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Postural and gait performance in children with attention deficit/hyperactivity disorder

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ABSTRACT

Up to 50% of children and adolescents with attention deficit/hyperactivity disorder (ADHD) exhibit motor abnormalities including altered balance. Results from brain imaging studies indicate that these balance deficits could be of cerebellar origin as ADHD children may show atrophy in those regions of the cerebellum associated with gait and balance control. To address this question, this study investigated postural and gait abilities in ADHD children and compared their static and dynamic balance with children with known lesions in the cerebellum.

Children diagnosed with ADHD according to DSM IV-TR diagnostic criteria were compared with children with chronic surgical cerebellar lesions and age-matched controls. A movement coordination test was used to assess differences in motor development. Postural and gait abilities were assessed using posturography, treadmill walking and a paced stepping task. Volumes of the cerebellum and the cerebrum were assessed on the basis of 3D magnetic resonance images (MRI).

Children with cerebellar lesions showed significant performance decrements in all tasks compared with the controls, particularly in the movement coordination test and paced stepping task. During dynamic posturography ADHD-participants showed mild balance problems which correlated with findings in cerebellar children. ADHD children showed abnormalities in a backward walking task and minor abnormalities in the paced stepping test. They did not differ in treadmill walking from the controls.

These findings support the notion that cerebellar dysfunction may contribute to the postural deficits seen in ADHD children. However, the observed abnormalities were minor. It needs to be examined whether balance problems become more pronounced in ADHD children exhibiting more prominent signs of clumsiness.

1. Introduction

Attention deficit/hyperactivity disorder (ADHD) is a developmental disorder characterized by inattentiveness, motor hyperactivity and impulsivity. ADHD is estimated to affect between 3% and 5% of children of primary school age [1]. According to the established clinical criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM IV-TR), there are three types of ADHD [2]: the predominantly hyperactive, the predominantly inattentive and the combined type. Although its aetiology remains unclear, its strong familial nature points to a genetic origin [3]. Besides behavioural deficits, approximately 50% of the children suffering from ADHD are reported to also show 'clumsiness', i.e. motor performance below the age norm [4,5].

Several studies suggest a strong association between developmental coordination disorder (DCD) and ADHD [6–8]. Although DSM IV-TR does not link DCD with ADHD, the disorders co-exist in about 50% of cases [9–11]. A shared, additive genetic component has been suggested between ADHD and DCD. Despite a large number of neuroimaging and neuropsychological studies on this subject, the neural basis of ADHD is unknown. Converging data suggest that ADHD symptoms may be secondary to abnormalities in fronto-striatal-cerebellar circuits [12].

Brain regions like basal ganglia and frontal lobes may reveal altered volumes in ADHD children [12]. There are further results from MRI studies showing volume reduction of the cerebellar

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vermis [13–16]. The cerebellar vermis is known to be crucial for postural and gait control [17]. Thus, the postural and gait disturbances in ADHD children may resemble those of ataxic patients with cerebellar disorders. However, no previous study has compared balance function in these two groups.

Consequently, this study set out to investigate the scale of postural and gait abnormalities present in ADHD and to examine whether those abnormalities are comparable to the postural deficits of children with cerebellar lesions. In order to examine motor development, participants performed a movement coordination test [18] and postural control was assessed using static and dynamic posturography. Gait abilities were investigated using gait analysis including treadmill walking. In addition, paced stepping was examined because movement timing is another important function of the cerebellum [19]. Finally, volumes of the cerebellum and the cerebrum were assessed based on 3D MRI.

2. Materials and methods

2.1. Participants

Ten boys with ADHD (mean age 12.3 ± 1.3 years; ADHD-group) treated as outpatients at the local Department of Child and Adolescent Psychiatry were tested. Seven children with chronic surgical cerebellar lesions following astrocytoma resection (mean age 12.3 years ± 2.5; four boys; CER-group) were selected from the database of the local Department of Neurosurgery, and eleven healthy control children (mean age 12.1 years ± 1.8; nine boys; CON-group) were recruited from the families of hospital staff and friends.

All ADHD-participants matched the DSM IV-TR diagnostic criteria for the combined type [2] and were treated with methylphenidate at the time of testing. None of the cerebellar children had received chemotherapy or cranial radiation. All participants underwent a neurological examination including the International Cooperative Ataxia Rating Scale (ICARS) [20]. The mean total ICARS-score was 1.5 (range 0–10) in ADHD-participants and 8.4 (range 1–14) in CER-participants [Total ICARS-score ranges from 0 (no ataxia) to 100 (severest ataxia)].

IQ testing (short version of the German WISC; [21]) was performed in all participants. The mean estimated IQ was 101.8 ± 16.2 in the ADHD-group, 94.6 ± 9.1 in the CER-group and 110.3 ± 9.2 in the CON-group ($p = 0.127$; one-way ANOVA).

For all CON and CER-participants, Conners' questionnaires for the assessment of ADHD were completed by their parents and teachers. One CER-participant showed increased values (Conners' parent total *T*-score 69, Conners' teacher total *T*-score 73). Two out of a total of initially 13 controls were excluded because of increased values in Conners' scales. Conners' scales were abnormal in all ADHD-participants before they were started on medication. Written informed consent was obtained from all children and parents. The local research ethics committee approved the study (ethics approval number 05-2672).

2.2. Brain MR-imaging

High-resolution 3D T1-weighted MPRAGE scans were obtained for each subject on a Siemens Sonata 1.5-tesla MRI scanner (TR = 2400 ms, TE = 4.38 ms, FOV = 256 mm, 160 slices, voxel size 1.0 mm × 1.0 mm × 1.0 mm).

In the CON and ADHD-participants, volumetric analysis of MR images was performed semi-automatically with the help of ECCET software (http://www.eccet.de/). Total cerebellar, cerebral (cerebellum excluded, TCV) and total intracranial (TICV) volumes were assessed as described previously. Two examiners performed volumetric assessment independently for every subject (P.B. and K.G.). Interrater reliability was established using intra-class correlation coefficients (ICCs), which were above the cutoff value of 0.8. Hence the mean of each measure of the two examiners was entered in the analysis. Cerebellar and cerebral volumes were both expressed as percentage TICV and normalized with respect to body height (volume/body height).

In the CER-group surgical lesions were traced manually in non-normalized 3D MRI data sets and saved as regions of interest (ROIs) using MRIcro software (http://www.mricro.com). Individual ROIs and complete 3D MRI data sets were simultaneously spatially normalized into a standard proportional stereotaxic space using SPM2 (http://www.fil.ion.ucl.ac.uk/spm/). The affected cerebellar lobules and nuclei were defined with the help of 3D MRI brain atlases [22,23]. In addition, sagittal divisions of the cerebellum (that is vermis, paravermis and lateral hemispheres) were defined [23].

2.3. Movement coordination test

Movement coordination was assessed using the "Körperkoordinationstest für Kinder" (KTK), a German test to assess motor development, which has been validated for children aged 5–14 years [18]. The KTK consists of four tasks: (1) walking backwards on beams of decreasing width; (2) one leg jumps over foam plates of increasing height (25–60 cm); (3) jumping laterally to and fro with both legs; (4) stepping on moveable plates, which had to be replaced manually by the participants. Performance in the KTK was quantified by a standardized motor quotient (MQ) with a mean of 100 and normal values ranging from 86 to 115.

2.4. Posturography

Postural control was assessed using static and dynamic posturography (NeuroCom Inc., Portland, OR). The motion of the platform or the visual surroundings could be linked online to the participant's anterior–posterior sway. Six different conditions were used in order to examine balance under different sensory conditions (Sensory Organization Test; see [24]). Three trials were recorded for each condition. In each trial, ground reaction forces were recorded for a 20-s interval at a sampling frequency of 100 Hz. Sway area was assessed [24]. Stepping off the platform was marked as a "fall".

2.5. Gait analysis

Kinematic data were collected using an ultrasound-based movement analysis system (Zebris CMS-HS, Germany). Twelve ultrasound-emitting markers were fixed to the legs of the participant (three markers on each knee and foot). Two ultrasound receivers recorded pulses emitted by the markers (sampling frequency 25 Hz). Anatomical landmarks of both legs were defined electronically. Using triangulation, the spatial position of each marker was calculated and transformed into a three-dimensional model of the subject's gait. Participants wore a safety harness.

First, participants walked on a treadmill at 2 km/h. They performed normal walking and tandem gait in a randomized order. In each condition, three 20 s intervals were recorded. Stride length, cadence (steps per second), percentage of stance and swing phase, and double limb support time were analyzed using gait analysis software (WinGait, Zebris, Germany). Stride length was adjusted to the participant's height.

Next, participants performed "in-place stepping" paced to the beat of a metronome. Metronome frequencies were set to 1, 2 and 3 Hz and were presented in randomized order. Each frequency was presented three times with each trial lasting 15 s. The participant's mean stepping frequency over 15 s was assessed. Participants were instructed to lift the foot from the ground to one beat and return it to the floor on the next one. Therefore, the expected stepping frequencies were half the metronome frequency (0.5, 1 and 1.5 Hz). The achieved stepping frequency and the percentage of target frequency achieved (achieved frequency/target frequency × 100) were calculated.

2.6. Statistical analysis

One-way analysis of variance (ANOVA) procedures were used to compare the motor quotient and the volumetric MRI data between groups. Repeated measures ANOVAs were used for the analysis of the gait variables during the walking and "in-place stepping" task with condition as within-subject factor and group as between-subject factor. The level of significance was set to 0.05. Post hoc analyses comparing two groups were performed subsequently when appropriate. Data were analyzed using SPSS 13 for Mac OS X.

3. Results

3.1. Brain MRI analysis

Absolute cerebellar and cerebral volume did not differ between ADHD-participants and controls ($p > 0.13$). ADHD-participants were found to have a significantly larger cerebellar volume normalized with respect to TICV compared with controls ($p < 0.001$). Cerebellar volumes normalized with respect to body height, TCV normalized with respect to TICV, and TCV normalized with respect to body height did not, however, differ between groups ($p > 0.079$; Table 1).

Fig. 1 shows the lesion sites of the seven CER-participants superimposed on axial MRI scans of a healthy subject. Cerebellar vermis was affected in all seven CER-participants, fastigial nuclei in five.

3.2. Movement coordination test

The mean motor quotient differed significantly between the three groups ($p < 0.001$; Fig. 2), with the MQ being significantly lower in the CER compared with the CON-group ($p = 0.001$).

Table 1
Absolute and normalized volumetric measurements in ADHD- and CON-participants.

Group	ADHD	CON	*p*-Value
CER (cm^3)	151.12 ± 10.38	148.3 ± 10.86	0.571
TICV (cm^3)	1530.28 ± 114.75	1668.54 ± 97.25	0.011
TCV (cm^3)	1180.53 ± 68.54	1236.4 ± 83.3	0.131
CER/TICV	9.9 ± 0.68	8.89 ± 0.41	0.001
TCV/TICV	77.25 ± 2.57	74.17 ± 4.29	0.079
CER/height (cm^2)	0.99 ± 0.6	0.92 ± 0.11	0.124
TICV/height (cm^2)	10.02 ± 1.0	10.38 ± 1.09	0.466
TCV/height (cm^2)	7.73 ± 0.71	7.69 ± 0.83	0.902

CER: cerebellar volume; TICV: total intracranial volume; TCV: cerebral volume (total cortex volume).

ADHD-participants did not have a significantly lower mean MQ in comparison to controls ($p = 0.187$). CER-participants performed significantly worse in all subtests compared with controls ($p < 0.017$). Although the ADHD-participants performed within normal limits in the four subtests, they performed significantly below controls in the backward walking task ($p = 0.002$). Performance in the other three subtests was not significantly different ($p > 0.07$).

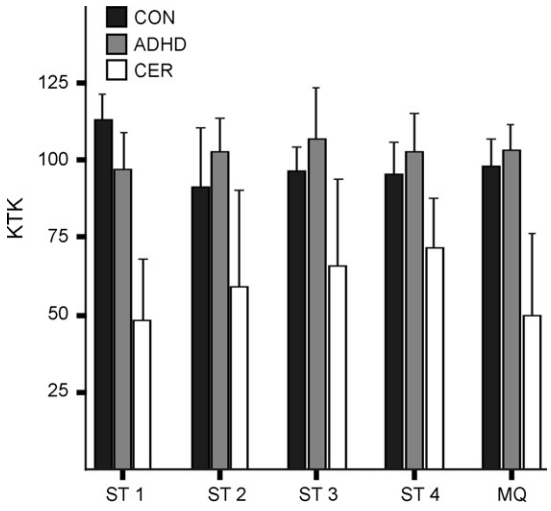

Fig. 2. Results of the movement coordination test (KTK). Mean and standard deviation of motor quotient (MQ) and KTK subtests (ST) in the three groups. ST 1: walking backwards; ST 2: monopedal jumping; ST 3: jumping laterally; ST 4: moving through the room with the help of foam plates.

3.3. Posturography

Fig. 3 shows the mean individual sway areas and number of falls for the three groups in the six conditions. Because postural abilities in chronic cerebellar children are impaired mostly in cases with lesions of the fastigial nuclei [24], CER-participants with ($n = 5$) and without ($n = 2$) lesions of the fastigial nuclei are shown separately. Mean sway area did not differ in conditions 1–3 between groups. In the fourth and fifth condition, CER-participants with lesions of the fastigial nuclei showed increased sway area compared with controls. ADHD-participants showed increased sway in condition 4. CER-participants showed an increased number of falls in conditions 5 and 6, and ADHD-participants in condition 6.

"Abnormal postural sway" was defined as the mean sway area outside the range of the control group (that is in condition 4 > 14.5 cm^2; condition 5 > 66.7 cm^2; condition 6 > 47.0 cm^2) or the occurrence of one "fall" [24].

In condition 4, 9% of the CON-group (1/11), 60% (6/10) of the ADHD-group and 43% (3/7) of CER-participants displayed abnormal postural sway. 9% of CON-participants (1/11), 20% (2/10) of the ADHD-group and 29% (2/7) of CER-participants displayed abnormal postural sway in condition 5. In condition 6, 9% of the controls

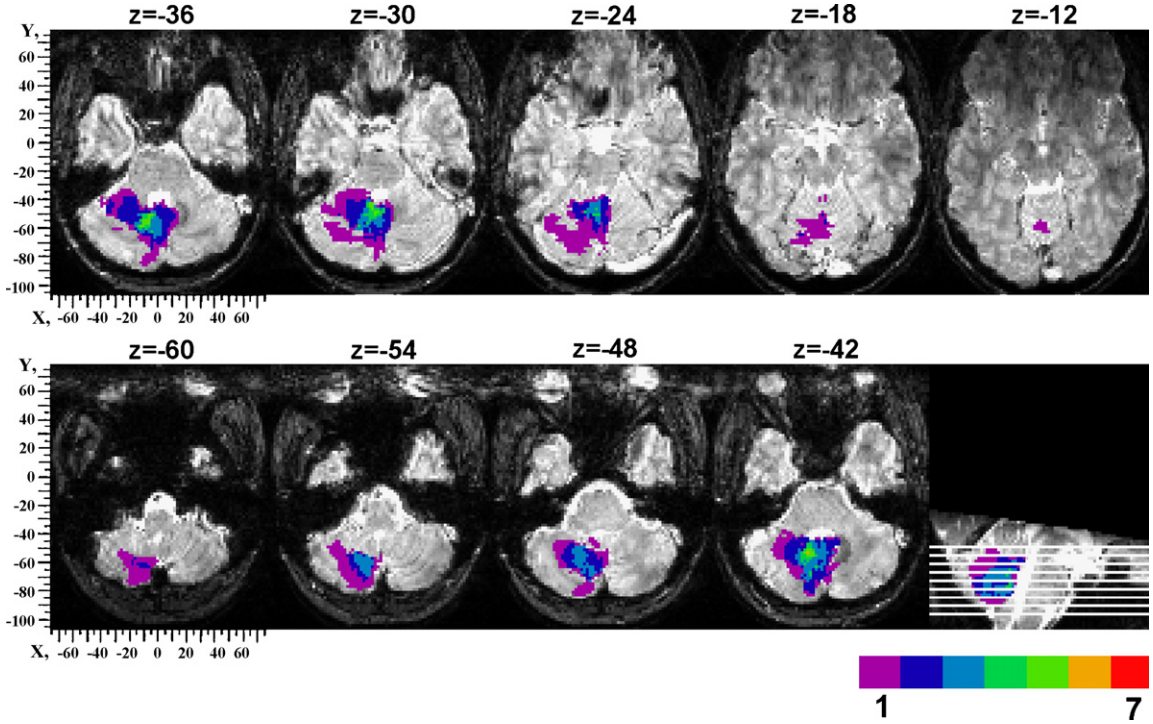

Fig. 1. shows the lesion sites of the seven cerebellar participants superimposed on axial MRI scans of a healthy participant. Right-sided lesions were flipped to the left. *Z* = mm below AC–PC line.

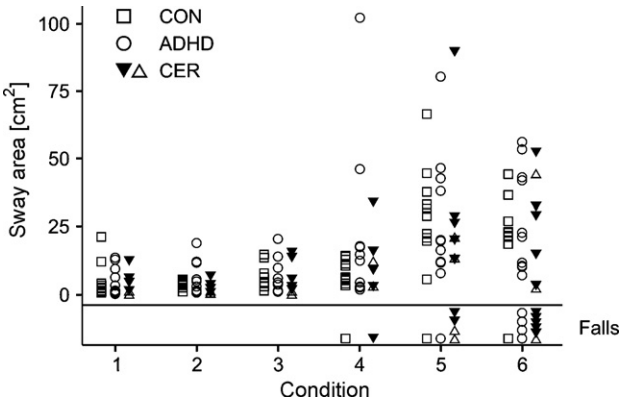

Fig. 3. Mean sway areas in individual subjects in the posturography. Filled triangles indicate cerebellar children with lesions including fastigial nuclei. The number of falls is indicated by number of X's. Condition 1: visual surroundings and platform stable; condition 2: eyes closed, platform stable; condition 3: visual surround sway-referenced, platform stable; condition 4: visual surround stable, platform sway-referenced; condition 5: eyes closed, platform sway-referenced; condition 6: visual surround and platform sway-referenced.

(1/11), 50% of the ADHD-group (5/10) and 57% of CER-participants (4/7) displayed abnormal postural sway.

3.4. Gait analysis

Performance in treadmill walking showed only minor differences between groups. CER-, but not ADHD-participants showed an increased percentage of stance phase and increased double limb support time in normal and tandem gait compared with controls (Fig. 4C and D).

The results from 2× Condition (tandem gait/normal gait) and 3× Group (Controls/ADHD/Cerebellar) repeated measures ANOVAs on stride/height, cadence, stance phase and double limb support time did not yield significant differences between groups ($p > 0.087$). Likewise, no statistically significant results were observed when only the five participants in the cerebellar group with lesions including the fastigial nuclei were considered.

To examine whether the groups revealed differences in variability in any of the four gait variables, subsequent ANOVA procedures were performed comparing the group standard deviations of each gait parameter. No significant group differences were observed for any gait kinematic variable.

In the paced stepping task CER-participants showed generally lower stepping frequencies and a higher variability compared with the ADHD- and CON-groups in the 1 and 1.5 Hz conditions (Fig. 5).

To determine differences in the stepping frequency between the groups, a 3× Target Frequency by 3× Group ANOVA on "percentage of target frequency achieved" was performed. The main effects for target frequency ($p < 0.001$) and group ($p = 0.031$) and the target frequency by group interaction were significant ($p = 0.002$). ANOVA comparing groups separately revealed a significantly impaired performance in CER-participants compared with controls (group effect $p = 0.029$; group by target frequency effect $p < 0.001$). ADHD-participants performed slightly below controls in the fastest condition (group by target frequency effect $p = 0.042$).

4. Discussion

In this study, few motor abnormalities were observed in children with ADHD. In the movement coordination test, ADHD-participants scored significantly lower only when walking backwards on a beam.

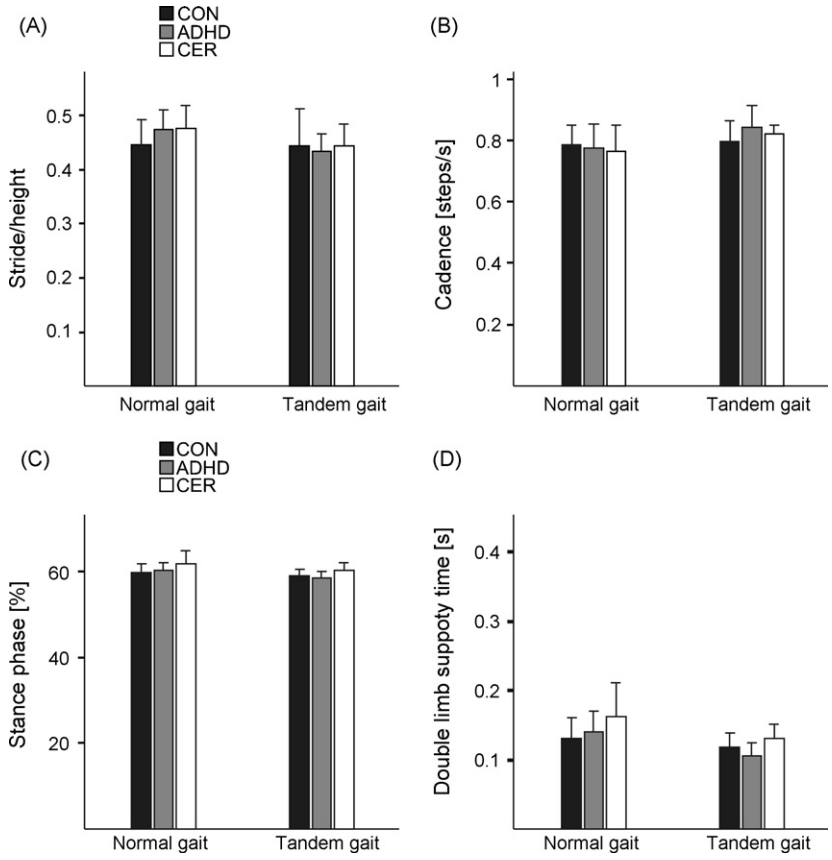

Fig. 4. Mean values and standard deviations of gait parameters for each group in the four conditions.

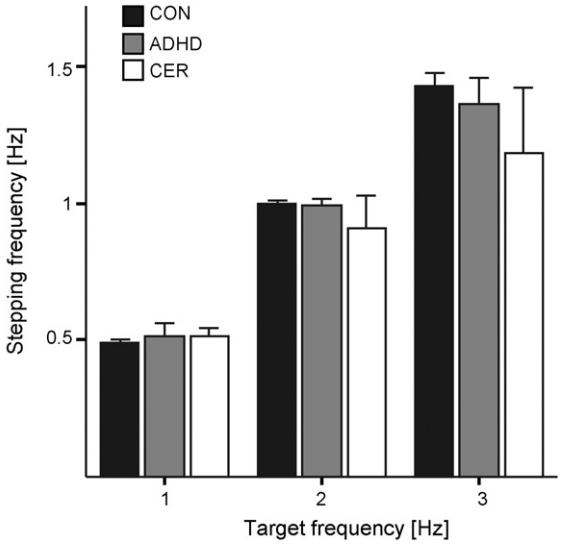

Fig. 5. Mean stepping frequency and standard deviation for each group in the "in-place stepping" task. The expected stepping frequencies were 0.5, 1 and 1.5 Hz.

Otherwise, performance in all four subtests was within the normal range.

In ADHD-participants balance disorders in stance and gait appear to be minor. Abnormalities were most prominent in the most difficult conditions of dynamic posturography. In these conditions subjects had to rely primarily on vestibular information as proprioceptive and/or visual information was reduced or not available to stabilize posture. For the children with cerebellar lesions the abnormal postural control under impoverished sensory conditions was interpreted as an indication of their inability to integrate multimodal sensory information for balance control [24]. In addition, it is known that vermal or fastigial nuclear lesions disrupt the processing of vestibular information. This would explain why the children's balance is most compromised when vision and ankle proprioceptive information is diminished. The fact that a subset of ADHD children performed similarly to the children with cerebellar lesions supports the notion that ADHD may be associated with a cerebellar dysfunction leading to balance problems in these children.

Furthermore, mild abnormalities were observed in the fastest condition of the paced stepping task. Given that paced stepping was clearly abnormal in the cerebellar children, these findings are compatible with mild cerebellar dysfunction in ADHD.

ADHD-participants performed similarly to controls in the treadmill walking tasks although the tandem gait in particular required a high level of coordination ability. Overall, the present gait and balance abnormalities in ADHD-participants appeared to be less severe when compared with previous findings indicating a deficient coordination of postural adjustments during a lifting task [25] and poor balancing [26].

Medication may have ameliorated motor signs. Methylphenidate has demonstrated positive effects on fine motor skills. In the only gait analysis study focusing on ADHD to date, Leitner et al. found increased variability in stride length which returned to normal under treatment with methylphenidate [27]. Qualitative aspects of handwriting, such as legibility and accuracy, improved markedly after treatment with methylphenidate [28]. In contrast, kinematic aspects of handwriting movements, namely fluency, deteriorated while on medication [28]. Furthermore, Rubia et al. showed that methylphenidate has a positive effect on motor timing deficits [29]. Although it cannot be ruled out that the effect of medication could explain at least in part why motor abnormalities were comparatively minor, it seems unlikely that findings within the normal range in the motor coordination task can be explained by methylphenidate therapy alone. It seems more likely that it was a mere coincidence that none of the ADHD-participants presented with accompanying MCD.

Interestingly, in the ADHD-group the volume of the cerebellum was not reduced compared with the CON-group. Based on the available literature [15] decreased cerebellar volumes were expected. In conjunction with the mild motor abnormalities seen in the cohort of ADHD-participants, the finding of normal absolute cerebellar volumes indirectly suggests that the motor coordination disorder in ADHD may primarily be associated with reductions in cerebellar volume. However, one needs to be aware of the fact that this ADHD-group was small.

The type of ADHD did not appear to be a likely explanation for these findings. Piek et al. [8] showed that fine motor skills are impaired mainly in children with the inattentive subtype of the disease, whereas gross motor skills are affected more in children with combined type ADHD. In this study, all children suffered from the combined type and no fine motor skills were assessed.

Interestingly, one of the CER-participants showed abnormal values in the Conners' questionnaires indicating the presence of the inattentive type of ADHD. It could be argued that the presence of ADHD in one of the CER-participants supports the notion that the pathogenesis of ADHD is associated with cerebellar dysfunction. However, high scores on the Conners' scale in healthy children reflect the high prevalence of the disorder in the normal population. In fact, two of the randomly selected 13 controls were excluded due to increased values in the Conners' scales.

In conclusion, minor balance and stepping disorders were observed in ADHD-participants. Motor deficits were compatible with mild cerebellar dysfunction. Future studies in a larger sample of unmedicated ADHD-participants with and without clumsiness are needed to determine the extent to which cerebellar dysfunction contributes to motor abnormalities in ADHD.

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Conflict of interest

None.

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