., 2009; Goulardins et al., 2015; Kaiser et al., 2015), their relationship remaining pretty unknown (Sergeant et al., 2006). Moreover, both disorders have been linked to psychological problems, reduced academic performance, and reading and spelling difficulties, thus the idea of a single etiology has been suggested (Dewey and Bernier, 2016; Kaplan et al., 1998).

According to the *diagnostic and statistical manual of mental disorders* (DSM-5TM, 5th edition) (American Psychiatric Association, 2013) and the *international classification of mental and behavioral disorders* (ICD-10, 10th revision) (World Health Organization, 1992), the diagnosis of motor difficulties in children can be made by examining the medical history, by filling questionnaires for parents/teachers, and by motor tests. However, different authors have

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pointed out that there is no gold standard for the assessment of motor skills, and thus the identification of motor impairments in children is complex (Kaplan et al., 1998; Smits-engelsman, 2011; Venetsanou et al., 2011; Visser, 2003). Indeed, the identification of motor disturbances through the use of these motor tests is limited to the personal interpretations and experience of the clinicians. Moreover, questionnaires are subjective, relying on the parent's symptoms perception.

All in, an objective measure of motor abilities can play a primary role in supporting medical diagnosis, therefore some objective measurement systems have been adopted (Artusi et al., 2018; Capecci et al., 2018; Greene et al., 2015; Saggio et al., 2015; Simon, 2004). Force platforms and optical systems have been used to assess single aspect of motor skills in children with DCD, such as gait, balance and hopping (Geuze, 2003; Larkin and Parker, 1998; Masci et al., 2012; Tsai et al., 2008; Wilmut et al., 2016; Woodruff et al., 2002); infrared motion system and inertial sensors were proposed to assess the impulsivity in ADHD (Delgado-Gomez et al., 2017; O'Mahony et al., 2014; Teicher et al., 1996).

Within this frame, as far as we know, this work represents the first deep investigation to objectively assess the motor coordination in DCD/ADHD, based on a cost-effective inertial sensor network, full-body adopted during a complete set of motor tasks.

2. Materials and methods

2.1. Participants

Seventeen children with ADHD/DCD comorbidity, 8.5 ± 1.25yo, 12 boys and 5 girls, patients hereafter, and twenty healthy children, 9 ± 0.95yo, 15 boys and 5 girls, controls hereafter, were involved in motor tasks (Table 1). Each patient was diagnosed after a comprehensive neurological examination by an expert clinician according to DSM–V criteria (American Psychiatric Association, 2013). None of the participants had history of stimulant therapy or was mentally retarded. Parents of children of both groups completed the DCD Questionnaire (DCDQ) to attest motor impairment, if any, according to DSM–V (American Psychiatric Association, 2013). PANESS test (Physical and Neurological Examination for Subtle Signs) (Denckla, 1985) was used to evaluate motor skills. Wechsler test Intelligence Scale for Children (WISC) test was used to evidence IQ for all participants, whereas Conners Parent Rating Scale, Conners Teacher Rating Scale, CBCL (Child Behavior Checklist for Ages 6–18), and Tower of London were used to evaluate ADHD executive function.

The children's parents signed informed consent form and received a full explanation of the procedures, which were approved by the ethical Committee of the University of "Tor Vergata".

2.2. Measurement system

We used a network of 12 wearable lightweight IMUs. The IMU, termed *Movit G1* (by Captiks Srl, Rome, Italy), is equipped with the Motion Processing Unit MPU-9150 (by InvenSense) that combines a tri-axis accelerometer (sensitivity: 4096 LSB/g, range: ±8g) and a tri-axis gyroscope (sensitivity: 32.8 LSB/°/s, range: ±1000°/s). This IMU-based technology was validated against the gold standard camera based Smart DX-100 system, by BTS Corp (Quincy, MA 02169 USA). The validation test, performed on motor tasks of three healthy subjects, resulted with an error of 3.0 ± 2.6(SD) degree at a sampling rate of 100 Hz (frequency of the BTS system). Further information regarding validation against a platform for static posturography (EDM Euroclinic®) are reported in (Alessandrini et al., 2017). The networked *Movit G1s* synchronously send data to a receiver connected to a personal computer, on which an application, termed *Captiks Motion Studio*, runs.

The values of the angles of the joints are calculated from the related quaternions applying Euler decomposition. Data, generated by the 3D accelerometer and the 3D gyroscope at a data rate of 200 Hz, provide quaternions, using the Kalman filter, as orientations in the IMU local frame. A patented calibration procedure transforms the sensor orientations from the sensor frame into the human joint frame when the network of IMUs is "dressed" by the user. Data gathered from each IMU are so related to its orientation as the difference from its initial condition. Each angle between two IMUs is gathered as forward kinematic procedure in a parent-child hierarchy. Finally, the value of the single angle is calculated from the related quaternion applying Euler decomposition of the human joint under examination. While sampling rate of sensors is 200 Hz, the IMU network data transmission rate is 50 Hz, to increase battery autonomy (though the power consump-

Table 1
Subjects characteristics.

Patient	Age	Gender	DCDQ	Control	Age	Gender	DCDQ
1	8.6	M	51	1	9.11	F	59
2	10.2	M	37	2	10.5	M	60
3	7	M	41	3	7.6	M	67
4	7.8	M	30	4	9.6	F	63
5	8.8	M	40	5	10.1	M	72
6	8.11	M	41	6	8.5	M	72
7	8.5	F	51	7	8.7	F	57
8	7	F	39	8	8.9	F	63
9	7.8	M	43	9	8	M	66
10	10.5	F	41	10	9.2	F	61
11	7.1	F	29	11	9.8	M	64
12	7.2	M	36	12	10.1	M	67
13	10.4	M	50	13	7.1	M	68
14	10.2	M	33	14	10	M	68
15	8.8	M	29	15	10.1	M	65
16	7.2	F	46	16	9.6	M	64
17	9.3	M	45	17	8.8	M	68
				18	8	M	60
				19	8.6	M	62
				20	9.4	M	60

Score for indication of DCD (5 years 0 months to 7 years 11 months): 15–46.
Score for indication of DCD (8 years 0 months to 9 years 11 months): 15–55.
Score for indication of DCD (10 years 0 months to 15 years): 15–57.

tion is not a bottleneck in our tests, but it is in view of further daily tele-monitoring purposes).

The IMU's case is provided with Velcro® strip useful to be easily attached to the elastic band located to the body's segment in accordance to the type of motor task to be performed (Fig. 1).

2.3. Motor tasks

Participants were requested to perform nine motor tasks according to standard clinical protocols: MABC-2 (Movement Assessment Battery for Children, 2nd edition) (Brown and Lalor,

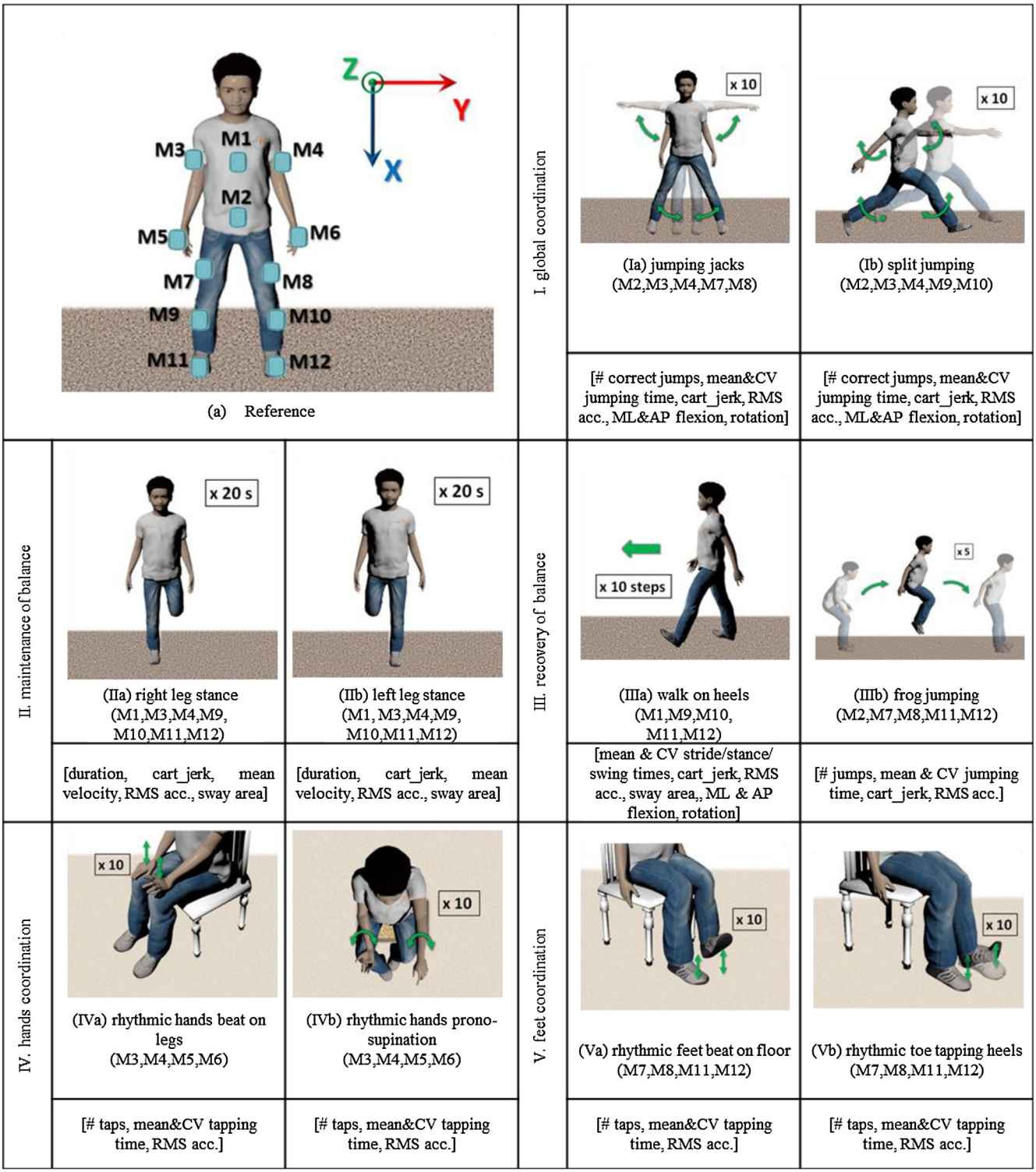


Fig. 1. The motor tasks devoted to I. global coordination (jumping jacks and split jumping), II. maintenance of balance (right and left leg stance), III. recovery of balance (walk on hells and frog jumping), IV. hands coordination (rhythmic hands beat on legs and prono-supination) and V. feet (rhythmic feet beat on floor and toe tapping heels).

2009), PANESS (Physical and Neurological Examination for Subtle Signs) (Denckla, 1985), and APCM-2 (Abilità Prassiche e della Coordinazione Motoria, second version) (Sabbadini, 2015). These motor tasks were selected to evidence the tendency to work slowly, the difficulties in dissociating movements, the balance deficit, the gait impairments and the lack of coordination in children with coordination disorders (Wilson et al., 2017). Accordingly, the motor tasks were divided into five parts, devoted to the: I. *global coordination*; II. *maintenance of balance*; III. *recovery of balance*; IV. *hands coordination;* V. *feet coordination*.

In particular, I. includes (Ia) *jumping jacks*, (Ib) *split jumping*; II. includes (IIa) *right leg stance*, (IIb) *left leg stance*; III. includes (IIIa) *walk on heels*, (IIIb) *frog jumping*; IV. includes (IVa) *rhythmic hands beat on legs*, (IVb) *rhythmic hands pronation-supination*; V. includes (Va) *rhythmic feet beat on floor*, (Vb, Vc) *rhythmic toe tapping heels* (Fig. 1).

The *jumping jacks* (Ia) and *split jumping* (Ib) are useful to evaluate the upper and lower limb coordination and the motor planning. For *jumping jacks*, children were asked to execute 10 jumps on the spot starting from the position of adducted-arms abducted-legs to vice-versa (abducted-arms, adducted-legs). In *split jumping*, the participants are requested to execute 10 jumps on the spot alternating left-arm/right-leg to right-arm/left-leg. *One leg stance* (II) requires to standing still for 20 s with arms outstretched at his/her sides, one leg raised and 90° bent. *Walk on heels* task (IIIa) consisted of a ten steps walk with toes raised, whereas *frog-jumping* task (IIIb) consists of five forward leaps with joined legs and stop-on-site at the end of the fifth leap. The hand (IV) and feet (V) coordination tasks were useful to assess inter-limb coordination, speed and rhythm. In rhythmic *hands beat on legs* (IVa) and rhythmic *feet beat on floor* (Va), the subject has to tap the hand/toes alternating 20 times the movement as fast as possible. Rhythmic *hands pronation-supination* (IVb) consists of turning the palm up and down alternately for 10 times as fast and as fully as possible. In rhythmic *toe tapping heels* (Vb, Vc) the subject had to alternatively and rhythmically 10 times tap heel and toe of the foot on the floor, mainly flexing the ankles.

2.4. Data analysis

For each task we defined several features which are reported in Table 2, according to the specific motor task.

2.4.1. Global coordination (I)

From *jumping jacks* (Ia) and *split jumping* (Ib) we extracted 12 features. The IMUs were placed on thighs, arms and hips to gather the orientations and accelerations of the joints. Each jump is considered correctly executed when the movements of the arms are synchronized with the thighs (for example, in *jumping jacks* the thighs-abduction must be simultaneous with the arms-adduction). To evaluate the number of correctly executed jumps (*# correct jumps*), we extracted the time occurrence of the peak and valley from the abduction/adduction angle and flexion/extension angle of the upper and lower limbs, during the *jumping jacks* and *split jumping* task, respectively. The *i*-th jump is considered correctly executed if the time $t_1(i)$, corresponding to the peak/valley of the angle of the thigh, is between the time $t_2(i) \pm dt$ corresponding to the peak/valley of the angle of the arm. We computed the *mean* and *coefficient of variation* (CV) of the periods between the jumps to assess the velocity and the rhythm. The *Cartesian jerk (cart_jerk)*, defined as the time integral of the square of the magnitude of *jerk* (see Table 2) (Flash and Hogan, 1985), and the angular range of motion in the three directions, were used to assess the mobility and smoothness of the movements of the hips. The Cartesian jerk is an empirical measure of the quality of smoothness and can be seen as a measure of the ability to control and/or to decelerate motion and as such, has been related to stability (Chen et al., 2014; Mancini et al., 2012, 2011; Solomon et al., 2015). Finally, the root-mean-square (*RMS*) value of the modulus of the 3D accelerometer vector is computed for the four limbs.

2.4.2. Maintenance of balance (II)

During *one leg stance* (II), the IMUs were placed on arms, legs, feet and sternum. The time (*duration*) during which the subject was able to maintain one-leg balance (the other leg movement detected by the vertical acceleration of the IMU placed on the foot), was recorded. Taking a cue from the work of (Mancini et al., 2011), we computed the *cart_jerk*, the *mean velocity* and the *sway area* (i.e. the ellipse that encompasses 95% of the values of medial-lateral (ML) and anterior-posterior (AP) acceleration around their mean values), through the horizontal plane acceleration. We computed the *RMS* value of the module of the accelerations measured by the sensor placed on the support foot, to take into account the excessive movements, *index of unsteadiness*.

2.4.3. Recovery of balance (III)

During *walk on heels* task (IIIa), the IMUs were placed on ankles, feet and sternum. A stride detection algorithm was developed to automatically acquire gait information of each gait cycle from the filtered angular velocity signals along the ML axes, with the sensors placed on the ankles (Gnucci et al., 2018). Fig. 2 shows the temporal gait event detection as local minimum/maximum. Gait parameters include *stride time, stance time, swing time* (mean and CV). Data gathered from the IMU placed on sternum were used to calculate the *cart_jerk* and the *sway area*, and the trunk angular range of motion in pitch (*AP flexion*), roll (*ML flexion*) and yaw (*rotation*) axis. High values of these parameters suggest poor dynamic balance control during gait (Spain et al., 2012).

In the *frog-jumping* task (IIIb), the IMUs were placed on hips, thighs and feet. The number of jumps and the temporal parameters were obtained from the vertical acceleration signals of the sensor placed on the hips, assuming the x-axis aligned with the gravitational acceleration vector. The duration of each jump was calculated considering the acceleration peak due to the impact during landing, and determining the time interval between the two consecutive peaks. The IMU placed on hips was also used to compute the *cart_jerk* and the *RMS*, while the IMUs placed on the thighs were used to compute the *RMS* values of the accelerations.

2.4.4. Hands coordination (IV) and feet coordination (V)

The IMUs were placed on hands and arms during the hand coordination tasks (IV) and on feet and thighs during feet coordination tasks (V). The temporal parameters (mean and CV), related to the hand (IV) and feet (V) coordination, were extracted from the angular velocity measured by the sensors placed on hands/feet, the movements consisting of a rotation on the AP axis (except for pronation-supination (IVb) which is related to vertical axis). Coordination was assessed by evaluating the number of correctly alternated taps (*# taps*) verifying the expression: $t_1\ (k-1) < t_2\ (k) < t_1\ (k)$; where t_1 and t_2 represent the time vectors of the taps occurrences of the right and left limbs. Moreover we extracted the RMS values of the accelerations of the IMUs placed on hands, arms, feet and thighs.

3. Results

3.1. Questionnaire

Results of DCD questionnaire (DCDQ) (Table 1) attested that the patients presented motor difficulties. Results from WISC test excluded any intellectual deficit for both patients and controls.

Table 2
Parameters' description.

Parameter	Task	Description	M.U.
# Correct jumps	Jumping jacks	Number of jumps considered correctly executed, i.e. the movements of the arms are synchronized with the thighs. The i-th jump is considered correctly executed if the time t1(i) corresponding to the abduction of the thighs is between the time t2 (i) ± dt corresponding to the adduction of the upper limbs and vice versa.	–
# Correct jumps	Split jumping	Number of jumps considered correctly executed, i.e. the movements of the arms are synchronized with the thighs. The i-th jump is considered correctly executed if the time t1(i) corresponding to the flexion of the thigh is between the time t2(i) ± dt corresponding to the extension of the ipsilateral upper limb and vice versa.	–
# Jumps	Frog jumping	Number of consecutive jumps without long pauses between them (>1s). If the participant was not able to stop on-site at the end of the fifth leap, the following jumps are also counted.	–
# Of taps	Rhythmic hands beat on legs, rhythmic hands pronation-supination, rhythmic feet beat on floor, rhythmic toe tapping heels	It corresponds to the number of taps performed in an alternating pattern. To verify that the taps were alternated we checked the expression: t1 (k−1) < t2 (k) < t1 (k); where t1 and t2 represent the time vectors of the taps occurrences of the right and left limbs. In rhythmic hands pronation-supination task, we checked that time t1 (i) corresponding to the i-th pronation of the right hand is between the time t2(i) ± dt corresponding to the i-th supination of the left hand and vice versa.	–
Area	One leg stance, walk on heels	Sway area is the area spanned from anterior-posterior and medial-lateral acceleration. It is calculated as the ellipse area that encompasses 95% of values of medial-lateral and anterior-posterior acceleration around their mean values.	m^2/s^5
AP flexion	Walk on heels, jumping jacks, split jumping	Trunk angular range of motion in the anterior-posterior axis.	°
Duration	One leg stance	The number of seconds that the subject was able to maintain balance without touching the ground with the elevated leg	s
Cart_jerk	One leg stance, walk on heels, frog jumping, jumping jacks, split jumping	Sway jerkiness is defined as: $cart\_jerk = \frac{1}{2}\int_0^t \left(\frac{dAcc_{Ap}}{dt}\right)^2 + \left(\frac{dAcc_{ML}}{dt}\right)^2$ where Acc_{AP} stands for the acceleration in anterior-posterior direction and Acc_{ML} stands for the acceleration in medial-lateral direction.	m^2/s^5
Jumping time (mean and CV)	frog jumping, jumping jacks, split jumping	Mean and coefficient of variation of the jump duration	s
Mean velocity	One leg stance	Mean velocity is computed summing the distance between each point and dividing this over the total duration time. $\frac{1}{t} * \sum \sqrt{(Acc_{Ap}(n+1) - Acc_{Ap}(n))^2 + (Acc_{ML}(n+1) - Acc_{ML}(n))^2}$	m/s
ML flexion	Walk on heels, jumping jacks, split jumping	Trunk angular range of motion in the medial-lateral axis.	°
RMS	All	Root mean square of the 3D accelerometer vector.	m/s^2
Rotation	Walk on heels, jumping jacks, split jumping	Trunk angular range of motion in the vertical axis.	°
Stance time (mean and CV)	Walk on heels	Mean and coefficient of variation of the stance phase periods computed as: toe-off (n + 1) – heel-strike (n)	s
Stride time (mean and CV)	Walk on heels	Mean and coefficient of variation of the step duration periods computed as the time distance between two consecutive toe-off: toe-off (n + 1) - toe-off (n)	s
Swing time (mean and CV)	Walk on heels	Mean and coefficient of variation of the swing phase periods computed: heel-strike (n) – toe-off (n)	
Tapping time (mean and CV)	Rhythmic hands beat on legs, rhythmic hands pronation-supination, rhythmic feet beat on floor, rhythmic toe tapping heels	Mean and coefficient of variation of the periods between a tap and the next one.	s

3.2. Motor tasks

The Wilcoxon-Mann-Whitney test (level of significance: 0.05) was performed to investigate the differences between patients and controls. Tables 3–7 report mean values and standard deviations of each measure.

3.2.1. Global coordination (I)

During global coordination tasks (Table 3), (Ia) *jumping jacks* and (Ib) *split jumping*, patients, with respect to the control counterparts, performed in average with: higher CV jumping time [%] (Ia: 23.93 vs. 15.02, $p = 0.008$; Ib: 27.26 vs. 15.64, $p = 0.004$), lower number of correct jumps (Ia: 4.76 vs. 9.95, $p < 0.001$; Ib: 2.59 vs. 8.70, $p < 0.001$), higher trunk rotation (Ia: 36.51° vs. 21.76°, $p = 0.031$; Ib: 107.25° vs. 56.61°, $p = 0.002$) and, in the jumping jacks higher *cart_jerk* (Ia: 278.47 m^2/s^5 vs. 96.01 m^2/s^5, $p < 0.001$).

3.2.2. Maintenance of balance (II)

During maintenance of balance tasks, (IIa) right leg stance and (IIb) left leg stance (Table 4), patient demonstrated higher *cart_jerk* (IIa: 2.32 m^2/s^5 vs. 0.65 m^2/s^5, $p = 0.049$; IIb: 3.12 m^2/s^5 vs. 0.952 m^2/s^5, $p = 0.032$) and sway area (IIa: 1.99 m^2/s^5 vs. 0.49 m^2/s^5, $p < 0.001$; IIb: 2.90 m^2/s^5 vs. 0.86 m^2/s^5, $p = 0.002$).

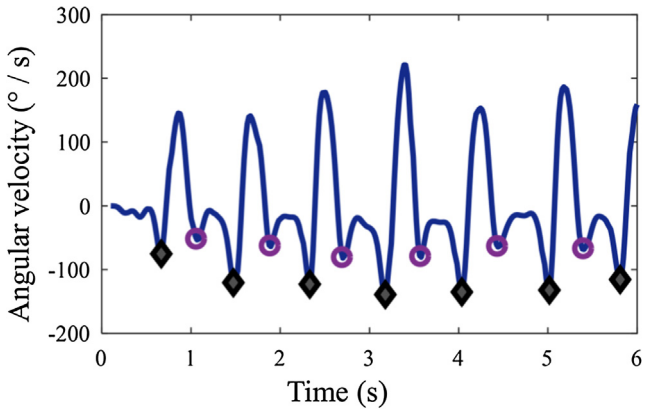


Fig. 2. Extraction of heel-off (◇) and heel strike (o) obtained from the application of the detection algorithm to the angular velocity along ML axis from the IMU placed on the ankle.

3.2.3. Recovery of balance (III)

For (IIIa) *walk on heels*, all the temporal parameters of gait (*stride time*, *stance time* and *swing time*) were not significant. On the other hand, the medial-lateral flexion (21.46° vs. 11.16°, $p < 0.001$) and rotation (37.31° vs. 23.10°, $p = 0.007$) of trunk resulted to be higher (Table 5).

For and (IIIb) *frog jumping*, patients demonstrated lower RMS acceleration (right thigh: 20.07 m/s^2 vs. 22.31 m/s^2, $p = 0.049$; left thigh: 19.20 m/s^2 vs. 22.38 m/s^2, $p = 0.006$), higher CV jumping time [%] (24.22 vs. 10.77, $p < 0.001$), duration (3.76 s vs. 2.98 s, $p = 0.001$) and number of jumps (6.35 vs. 5.10, $p = 0.003$).

3.2.4. Hands coordination (IV)

Hand coordination: (IVa) rhythmic hands beat on legs, (IVb) rhythmic hands pronation-supination (Table 6). In (IVa) patients performed with higher CV tapping time [%] (13.06 vs. 6.60, $p = 0.003$), lower number of taps (8.00 vs. 10.00, $p = 0.002$) and lower RMS acceleration (right hand: 14.62 m/s^2 vs. 17.59 m/s^2, $p = 0.009$; left hand: 14.59 m/s^2 vs. 12.49 m/s^2, $p = 0.022$). In (IVb) significant difference were found only in the number of taps (6.47 vs. 10.00, $p = 0.002$).

3.2.5. Feet coordination (V)

During feet coordination tasks (Table 7), (Va) rhythmic feet beat on floor and (Vb, Vc) rhythmic toe tapping heels, patients had higher CV tapping time [%] (Va: 17.03 vs. 7.18, $p < 0.001$; Vb: 31.01 vs. 15.58, $p < 0.001$; Vc: 42.30 vs. 23.62, $p < 0.001$) and lower number of taps (Va 7.12 vs. 9.70, $p = 0.007$; Vb: 6.00 vs. 9.30, $p = 0.005$; Vc: 5.88 vs. 9.37, $p = 0.001$).

4. Discussion

We explored different aspects of the motor coordination in order to provide new parameters aimed at objectively supporting the clinical evaluation of DCD/ADHD motor impairments. Our results demonstrated new findings on four main topics: *static balance*, *dynamic balance*, *inter-limb coordination,* and *timing*.

One leg stance task (IIa, IIb) was used to assess the *static balance*. We used IMU data in particular focusing on two motor features related to a "poor" static control: the *sway area* and the *cart_jerk*. The first was related to the effectiveness of the postural control system; the latter was considered as an empirical measure of the quality of smoothness. The ADHD/DCD subjects respond with quicker movements than the control counterparts in trying to maintain the equilibrium, a result consistent with findings in (Mao et al., 2014). In addition, we found that the patients tend to spend more energy, evidenced by the "larger" area they cover, a result which is consistent with (Buderath et al., 2009) and (Tsai et al., 2008). Fig. 3 shows the comparison between the accelerations in the AP and ML directions of a healthy subject and a patient.

Walk on heels task (IIIa), *frog jumping* (IIIb), *jumping jacks* (Ia) and *split jumping* (Ib) were useful to evaluate the dynamic balance, regarding which it is known that DCD children present less uniform muscular activity in motor control strategies than their healthy peers (Fong et al., 2012). Consistently, we observed lower RMS values in measuring the acceleration of the thighs during *frog jumping* task (IIIb). Such lower values may suggest poorer muscle strength and subsequent less efficiency, given the difficulty in stopping during landing, highlighted by higher number of the jumps required. Children with motor impairments often lacks of precise postural and balance control driven by anticipatory adjustments. In this respect, a detailed examination of the motion of the center of mass and gait pattern clarified what is the amount of impairment in dynamic balance for ADHD/DCD children. Results from *jumping jacks* (Ia), *split jumping* (Ib), and *walk on heels* task (IIIa) showed higher trunk range of motion as expected (Deconinck et al., 2010). Conversely, we didn't observed relevant information in temporal parameters of gait as in (Wilmut et al., 2016) and (Woodruff et al., 2002).

Children with ADHD/DCD demonstrated difficulties for *inter-limb coordination*, in some movement dissociation and poorer accuracy, as partially evidenced in (Wilson et al., 2017) and (Tallet et al., 2013). *Global coordination* (Ia, Ib), *hands coordination* (IVa, IVb) and

Table 3
Differences between patient and control subjects in kinematic variables for global coordination tasks: jumping jacks (Ia) and split jumping (Ib).

Task	Measure	Mean ± SD Patients		Mean ± SD Control		P-value	
		Ia	Ib	Ia	Ib	Ia	Ib
	**# Correct jumps**	4.765 ± 4.617	2.588 ± 4.017	9.950 ± 0.224	8.700 ± 2.849	**<0.001**	**<0.001**
	Mean jumping time (s)	1.887 ± 0.639	1.980 ± 0.811	1.549 ± 0.475	1.973 ± 0.892	0.124	0.751
	CV jumping time (%)	23.928 ± 10.687	27.259 ± 11.480	15.021 ± 4.622	15.644 ± 10.957	**0.008**	**0.004**
	Cart_jerk (trunk) (m^2/s^5)	278.474 ± 148.200	178.907 ± 145.416	96.013 ± 53.907	159.350 ± 83.094	**<0.001**	0.985
	RMS Acc (trunk) (m/s^2)	6.662 ± 2.112	6.750 ± 2.308	5.333 ± 1.682	6.747 ± 1.854	0.090	0.842
 (Ib) split jumping	**ML flexion (trunk) (°)**	14.820 ± 3.584	22.884 ± 8.527	10.845 ± 4.151	20.934 ± 6.551	**0.007**	0.651
	AP flexion (trunk) (°)	41.382 ± 10.690	40.393 ± 16.264	30.625 ± 7.866	34.400 ± 13.258	**0.018**	0.270
	Rotation (trunk) (°)	36.511 ± 29.173	107.253 ± 59.858	21.756 ± 4.636	56.610 ± 11.526	**0.031**	**0.002**
	RMS Acc (right thigh) (m/s^2)	18.269 ± 1.759	16.531 ± 2.776	18.897 ± 2.728	18.742 ± 3.319	0.703	**0.053**
	RMS Acc (left thigh) (m/s^2)	18.388 ± 1.695	16.799 ± 2.496	18.429 ± 2.728	18.849 ± 3.831	0.796	0.070
	RMS Acc (right arm) (m/s^2)	15.085 ± 2.086	13.858 ± 3.658	15.786 ± 2.789	14.830 ± 2.161	0.658	0.542
	RMS Acc (left arm) (m/s^2)	15.201 ± 2.325	14.606 ± 2.453	15.767 ± 2.797	14.740 ± 2.204	0.726	0.939

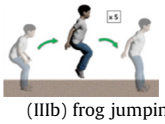
Bold values highlight a level of significance (P-value) less than 0.005.

Table 4
Differences between patient and control subjects in kinematic variables for maintenance of balance tasks: right leg stance (IIa) and left leg stance (IIb).

Task	Measure	Mean ± SD Patients		Mean ± SD Control		P-value	
		IIa	IIb	IIa	IIb	IIa	Iib
 (IIa) right leg stance	**Duration (s)**	14.867 ± 5.691	15.220 ± 7.039	19.537 ± 1.429	19.641 ± 1.022	**0.003**	0.062
	Cart_jerk (trunk) (m^2/s^5)	2.316 ± 2.593	3.124 ± 3.970	0.654 ± 0.326	0.952 ± 1.149	**0.049**	**0.032**
	Mean velocity (trunk)	0.223 ± 0.421	0.383 ± 0.687	0.102 ± 0.081	0.147 ± 0.202	1.000	0.055
 (IIb) left leg stance	**RMS Acc (trunk) (m/s^2)**	2.389 ± 0.772	3.089 ± 1.264	2.405 ± 0.772	2.189 ± 0.875	1.000	**0.024**
	Sway area (m^2/s^5)	1.988 ± 1.705	2.897 ± 3.556	0.494 ± 0.521	0.856 ± 1.257	**<0.001**	**0.002**
	RMS Acc (foot) (m/s^2)	2.949 ± 1.227	3.649 ± 2.042	2.197 ± 0.885	2.164 ± 0.943	0.070	**0.006**

Bold values highlight a level of significance (P-value) less than 0.005.

Table 5
Differences between patient and control subjects in kinematic variables for recovery of balance tasks: walk on heels (IIIa) and frog jumping (IIIb).

Task	Measure	Mean ± SD Patients	Mean ± SD Control	P-value
 (IIIa) walk on heels	**Mean stride time (s)**	0.951 ± 0.208	0.960 ± 0.187	0.960
	Mean stance time (s)	0.470 ± 0.115	0.474 ± 0.099	1.000
	Mean swing time (s)	0.484 ± 0.102	0.486 ± 0.101	1.000
	CV stride time (%)	15.321 ± 8.260	11.811 ± 5.596	0.250
	CV stance time (%)	19.077 ± 8.427	17.109 ± 9.036	0.453
	CV swing time (%)	25.564 ± 13.090	15.690 ± 5.430	0.052
	Cart Jerk (trunk) (m^2/s^5)	14.351 ± 10.842	16.724 ± 18.005	0.786
	Sway area (m^2/s^5)	5.230 ± 1.577	7.343 ± 7.266	0.899
	ML flexion (trunk) (°)	21.464 ± 9.536	11.161 ± 3.925	**<0.001**
	AP flexion (trunk) (°)	24.409 ± 13.281	16.364 ± 5.237	0.055
	Rotation (trunk) (°)	37.312 ± 16.861	23.102 ± 6.188	**0.007**
 (IIIb) frog jumping	**# jumps**	6.353 ± 1.656	5.100 ± 0.308	**0.003**
	Mean jumping time (s)	0.632 ± 0.210	0.596 ± 0.123	0.843
	CV jumping time (%)	24.222 ± 10.004	10.773 ± 6.680	**<0.001**
	Cart Jerk (trunk) (m^2/s^5)	191.040 ± 132.894	227.422 ± 194.950	0.871
	RMS Acc (trunk) (m/s^2)	8.888 ± 1.882	9.056 ± 2.786	0.899
	RMS Acc (right thigh) (m/s^2)	20.066 ± 3.184	22.314 ± 3.379	**0.049**
	RMS Acc (left thigh) (m/s^2)	19.199 ± 2.791	22.384 ± 3.633	**0.006**

Bold values highlight a level of significance (P-value) less than 0.005.

Table 6
Differences between patient and control subjects in kinematic variables for hands coordination tasks: rhythmic hands beat on legs (IVa) and rhythmic hands prono-supination (IVb).

Task	Measure	Mean ± SD Patients		Mean ± SD Control		P-value	
		IVa	IVb	IVa	IVb	IVa	IVb
 (IVa) rhythmic hands beat on legs	**# Taps**	8.000 ± 2.761	6.471 ± 4.557	10.000 ± 0.000	10.000 ± 0.000	**0.002**	**0.002**
	Mean tapping time (s)	0.634 ± 0.196	1.264 ± 0.581	0.625 ± 0.144	1.100 ± 0.293	0.915	0.726
	CV tapping time (%)	13.057 ± 10.461	14.462 ± 14.935	6.604 ± 3.005	7.067 ± 2.605	**0.003**	0.148
 (IVb) rhythmic hands prono-supination	**RMS Acc (right hand) (m/s^2)**	14.625 ± 2.664	13.082 ± 2.750	17.588 ± 3.193	12.148 ± 1.960	**0.009**	0.428
	RMS Acc (left hand) (m/s^2)	14.594 ± 2.842	13.450 ± 3.328	16.986 ± 2.888	12.490 ± 2.075	**0.022**	0.612
	RMS Acc (right arm) (m/s^2)	9.930 ± 0.150	9.976 ± 0.277	9.909 ± 0.286	9.957 ± 0.180	0.796	0.615
	RMS Acc (left arm) (m/s^2)	10.019 ± 0.175	10.096 ± 0.223	10.006 ± 0.115	9.986 ± 0.158	0.915	0.053

Bold values highlight a level of significance (P-value) less than 0.005.

feet coordination (Va, Vb) exercises were useful to objectively evidence this assertion. Here, patients were able to perform a reduced number of jumps/taps with respect to their healthy counterpart. We found the *jumping jacks* and the *split jumping* to be the exercises with the higher informative content where, in particular, the average number of correctly executed jumps is lower than the half of the required. Meaningfully, the patients demonstrated trouble in dissociating the movements of their upper limbs from the lower limbs. The overall performance of the inter-limb coordination tasks shows a lack in the ability to inhibit a particular response, to develop a plan of action sequences, and to hold a mental representation of the task. As an example, Fig. 3 evidences the asynchrony of the movements of the upper and lower limbs in a patient during split jumping task.

Table 7
Differences between patient and control subjects in kinematic variables for feet coordination tasks: rhythmic feet beat on floor (Va), right rhythmic toe tapping heels (Vb), and left rhythmic toe tapping heels (Vc).

Task	Measure	Mean±SD patients		Mean±SD control		P-value	
 (Va) rhythmic feetbeat on floor		Va		Va		Va	
	# taps	7.118 ± 3.822		9.700 ± 1.342		**0.007**	
	Mean tapping time (s)	0.716 ± 0.200		0.748 ± 0.120		0.594	
	CV tapping time (%)	17.033 ± 12.088		7.175 ± 3.870		**<0.001**	
	RMS Acc (right foot) (m/s^2)	11.905 ± 1.351		12.439 ± 1.900		0.568	
	RMS Acc (right foot) (m/s^2)	11.628 ± 1.263		12.250 ± 1.373		0.106	
	RMS Acc (right thigh) (m/s^2)	9.747 ± 0.292		9.965 ± 0.208		**0.037**	
	RMS Acc (left thigh) (m/s^2)	10.077 ± 0.676		9.936 ± 0.196		**0.022**	
 (Vb) right rhythmic toe tapping heels		Vb	Vc	Vb	Vc	Vb	Vc
	# taps	6.000 ± 3.873	5.882 ± 3.706	9.300 ± 1.490	9.368 ± 1.342	**0.005**	**0.001**
	Mean tapping time (s)	1.099 ± 0.328	1.075 ± 0.336	1.146 ± 0.194	1.123 ± 0.227	0.241	0.466
 (Vc) left rhythmic toe tapping heels	**CV tapping time (%)**	31.007 ± 11.640	42.297 ± 14.198	15.584 ± 8.366	23.624 ± 12.248	**<0.001**	**<0.001**
	RMS Acc (foot) (m/s^2)	12.350 ± 1.984	11.963 ± 1.081	12.348 ± 2.476	12.222 ± 2.074	0.819	0.751
	RMS Acc (thigh) (m/s^2)	10.137 ± 0.675	10.281 ± 0.282	10.376 ± 1.285	10.376 ± 0.919	0.636	0.199

Bold values highlight a level of significance (P-value) less than 0.005.

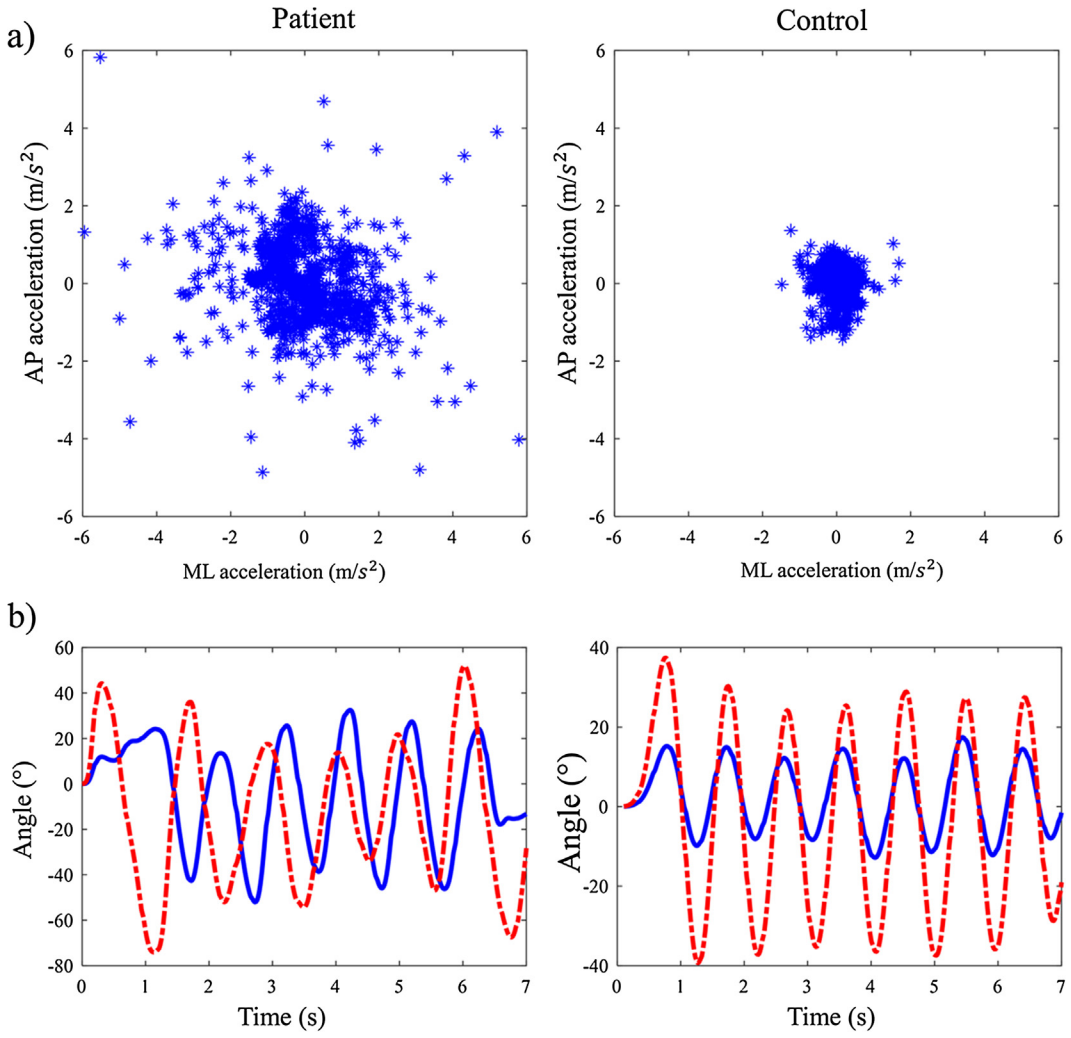


Fig. 3. (a) Acceleration values in the horizontal plane for a control subject (right) and a patient (left) during right leg stance. Patient shows larger sway area. (b) Flexion/extension movement of the arm (red dotted trace) and the thigh (blue trace) during split jumping in a control subject (right) and patient (left). It is possible to see that the patient's movement of arm and thigh are not synchronized. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Finally, the *timing* among all the tasks (involving hand/feet movements and jumping) added information with respect to a previous work focused on the bilateral hand tapping only (Geuze and Kalverboer, 1994; Roche et al., 2016, 2011). Our results show that patients do have timing deficit in term of rhythm (the coefficient of variation of execution time is roughly double in all task), but not in term of speed (mean execution time is comparable between the two groups) as elsewhere reported in DCD children (American Psychiatric Association, 2013).

As pointed out in (Kaplan et al., 1998), ADHD/DCD profiles may differ from child to child, depending on the "weight" of ADHD and DCD singularly. The deficit in motor coordination can invest any motor skill or, more selectively, may be present only in one area; for example, gross-motor skills excluding fine motor skills or static and dynamic equilibrium. So, what is the minimum number of motor tasks that the child should be evaluated for? Our conclusion is that quantitative tests that cover a wide range of motor coordination tasks should be used and not limited only in one area. Particular consideration should be given to the exercises focused on balance (e.g. *maintenance of balance* (II) and *recovery of balance* (III)) and coordination between limbs (e.g. one task from global coordination (I) and one task from feet coordination (V)).

5. Conclusion

DCD and ADHD present a high rate of overlapping in school-aged children, who suffer from impaired motor skills in terms of poor coordination, poor postural control and motor clumsiness.

Currently, there is no objective assessment of motor skills impairments in DCD/ADHD children, since it is mainly based on experienced practitioners. Therefore, a quantitative criterion can be appropriate, to better fulfill an objective rate of the disorder, in view of developing a more effective personalized rehabilitation program.

Our work, which represents a first step to objectively assess motor coordination impairments, demonstrated that such a quantitative criterion can be obtained by data gathered by a network of IMUs and by focusing on specific features selected from the measurements of different motor tasks. Results objectively showed the difficulties of ADHD/DCD subjects related to inter-limb coordination, movement dissociation, visible balance deficits, and poor timing.

We could not assess the "fine" motor skills due to the dimensions of the IMUs. Nevertheless as far as we know our work represents a first deep investigation to objectively assess motor coordination impairments, in school-aged children, by means of a network of IMUs.

Conflict of interest statement

The authors have no conflict of interest to declare.

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