Is there a specific motor signature of autism? Exploratory studies from human-machine interaction

***Abstract*—Autism spectrum disorder (ASD) is a heterogeneous group of neurodevelopmental disorders whose core symptoms are impairments in socio-communication and repetitive interests and stereotypies. Although motor impairments are not cardinal symptoms per se, many children with ASD have postural and motor coordination disabilities. Here, we investigate them dynamically through human-machine interaction, analysing data previously collected during two experiments: a joint attention (JA) task involving a human-robot interaction with children with ASD and typically developing (TD) controls; a motor imitation task involving a tightrope walker avatar (TW), children with ASD, with developmental coordination disorder (DCD) and TD children. Participants were recorded using RGB and RGB-D cameras, allowing for the extraction of kinematic and spectral features. Movement Power Spectral Density analysis demonstrated that children with ASD displayed more energetically costly behaviors across all frequencies when contrasted with TD children (both experiments) and children with DCD (TW experiment). These findings affirm the distinct motor complexity of children with ASD, suggesting the presence of a unique motor signature potentially different from that observed in children with DCD.**

***Index Terms*—Autism Spectrum Disorder, Motor Signature, Smoothness, Power Spectral Density, Human-Machine Interaction**

I. INTRODUCTION

Although motor impairments are not cardinal symptoms of autism spectrum disorder (ASD) [1], many children with ASD have postural and motor coordination disabilities [1]–[3]. They show impaired performance in all fundamental movement skills [4], in skilled motor tasks [5], in motor control [6], [7], posture and balance [8], motor synchronization [9], motor imitation [10]. Motor impairments in autism have been linked to atypical movement kinematic, understood in terms of either micro-movements or sub-movements. Sub-movements are subtle accelerations and decelerations during movement production, related to intermittent control [11], [12]. When a movement is composed of a few sub-movements, it appears smoother [13]. Micro-movements are fluctuations in movement kinematic in the reproduction of the same movement and are less organized [14]. Several studies described disruption in movement kinematic in ASD [14]–[21], identified a motor signature allowing for automatic classification [22]–[24], or gave a predictive value of early motor dysfunction [25].

Although the underlying cause of motor skill impairments in ASD is open to debate, there is a scientific agreement that their quantitative observation is useful to build tools for the diagnosis of ASD [14], [25]. Knowing that motor skills underpin social engagement, emotional expression, and cognitive development, the understanding of these impairments is a target for the development of early interventions [26], [27]. Additionally, it remains difficult to ascertain if these motor impairments are specific to ASD [28], i.e., could constitute a motor signature, in comparison to other neurodevelopmental disorders such as Developmental Coordination Disorder (DCD) which are highly frequent in ASD and characterized by poor movement skills [29]. Few studies have explored the differences in terms of micro-instabilities between DCD and typically developing (TD) children. Comparisons of movement smoothness between DCD children and TD children while reaching for a target [30], drawing [31], [32], throwing a ball [33], and pedaling [34] have provided contrasting results: significant differences can be found for some tasks, but not for all.

In the last decade, automated and semi-automated movement impairment characterisation has gained significant attention thanks to advancements in hardware and innovative machine learning based algorithms [35]. The use of RGB-D sensors, such as Microsoft Kinect and Intel RealSense, and deep-learning based methods, such as OpenPose or Google's MediaPipe, has rapidly become the standard to detect and track human movements in real-life scenarios. Unlike traditional methods such as marker-based motion capture systems or pressure plates, which require controlled experimental settings, these perception systems enable the observation of human behaviors in naturalistic environments with a commendable level of accuracy.

Concurrently, alongside these ecologically valid perception systems, novel metrics have been devised to investigate typical motor behavior, sub-movements, and motor impairments. In this paper, we explore the use of ecological perception systems to analyse movement kinematic in neurodevelopmental disorders in terms of smoothness, kinematic features and movement power spectral density (MPSD), during two human-machine interaction tasks: the first using a Nao robot to elicit joint attention (JA) and the second featuring a tightrope walker avatar (TW) to dynamically explore motor imitation. We selected these two experimental tasks as they involve basic building blocks of social interaction, joint attention and imitation, respectively. These tasks require children to perform movements that are inherently social in nature. By focusing on the production of such socially relevant movements, we aim to explore motor functioning during social interactions in children with ASD and how it may differ in children with DCD. This distinction is supported by previous studies comparing movement production in ASD and DCD, which have highlighted the particular relevance of socially oriented movements in differentiating between the two groups [36]. Furthermore, since the proposed tasks involve actions performed with different body parts, specifically the head and arms, they allow the identification of movement characteristics in ASD that may generalize across contexts. Utilizing robots and virtual agents to elicit behaviors in children holds particular convenience in this context. These interactive platforms can be programmed to exhibit high predictability, focusing on particular tasks or aspects of interaction. This simplifies the complexity of interpersonal communication, consequently reducing the cognitive load necessary to interpret these interactions [37].

With the aid of this experimental platform, we propose the existence of a shared motor signature across the two tasks, characterized by reduced smoothness and heightened frequency components as indicated by MPSD in children with ASD compared to TD and DCD children.

II. RELATED WORKS

Motor peculiarities in children with ASD have been documented in a number of scientific studies, literature reviews, and meta-analyses. Motor difficulties may concern up to 80 to 90% of children with ASD [38]–[40], and are present in both genders, although gender related nuance may be observed [41]. These motor differences notably encompass atypical development and impairments of gross and fine manual dexterity [38], [42]–[44], including handwriting [45]; as well as oromotor skills [46]; balance [8], [38], [44], [47]–[51] and gait [52], [53], impacting global motor performance [54]. Motor difficulties in children with ASD are both pervasive and clinically significant, affecting their life habits and independence [55], [56]. However, only a small percentage of children with ASD receive targeted treatment for their motor difficulties, as such impairments are often under-recognised and left untreated [40], [57].

Motor differences have also been identified in very young children (less than 2 years old, and as early as 6 months old) even before they receive a diagnosis of ASD [40]. Young children who will go on to later be diagnosed with ASD display altered gross and fine motor skills [58]–[60], in particular in the field of object exploration and manipulation [61]; delays in sitting, standing, and walking; and a more restricted repertoire of spontaneous movements [62]. These motor differences may, in turn, prevent these very young children from fully benefiting from the interaction opportunities offered by their environment, limiting their motor training and potentially impacting the development of their social communication skills [61]. They could also serve as an early marker of ASD [62].

In adults with ASD, motor differences continue to be present [63]. Adults with ASD display atypical walking patterns, altered balance and impaired manual dexterity [64]. Adults with ASD perceive their motor differences as pervasive, negatively affecting many aspects of their life, notably their social interactions, and requiring effortful adaptation and the development of coping strategies [65].

In the DSM-5 [29], atypical motor skills are described as an associated feature of ASD, indicating a likely co-occurrence but distinguishing them from the core symptoms of the condition (Zampella et al., 2021). However, the pervasiveness, clinical impact, and the lifelong presence of motor impairments in individuals with ASD led to a debate regarding whether they should rather be included as a diagnosis criterion or a specifier for ASD [66], [67]. Defenders of this inclusion argue this could lead to more routine assessment of motor abilities in individuals with ASD [68] and thus improved treatment plans [69], [70], but, to date, the status of motor impairments related to ASD in the DSM remains unchanged.

Moreover, the severity of motor skills impairments in children with ASD is correlated to the severity of various ASD symptoms and clinical manifestations. Notably, less severe ASD symptoms are associated with better motor skills [56], [66], [71], [72]. Several studies also established a correlation between motor skills and IQ scores in ASD, as in this case, ASD children with cognitive impairments exhibit more serious motor difficulties [40], while increased difficulties with manual dexterity and balance are associated with lower IQ scores [73]. Furthermore, motor impairments correlate with executive functions [74], in particular working memory and inhibition [75].

However, most of the research on the association between symptom severity and degree of motor impairments in ASD focuses on social interaction. Wang et al.'s meta-analysis [44] identified a correlation between altered gross motor skills and impaired social skills in children with ASD, whereas Ohara et al.'s systematic literature review [76] highlighted a highly likely association between social and motor skills in ASD, with a stronger association between fine motor skills and social abilities. Similar results were obtained in toddlers with ASD, in which both fine and gross motor skills impairments are correlated with social communicative skills deficits [77]. Altered fine motor skills and motor developmental delays in children with ASD have also been found to be associated with challenged verbal abilities [78], [79].

These correlations led researchers to advocate for an increased focus on how motor skills are linked to the development of social communication and adaptive and cognitive functioning, suggesting that motor skills are fundamental in human development [40]. Following this approach, longitudinal studies are particularly relevant to explore the mutual relationship between ASD symptoms and motor deficits. An example of such a longitudinal study is offered by the ELENA Cohort, which evaluated the evolution of motor and social skills in children with ASD over 3 years, identifying that children with greater motor difficulties displayed less favorable developmental trajectories in social skills acquisition, thus providing support to the idea of a negative impact of motor impairment on social skills development [80].

A. *Challenges and limitations*

Despite numerous studies supporting the idea of motor impairments in children with ASD, the research field on this topic is facing several challenges. Mainly, there is a lack of consensus on the specific characteristics of motor atypicalities in ASD [40].

1) Do movement impairments in ASD differ from movement impairments in other neurodevelopmental disorders?: It is not yet fully clear how the patterns of motor impairments identified in children with ASD are specific to ASD compared to other neurodevelopmental disorders, in particular DCD and ADHD [61], [69], in which motor impairments are also observed [81]. A meta-analysis focusing on very young children who would later gain a diagnosis of ASD, ADHD or DCD identified that children from all neurodevelopmental groups displayed delays in motor skills acquisition when compared to typically developing children, with children with ASD presenting with the most important delays [82].

Comparison of motor skills between children with ASD and children with ADHD elicits diverging results. De Francesco et al. [83] compared motor performances of children with ASD, ADHD, and typically developing children thanks to the developmental coordination disorder questionnaire (DCDQ), the movement assessment battery for children 2 (MABC2), the sensorimotor subtests of NEPSY-II, and the kinematic analysis (velocity and acceleration, temporal characteristics of submovements, wrist inclination) of a reach-to-drop task. While clinical assessments raised differences between groups, it was not the case for the kinematic analysis, which did not allow for the differentiation of children with ASD, ADHD, or typically developing. In another study, Dionisio et al. [84] compared the motor performances of children with ASD and with ASD combined with ADHD through the Motor Competence Assessment (MCA). The presence of ADHD in addition to ASD did not lead to significant differences in terms of motor competence. Dewey et al. [85], on the other hand, investigated motor difficulties in children with ASD, DCD, and DCD combined with ADHD. In their study, only children with ASD displayed a global impairment in gestual performance.

Children with ASD and children with DCD may also have overlapping motor skills impairments [86], and the presence of undiagnosed DCD in children with ASD may be frequent, further complicating the distinction between ASD and DCD-specific motor difficulties. In a study comparing children with ASD, DCD, and typically developing children, Kilroy et al. [36] identified similar patterns of motor impairments in both the DCD and ASD groups, but differences in praxis and imitation. Paquet et al. [87] explored differences between ASD and DCD children in terms of motor abilities through a neuropsychological evaluation (NPMOT battery). They identified both similarities and differences between the groups, with children with ASD performing generally better than children with DCD. Miller et al. [88] focused on postural control in typically developing, ASD and DCD children and highlighted differences in how ASD and DCD children dynamically controlled their centre of pressure, a result consistent with Fears et al.'s study [48]. Exploring the kinematic characteristics of the movements produced during a colouring game, Butera et al. [89] were able to differentiate between ASD and DCD children. However, there is not yet a consensus regarding how motor difficulties in ASD and DCD are distinct [36], [90].

In the SPARK Cohort, which comprises data on more than 10 000 children with ASD, 85% of children with ASD have DCDQ scores putting them as 'at risk' for DCD, while only 14% have received a formal diagnosis of DCD in addition to ASD [70], [91]. This is consistent with the results obtained by Green et al. [92], who evaluated the presence of DCD in children with Asperger syndrome thanks to the MABC. Thus, some of the motor difficulties identified in ASD children could also be related to undiagnosed DCD. Accordingly, researchers highlight the pressing need for a better understanding of motor impairments in ASD and DCD, their potential overlap or specificities, and whether motor impairments in ASD indicate co-occurring DCD, or are related to autism alone [93]–[95].

2) Movement impairments characterization: Most studies investigating motor differences in ASD tend to rely on observational and clinical motor assessments, which may limit the identification and evaluation of subtle motor deficits, potentially invisible to the naked eye [62], [96]. The use of new technologies enabling ecological assessment of motor skills, along with novel metrics providing fine-grained measurements, would be a necessary step toward a better understanding of motor impairments in ASD [97], [98].

A few recent studies have proposed original metrics to assess the motor signature of autism. Krishnappa Babu et al. [99] used computer vision to evaluate the kinematic characteristics of toddlers' head movements (acceleration and sample entropy, an estimate of irregularity) while they watched movies on a tablet. They show that both head acceleration and entropy significantly differ in toddlers with ASD compared to typically developing toddlers. Butera et al. [89] explored motor kinematics (gesture area variance, gesture acceleration, gesture directness variance) from the recordings of an inertial movement unit (IMU) sensor and the touch screen of a tablet while ASD children performed a colouring game. Crippa et al. [41] investigated the kinematic characteristics (total duration of submovements, number of submovements, peak velocity and acceleration, timing of peak velocity and acceleration within submovement, deceleration) of children's movements during a reach-to-drop task. In this study, children's movements were recorded through a motion capture system. Relying on a Microsoft Kinect, Cho et al. [64] investigated motor specificities in adults with ASD while they were performing different motor tasks (standing, walking, stepping in place, jumping jacks, finger tapping) and explored the kinematic characteristics of the movements recorded (sway movement of trunk, sway velocity, speed, hip movement, arrhythmicity, asymmetry). Using an optoelectronic system, Bäckström et al. [42] asked children to grasp and fit a semi-circular peg into a goal-slot, and studied the motor kinematics (peak velocity, duration and number of submovements, timing of peak velocity) of the movements they produced. Also using an optoelectronic motion capture system, Emanuele et al. [100] assessed inter-joint coordination and motor synergies during a reaching-grasping task. Synergies participate in motor control and enable co-controlling redundant motor degrees of freedom (e.g. joint angles, muscles) by mapping behavioural goals into coordinated motor patterns. Children with ASD had reduced coupling between degrees of freedom compared to typically developing children, and machine learning classification based on reaching-grasping kinematics reached promising scores. Fears et al. [48] evaluated dynamic postural control by asking children to move a virtual ball following their centre of pressure to a target, and explored trial duration, path efficiency and smoothness based on the log dimensionless jerk, captured thanks to a motion capture system. Cook et al. [101] asked autistic adults and matched controls to trace a range of shapes on a tablet to explore the typical power law relationship that links movement speed and curvature. Autistic adults showed deviations from power law, and Fast Fourier transform further exhibited less precise modulation of speed oscillations around the target frequency.

As previously highlighted, the scientific literature exploring motor impairments in children with ASD faces two persistent challenges: (i) it is not clear how motor difficulties in ASD differ from those observed in other neurodevelopmental disorders, in particular DCD; and (ii) many research studies rely on observational and clinical motor assessment that may be less sensitive to subtle alterations in movement. This study aims to address both gaps by combining ecological perception systems with the analysis of kinematic features (speed, acceleration, jerk, dimensionless jerk, and log dimensionless jerk) and spectral analysis (movement power spectral density, SPARC) to explore subtle motor deficits in ASD, as well as a comparison of ASD with TD and DCD children's performances while completing the same tasks to explore the specificities of motor difficulties in ASD.

III. MATERIALS AND METHODS

A. Ecological perception of human movements

Technologies and algorithms focusing on ecological perception of human movements exploit markerless algorithms that try to estimate and track humans using bi-dimensional or three-dimensional invariants, producing numerical series representing the evolution in time of tracked human features [102]. These features span from the body's barycenter to the limbs position to the key-points of the face. The kind of information tracked varies in accord with the algorithm or the specific technology employed. While still far from the performances obtained using more complex marker-based approaches, these systems focus more on the ease of use and deployment on real-life context and the possibility of capturing unconstrained motion [35]. Manageable constraints of such systems are usually the light conditions of the environment or the overlaps while tracking several people [103].

1) Head movements: Face detection and head movements tracking system, such as OpenFace [104] or CLM based approaches [105], exploit facial invariants present on RGB data. In such cases, the depth information is usually absent: together with roll, pitch and yaw, angular information of head's movement defined in degrees or radians (Figure 1), returned face landmarks are usually defined as 2D coordinates in the (u, v) normalised pixel space of each elaborated image. Three-dimensional data can be obtained trivially by using RGB-D training sets [106] or can be estimated through triangulation from multiple views, using several calibrated RGB cameras conveniently placed in the environment [107]. Alternatively, this information can be retrieved through the explicit integration of depth information on the face landmarks models, as exemplified by the CLM-Z method [108], or, more recently, by transform-based approaches [109] that leverage deep-learning architectures for generating such information.

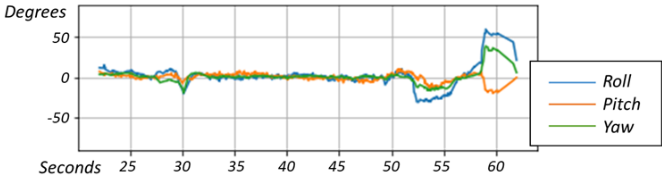

Fig. 1: Head data movements as captured by a CLM based algorithm on video data.

2) Body movements: Ecological people tracking systems are designed to detect and track localized body parts (Fig. 2), resulting in a wide range of retrieved information. RGB-D based systems, such as those offered by Microsoft Kinect [103] or Nuitrack [1], consistently provide three-dimensional data of human limbs and joints. Conversely, RGB-based systems such as OpenPose [110] can extract similar information but in the normalized 2D pixel space of detailed images. While three-dimensional information can be estimated using landmark data from various RGB cameras distributed throughout the environment [111], more recently, neural network-based models have been employed, as observed in BlazePose-based systems such as MediaPipe [112] [2] [113].

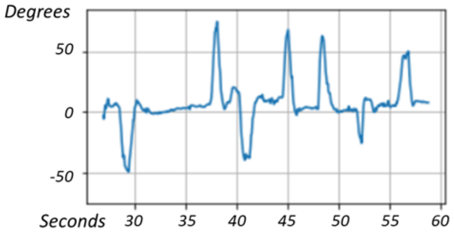

Fig. 2: Arm movements in an imitation game.

B. Movements features

The current state of the art characterizes movements based on their smoothness, a term referring to the fluidity and regularity of motion, marked by harmonious transitions and minimized irregularities [13]. These irregularities can be identified both in the time domain, through the analysis of kinematic features, and in the frequency domain.

1) Kinematic features: Speed, acceleration and jerk defined respectively as the first, the second and the third order derivative of the movement of a point in space can highlight coarse movements lacking in fluidity. These metrics can be readily computed from various sources, including head movements, joint angles of specific articulations, or by tracking specific

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[1] Nuitrack: https://nuitrack.com/

[2] Mediapipe https://developers.google.com/mediapipe

points of the body over time [102]. In the latter case, where tracked coordinates encompass the influence of human locomotion in space, metrics are typically calculated within a static, egocentric coordinate system centered on the body's barycenter.

Kinematic energy, defined as:

$$E(t) = \frac{1}{2}\sum_{i=0}^{N} M_i * x_i'(t)^2 + I_i * \alpha_i'^2 \tag{1}$$

with M_i and I_i, constants for each body part, representing respectively their mass and their inertia, and with $x_i(t)$ and $\alpha_i(t)$, representing for each body part their position in time their angle, respectively. This measure can be particularly useful to condensate the movements and rotations of each body part in a unique, insightful metric [37].

Valid jerk-based measures of the fluidity of movement are the dimensionless jerk (DLJ) and the log dimensionless jerk (LDLJ) [114], defined as:

$$\text{DLJ} \triangleq -\frac{(t_2 - t_1)^5}{v_{peak}^2}\int_{t1}^{t2}\left|\frac{d^2 v(t)}{dt^2}\right|^2 dt \tag{2}$$

$$\text{LDLJ} \triangleq -\ln|\text{DLJ}| \tag{3}$$

where $v(t)$ is the movement speed, t is time, t_1,t_2 are the start and end times of the movement, and $v_peak \triangleq \max_{t\in[t_1,t_2]} v(t)$ is the peak speed. Higher values of LDLJ measures are associated with smoother movements.

2) Spectral analysis: Frequency domain analysis offers valuable insights into movements by examining their spectral components. Irregularities and jerky motions within movements can be highlighted as high-frequency spectral components. Short-time spectral analysis can be conducted by computing spectrograms, achieved through Fourier transformation applied to a window sliding over the numerical series representing movement. This decomposition reveals the evolution over time of various frequency components within the movement, with the number of components dependent on the sampling rate. A specific case of frequency domain analysis is the Movement Power Spectral Density (MPSD, Fig. 3), where Fourier transformation is applied to the power of the movement time-series, representing the temporal evolution of movement power across different frequency bands.

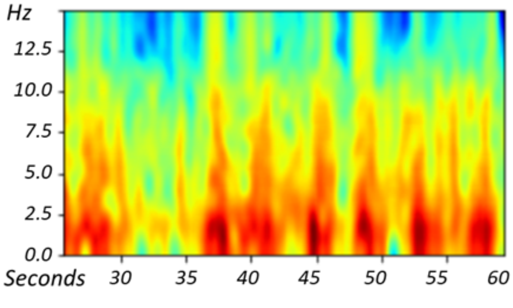

Fig. 3: MPSD of arm movements in an imitation game.

A valid Fourier transformation based measure to highlight fluidity and irregularities on the movements is the spectral arc length metric, SPARC [13]. The spectral arc length metric of movement smoothness is defined as negative arc length of the amplitude of the frequency-normalized Fourier magnitude spectrum of the movement speed profile:

$$\eta_{sparc} \triangleq -\int_0^{\omega_c}\left[\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2\right]^{\frac{1}{2}} d\omega \tag{4}$$

with:

$$\hat{V}(\omega) = \frac{V(\omega)}{V(0)} \tag{5}$$

and:

$$\omega_c \triangleq \min\{\omega_c^{max}, \min\{\omega, \hat{V}(r) < \overline{V} \quad \forall \quad r > \omega\}\} \tag{6}$$

where $V(\omega)$ is the Fourier magnitude spectrum of the first order derivative $v(t)$, $\hat{V}(\omega)$ is the normalized magnitude spectrum respect to the continuous magnitude component $V(0)$, and ω_c is adaptively selected based on a given threshold, with $\overline{V}$ upper-bound by ω_c^{max}. Higher values of SPARC measures are associated with smoother movements.

3) Movements segmentation and normalization: Aggregating motion data from multiple repetitions or trials of an experiment can yield valuable insights. However, in such cases, complex behaviors must be parsed and segmented into coherent and comparable movement instances. This segmentation process is essential for extracting meaningful patterns and trends from the aggregated data. While this can be done manually, the use of artificial agents to elicit behaviors can simplify their segmentation: synchronised log recordings of the agent, events, actions or states can be conveniently exploited as useful references to parse motions. Finally, further segmentation of movements can be achieved using supervised or unsupervised machine learning algorithms, leveraging the dynamic evolution of local features of the movements in time [115]. To ensure consistency in comparisons among parsed movements, extracted features should be normalized:

- **Mean** or **median** normalisation forces features to a common reference, centering the data around zero. This is particularly useful for establishing a common baseline for derivative features, such as a zero speed or a zero acceleration;
- **Z-score** removes the magnitude information of the features while preserving their shape. It centers them around zero and forces their standard deviation to 1. This can be useful, as instance, to compare movements of different size but with a common shape;
- **Integral scaling** normalizes features based on their integral. This methodology is particularly interesting, for example, to compare power spectral density distributions, as the MPSD, in an independent way to the absolute power level of the signal.

IV. CASE STUDIES

We explored the use of ecological perception systems to analyse movement from two experiments involving children with ASD interacting with a robot or an avatar. The first experiment elicited JA during an interaction with a Nao platform [20]. JA is a process in which two individuals share

	Experiment 1 - Joint attention		Experiment 2 - Tightrope walker imitation		
	ASD (N= 16)	TD (N=14)	ASD (N=26)	DCD (N=17)[2]	TD (N=39)
Age, mean (SD), year	7.94 (±1.67)	8.06 (±2.49)	12.65 (±3.66)	12.17 (±3.38)	11.95 (±4.08)
Male/Female	15/1	9/5	21/5	9/6	23/16
Developmental age, mean (SD)	7.47 (±2.9)	8.06 (±2.49)	11.75 (±5.08)	11.61 (±3.23)	11.95 (±4.08)
IQ[1], mean (SD)	89 (±18.2)	All >80	92.88 (±40.16)	95.4 (±26.5)	All >80
ADI-R scores, mean (SD)					
Social impairment	12.26 (±5.02)	Non relevant	14.87 (±6.86)	Non relevant	Non relevant
Communication	10.54 (±5.85)		10.04 (±5.35)		
Restricted interests	3.24 (±2.55)		3.83 (±3)		

ADI-R; Autism Diagnostic Interview – Revised version.

[1] Assessed with Wechsler Intelligence Scale for Children.

[2] Assessed with Movement Assessment Battery for Children: mean (standard deviation) total score=-1.49 (1.60)

TABLE I: Main characteristics of the participants. ASD: Autism spectrum Disorder; DCD: developmental coordination disorder; TD: children with typical development.

their gaze over the same focus of attention [116]. The second experiment was a dynamic imitation of a TW [117]. During both experiments, children's movements were recorded with an RGB camera and a Kinect. We developed algorithms to automatically extract kinematic features and MPSD from those recordings. Settings are described in figure 4 and 6.

A. Statistical analysis

Statistical analyses were performed using R Software, Version 4.1.2. The level of significance, alpha, was fixed at 5%. We assessed the following dependent variables using Generalized Linear Mixed Model (GLMM; lme4 & lmerTest packages): MPSD from 0-1 Hz to 8-9 Hz given Kinect resolution; movements' kinematic features (mean speed, acceleration, jerk, SPARC, and LDLJ). For experiment 2, the following explicative variables were entered in each model: age, group, and gender. These variables were chosen because they influence children's motor responses to the TW (50,54). Since variation in age and gender were very limited in experiment 1, the group was the only explicative variable entered. For each dependent variable, the normal distribution was checked. Variable transformations were conducted to reach normalization when needed.

B. Joint attention

Each child is introduced in the experimental room by a clinician and guided to establish a first contact with the robot, giving the child time for getting used to it as an interactive partner. Once comfortable, the child is then invited to stand in front of it. As shown in Figure 4, the robot then directs the child's attention to two targets, a picture of a cat and one of a dog, placed on each side of the room.

The robot progressively increases the amount of information conveyed to the child by using more modalities to communicate its focus: first through gazing, using head movements; then by combining gazing and pointing, using hands gestures; and finally by using gaze, pointing, and vocalization, as "look at the cat/dog". For the presented analysis, only the final interaction sequence (gaze + pointing + vocalization) was considered, as it was the only one performed similarly by both TD and ASD participants [20].

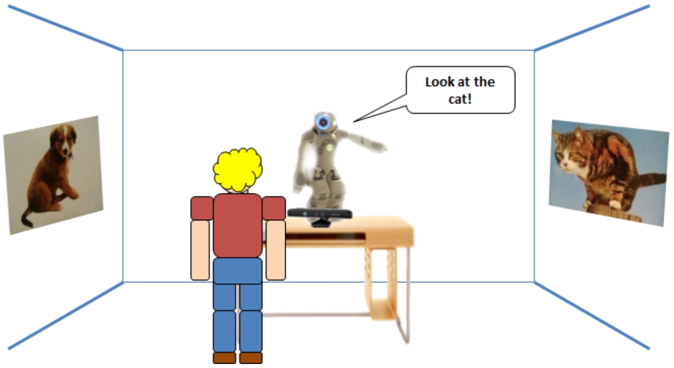

Fig. 4: The setup of the joint attention elicitation game, using a Nao robot.

Participants were recruited as part of the study described in [20], after obtaining parental signed informed consent and approval by local ethics committees. Participants' characteristics are summarized in Table 1. In this experiment , we compared 16 children with ASD and 14 TD children.

Figure 5.A shows the mean of all kinematic features of the head movements according to groups. The GLMM found several significant effects: jerk is significantly lower in ASD children compared to children with TD ($\beta = -0.702$, $SE = 0.284$, $p = 0.019$). LDLJ is significantly higher in ASD children compared to children with TD ($\beta = 0.712$, $SE = 0.314$, $p = 0.03$). Acceleration tends to be lower in ASD children compared to children with TD ($\beta = -0.508$, $SE = 0.279$, $p = 0.078$). However, we found no significant differences between groups for SPARC and speed. Figure 5.B shows children's MPSD during the experiment according to groups. The GLMM analysis revealed a significant difference between groups at all frequencies ($\beta \in [0.614; 0.724]$, $SE \in [0.217; 0.227]$, all $p < 0.001$), with individuals in the ASD group showing higher MPSD values than those in the TD group across the entire analyzed frequency range.

C. Tightrope walker imitation

The TW paradigm is an experimental setup allowing continuous motor imitation [118]–[120]. As shown in Figure 6, a 3D life-sized TW is walking on a rope, leaning alternatively on each side, holding a bar in front of him. Participants stood on a line prolonging the TW's rope, holding a bar in front

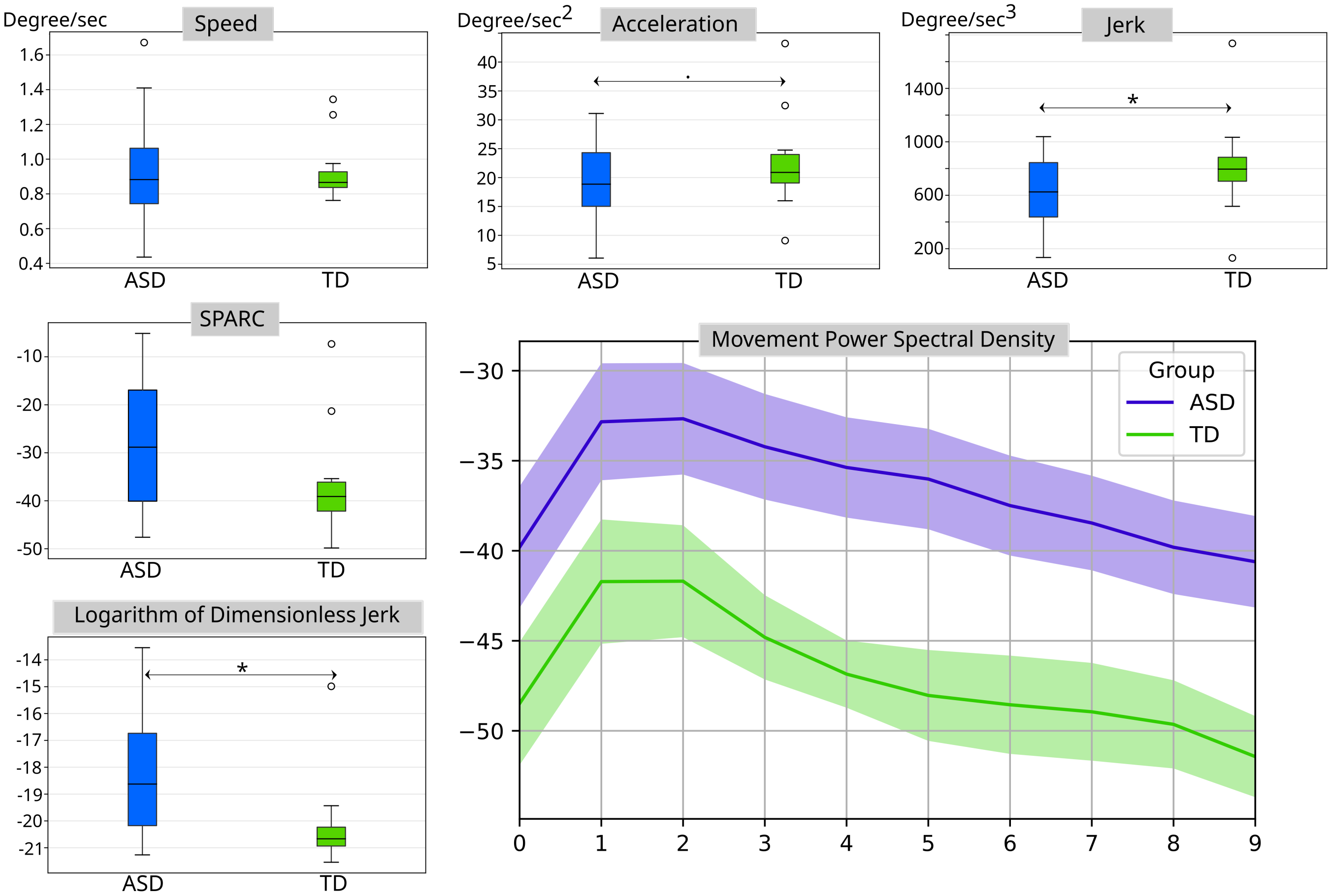

Fig. 5: Resuming motor instability during the joint attention task with Nao through kinematic features – speed, acceleration, jerk, SPARC, LDLJ – and through the movement power spectral density. .

of them. First, the TW is front-facing, standing still for 30 seconds. Then, during 7 trials, the TW, walking successively either forward or backward, is alternatively shown front-facing or back-facing. Participants are asked to imitate the leaning movements of the TW.

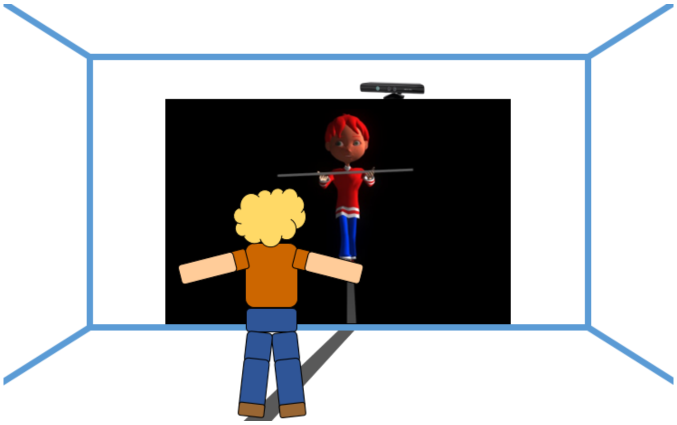

Fig. 6: The setup of the TW game, using a projected virtual agent.

Participants were recruited as part of the study described in [117], after obtaining parental signed informed consent and approval by local ethics committees. Participants' characteristics are summarized in Table 1. In this experiment , we compared 39 TD children, 26 children with ASD, and 17 children with DCD.

Figure 7.A shows the mean of all kinematic features according to groups. The GLMM found several significant effects: speed is significantly lower in TD and DCD children than in children with ASD (respectively, $\beta = -0.96$, $SE = 0.215$, $p < 0.001$; and $\beta = -0.99$, $SE = 0.272$, $p = 0.001$) as well as acceleration (respectively, $\beta = -0.865$, $SE = 0.224$, $p < 0.001$; and $\beta = -0.890$, $SE = 0.283$, $p = 0.003$) and jerk (respectively, $\beta = -0.826$, $SE = 0.227$, $p = 0.001$; and $\beta = -0.866$, $SE = 0.286$, $p = 0.004$). SPARC is significantly higher for TD children than children with ASD ($\beta = 0.453$, $SE = 0.182$, $p = 0.015$), with no significant differences between children with ASD and DCD. For all the proposed features, no significant differences were found between children with DCD and TD children. We found no significant differences between groups for LDLJ. Figure 7.B shows children's MSPD during the experiment according to groups. The GLMM revealed a significant difference at all frequencies between TD children and children with ASD ($\beta \in [-0.72; -0.88]$, $SE \in [0.205; 0.226]$, all $p < 0.002$), as well as between DCD and ASD children ($\beta \in [-0.828; -0.909]$, $SE \in [0.258; 0.286]$, all $p < 0.005$), with individuals in

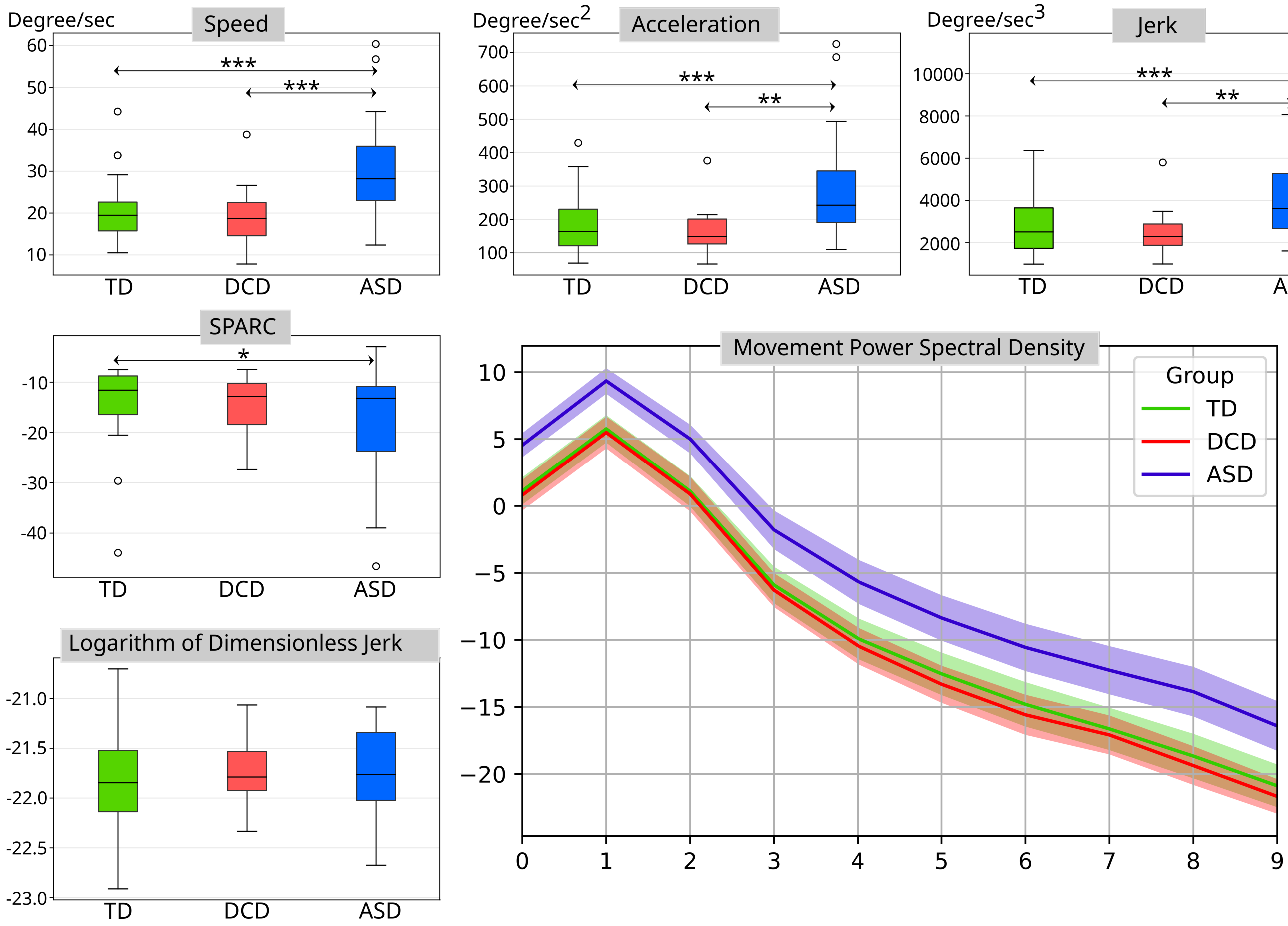

Fig. 7: resuming motor instability during the TW imitation with the virtual agent through kinematic features – speed, acceleration, jerk, SPARC, LDLJ – and through the movement power spectral density.

the ASD group showing higher MPSD values than those in the TD group and in the DCD group, across the entire analyzed frequency range. No significant differences were found between TD and DCD children.

V. Discussion

In this study, we investigated different motor characteristics - kinematic features and spectral properties - in children with ASD, DCD, or TD, across two socially interactive scenarios: a joint attention task and an imitation task. Our goal was to identify subtle motor atypicalities in ASD by comparing them to motor difficulties observed in DCD, highlighting how they may differ in these populations.

In the JA task, head movement data from TD children revealed more dynamic behavior compared to children with ASD. The higher jerk observed in TD participants may reflect faster and more frequent head reorientations in response to joint attention cues. In contrast, although movements in children with ASD are described by LDLJ as smoother, they tend to be more stationary, potentially indicating lower social responsiveness. This low responsiveness was observed in the movement amplitude in the ASD group [37], where such children performed smaller movements. Interestingly, the higher MPSD values observed in the ASD group suggest that, despite lower jerk values, their movements could be generally more energetically costly than those of TD children.

The results yielded by the JA task, focusing on head movement, are in partial accordance with Krishnappa Babu et al.'s results [99] . Studying autistic toddlers who were watching videos on a tablet, they also identified more complex head movements in ASD compared to TD. On the other hand, they identified higher acceleration in ASD, which was not the case in the proposed JA task. Similarly, Martin et al. [121] identified increased speed in the head movements performed by children with ASD while watching videos compared to TD children. However, the tasks performed in these two studies were slightly different compared to our JA attention task: watching a video generates head movements that are distinct from looking to your right or your left as in a joint attention task. This could help explain the partially diverging results.

In the TW task, children with ASD exhibited more dynamic profiles in terms of speed, acceleration, and jerk. Movements were described by SPARC as less smooth, reflecting a more complex, disorganized behavior. Deficits in motor imitation are well documented in ASD [10], [122], [123]. This result is in accordance with previously published studies, in particular the works of Cook et al. [15] who observed increased jerk, acceleration and velocity in the movements of adults with ASD, Yang et al. and Miller et al. [124], [125] who recorded less smooth movement (higher normalized jerk score) in children with ASD. However, Fukui et al. [126], on the contrary, did not find significant differences in terms of jerk and smoothness between TD and ASD young adults. As in the joint attention task, the higher MPSD values observed in the ASD group suggest that their movements may be more energetically costly than those of TD children.

Clinical assessment of autistic children usually fails to clearly answer whether motor problems in ASD are similar to that of DCD. In our study, children with DCD involved in the TW task showed a distinct movement profile compared to ASD, particularly in terms of speed, acceleration, jerk and MPSD, which appeared more similar to that of TD children. This pattern may reflect specific coordination deficits in DCD rather than the motor disorganization observed in ASD. A recent review and meta-analysis on the topic reports that the nature of motor and function problems in ASD were consistent with DCD; however, only three out of 20 papers (15%) that were published from 2014 described the motor problems as DCD [39]. Recently, using a reach-to-displace paradigm to clinically explore motor control, [127] found a preserved feed-forward control, but an impaired movement execution (atypical slowness) in children with DCD, while ASD children displayed the opposite pattern with an impaired feed-forward control, but a preserved feedback one. Importantly our results also show that kinematic features and MPSD for autistic children significantly differ from children with DCD's movements, making this motor characteristic potentially specific to children with ASD. These results are in accordance with the studies that underlined specificities of motor impairment in children with ASD compared to DCD [48], [85], [87]–[89], [127], [128]. Altogether, our results indicate a motor complexity with a distinct energetic profile in the movements of children with ASD compared to both DCD and TD children, as evidenced by higher MPSD intensities across all frequencies in both the JA and TW tasks. Thus, we believe that this exploratory study supports the existence of a motor signature in children with ASD.

This perspective aligns with recent research that has investigated the spectral features of movements to identify representative markers or recurring patterns of motor functioning. In particular, studies such as [129] and [130] have emphasized the potential of fine-grained spectral analysis for characterizing motor behavior in children with ASD across different scenarios. Our results contribute to this line of work by showing that children with ASD exhibit consistent spectral signatures across distinct social tasks, reinforcing the relevance of frequency-based descriptors for capturing meaningful aspects of motor atypicality.

Additionally, while we believe that our findings support the micromovement hypothesis proposed by some authors [14], their interpretation remains complex. The differences observed in movement descriptors across tasks underscore the importance of a multifactorial characterization of motor behavior in order to capture the specificity of motor impairments across different contexts. Moreover, it is difficult to determine whether the observed results can be generalized to everyday motor activities that do not involve human-machine interaction. The considerable variability in movement patterns among children with ASD, evident in both tasks, further reflects the heterogeneity that characterizes this condition. As a consequence, the limited sample size in this study (16 ASD and 14 TD children in the JA task; 26 ASD, 17 DCD, and 39 TD in the TW task), combined with the absence of DCD participants in the first experiment, emphasizes the importance of further investigations aimed at achieving broader generalization of these findings. Furthermore, while the use of a Microsoft Kinect enabled the exploration of naturalistic, social scenarios, it lacks the temporal resolution and spatial accuracy required for higher frequencies analysis. The use of wearable inertial measurement units (IMUs) [131] could provide more precise data, enabling a finer-grained characterization of motor impairments, particularly in the higher frequency ranges. Future studies should aim to validate and expand upon these findings by involving larger and more balanced cohorts of children with ASD, DCD, and TD, engaged in a broader set of everyday motor tasks, and employing more accurate motion capture technologies.

Although the present findings remain preliminary and call for further validation, they may inform future approaches to the early detection of motor difficulties in children with ASD. The intent of this study, in fact, is not to propose tools or activities ready for clinical application, but rather to contribute to the ongoing exploration of how movement analysis can help characterize motor atypicalities in ASD in a robust and interpretable way. The potential impact of motor impairments on cognitive and social development has led several authors to advocate for their early screening [14], [68] and intervention [26], [27]. In this perspective, identifying reliable motor descriptors, as the proposed one based on spectral features, may eventually contribute to the development of screening tools or intervention monitoring strategies. The tasks described in this study are relatively simple to implement and could, in principle, be considered in the context of early screening. However, further work is needed to determine which specific tasks, movement types, and neurodevelopmental profiles can be most effectively described by the proposed analysis. Establishing clear protocols and ensuring the use of accessible and replicable data collection methods will be essential for advancing this line of research.

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Ethics approval and consent to participate. Experiment 1 protocol was approved by the Pitié-Salpêtrière Hospital Ethics Committee. Experiment 2 protocol was reviewed and approved by the CERES (Comité d'Ethique de la Recherche en Santé) [N○ IRB: 20150700001072]. In both studies, all of the parents received information on the experiment and gave written consent before the participation of their child.

Consent for publication. Not applicable

Availability of data and materials. The datasets generated and/or analysed during the current study are available upon request to the authors.

Competing interests. The authors declare that they have no competing interests.

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Authors' contributions. SG and SA equally contributed to this article. SG, SA, JX and SB collected the data (Experiment 1 or 2) analyzed in this article. AB, MC and DC participated in the design of the experiments. SA created the algorithms allowing the extraction and the analysis of movements peculiarities. DC and SA analyzed the data. SG, DC and SA wrote the first draft. All authors contributed and revised the article.

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