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Full Length Article

Changes in dynamic balance control over time in children with and without Developmental Coordination Disorder

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ABSTRACT

The aim of this study was to examine differences in underlying adaptations of dynamic balance in children with and without Developmental Coordination Disorder (DCD) during a Wii Fit game and to measure changes over time and after intervention.

Twenty-eight children with DCD and 21 typically developing (TD) children participated in the study. Analyses of force plate variables showed that the TD group initially used a longer path length for the ski slope descent and tended toward more variation in Center of Pressure (CoP) displacement in lateral direction than the children with DCD. In contrast, the TD group showed a trend of fewer reversals per cm in both AP and lateral direction. After the nonintervention period, the TD group improved performance by decreasing the path length, while the DCD group improved by increasing the path length and by decreasing the number of reversals. After intervention, no changes were found in sway characteristics. Individual analyses within the DCD group showed that the path length per run fell more often within the 95% confidence Interval of the faultless runs. In conclusion both TD and DCD children modify the underlying kinetics of dynamic balance control, but in different ways and both lead to better performance.

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1. Introduction

Children with Developmental Coordination Disorder (DCD) are characterized by motor problems, which are not explained by medical, neurological disorders or an intellectual delay (APA, 2013). These movement difficulties often lead to reduced participation, e.g. in playing with peers at schoolyards or sport clubs or even at home (Linde et al., 2015). Consequently children with DCD get less practice and experience to develop and improve their motor skills. Motor proficiency appears to be a significant determinant of the diversity in activity participation by children with DCD; the lower the MABC-2 percentile score, the fewer types of activities they participate in (Fong et al., 2011). This increases the risk of not taking part in activities that promote physical fitness (Bar-Or, 1983; Batey et al., 2014).

Children with DCD demonstrate various movement difficulties, and the majority of children with DCD exhibit poor balance. Postural control studies have shown that both static and dynamic balance tasks show differences between children with and without DCD. In children with DCD, postural sway was larger in standing position, especially in more difficult

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conditions such as standing on one leg and in altered sensory conditions or unexpected perturbation (Cherng, Hsu, Chen, & Chen, 2007; Geuze, 2003; Grove & Lazarus, 2007). Studies of sway during gait show an amplification under more challenging circumstances (Deconinck et al., 2006) or when crossing obstacles (Deconinck, Savelsbergh, Clercq, & De Lenoir, 2010). Apart from a difference in sway, children with DCD also show increased levels of co-activation during knee extension and flexion tasks, more variable lower limb control during walking, as well as decreased knee and ankle joint moments and power during running (Raynor, 2001; Rosengren et al., 2009; Chia, Licari, Guelfi, & Reid, 2013).

The present study aims to scrutinize the control of dynamic balance and changes over time in children with DCD in a task that challenges balance. Kinetic data can be used to objectify different ways of controlling the interactions between the center of mass (CoM) and the base of support under fast changing task requirements. Virtual reality (VR) games that use a balance board offer opportunities to study kinetic behavior of the control of dynamic balance in children with DCD, in tasks that challenge and motivate the child to participate repeatedly in an interactive motor task. The use of video games as a tool for intervention or rehabilitation incorporates fundamental elements of motor learning in a dynamic environment close to daily life. Indeed, a VR environment allows for the manipulation of the environment and this has proven to be an advantage compared to traditional neuropsychological assessment measures or rehabilitation (Adams, Finn, Moes, Flannery, & Rizzo, 2009), although it cannot be considered as providing a natural interface for action. However, in the game the child chooses its own avatar, and experiences the movement of the avatar as its own. Additionally, a more realistic virtual environment allows participants to forget they are being assessed and allows researchers to study under safe and controlled circumstances (Bioulac et al., 2012; Smits-Engelsman, Jelsma et al., 2015).

Motivation and repetition are important ingredients for positive results, and are provided abundantly in these games. The VR tasks offer instruction and real-time visual and auditory feedback presented in a standardized manner. The use of the Wii (a VR system with movement games for children) has great potential for improving gross motor skills, posture and balance in children with developmental disabilities (Salem, Gropack, Coffin, & Godwin, 2012). This is supported by several studies in which VR has been used as an intervention tool in order to improve motor skills, including training of balance or gait in different clinical groups of children and adults (Hammond, Jones, Hill, Green, & Male, 2014; Jelsma, Pronk, Ferguson & Jelsma, 2013; Jelsma, Geuze, Mombarg, & Smits-Engelsman, 2014; Lohse, Hilderman, Cheung, Tatla & van der Loos, 2014; Deutsch, Merians, Adamovich, Poizner, & Burdea, 2004; Dareker, McFadyen, Lamontagne, & Fung, 2015).

For the current study we selected a VR game that requires active control of the position of an avatar or object on the video screen by the player's shifting bodyweight in lateral and anterior-posterior (AP) directions, without losing balance. Improvement after intervention is likely due to underlying adaptations in the control of dynamic balance. These may occur at the kinetic and/or the muscular level. So far, it is unknown which aspects of dynamic control differ between children with and without DCD and which aspects change after Wii intervention. This becomes especially interesting since we have shown in earlier work that although children with DCD perform less well on the Wii-Fit ski slalom game, their learning curves over 100 trials were not different from those of typically developing children (Smits-Engelsman, Jelsma et al., 2015). The ski slalom game is a task we also used in the present study. The objectives of this present study were to: 1) analyze whether children with and without DCD displayed initial differences in dynamic control of balance in anterior-posterior (AP) and lateral directions; 2) compare change between the groups when repeating the game after a period of 6 weeks of nonintervention; 3) compare in a subgroup of children with DCD the changes after VR intervention with changes after a similar period of non-intervention. To explore the control of dynamic balance we placed the Wii balance board on a force plate, and analyzed the variability and path length of the center of pressure (CoP) during the course of each game.

2. Methods

2.1. Participants

Pediatric physical therapists identified 28 children, aged 5–11 years, who were referred for treatment to their practice or to be treated at the school for special education they were associated with. Criterion B of the DSM-5 (APA, 2013) was confirmed when parents and/or teacher reported motor coordination problems during history taking, which was documented in the file of the child. It was also checked in the files that no diagnosis of any significant medical condition was reported known to affect motor performance and the IQ was >70 (Criterion D). Further inclusion criteria were a total score ≤ 7 th standard score on the Movement Assessment Battery for Children-2 (MABC-2) (Criterion A), a ≤ 7 th standard score on the component Balance. These children are referred to as DCD. Twenty-seven children with DCD scored a total standard score within the range of 1–5, one child scored a standard score of 6 (at risk), and a component balance score of 5. On the component balance 27 children scored within the range of 1–5 and one child scored a standard score of 7. For more demographic details of this group see Jelsma et al. (2014).

A group of 21 typically developing (TD) children was recruited from a mainstream primary school in the same region. Inclusion criteria were a MABC-2 score ≥ 9 th standard score on both total (all children scored within the range of 9–19) and component balance score (all children scored within the range of 9–17) and normal school progress. None of the children had a diagnosis of medical, neurological or mental disorder.

The Ethics Committee of the Department of Psychology of the University of Groningen approved the study. After the children and parents agreed to participate, parents signed the informed consent form and the child wrote his or her name on that form.

2.2. Instruments

2.2.1. The movement ABC2

The Dutch version of the Movement Assessment Battery for Children-second edition (MABC2) (Henderson, Sugden, & Barnett, 2007; Smits-Engelsman, 2010) is the version of the test with Dutch norms for children aged 3–16 years. The total score, representing overall motor performance, is the sum of three component scores for: i) dexterity; ii) aiming and catching; and iii) balance. The European Guidelines for DCD (Blank, Smits-Engelsman, Polatajko, & Wilson, 2012) recommends this test to discriminate among children with normal motor performance (>16th percentile), those at risk for motor problems (between ≥ 6 and ≤ 16 th percentile) and those with motor problems (≤ 5 th percentile).

2.2.2. Wii-Fit

We used a Nintendo® Wii-Fit balance board (WBB) system and its software. The WBB was placed on top of an AMTI force plate on the floor 2 m in front of a television, which was placed on a table at a height of 75 cm. The AMTI force plate was calibrated after the WBB was placed and centered on the AMTI force plate, before the child was standing on top of the WBB. Calibrated tri-axial forces and moments were stored as our force plate data. The study of Leach, Mancini, Peterka, Hayes, and Horak (2014) showed that CoP signals of the WBB correlate significantly with the CoP signals of the AMTI force plate across all sway amplitudes and frequencies, and in both sway directions (Leach et al., 2014).

The AMTI force plate measured the forces in anterior-posterior (Fx), lateral (Fy) and vertical (Fz) directions and the corresponding moments (Mx, My and Mz) with a sample frequency of 100 Hz. The hardware filter was set at low pass 10 Hz.

Our Wii-Fit test consists of a sequence of ten runs of the ski slalom game. The goal of the game is to ski through 19 gates along a ski slope without missing a gate and at highest speed. In the Wii-Fit ski slalom game lateral shifts of weight direct the skier (avatar) sideways and anterior-posterior (AP) shifts of weight speed or slow the avatar. The gates have an invariant spatial layout, but vary in lateral and down-slope distance. Passed gates and duration are recorded.

2.3. Procedure

For the initial setup the child stood on the balance board, feet 20 cm apart, and chose its own avatar. The balance board calibrated for the individual height and weight. Next, the Wii software coached the children through the basic balance test, such that they became acquainted with the Wii balance board (WBB) system in a standardized way.

Both groups started with the Wii test, consisting of ten runs of the slalom game, to determine a baseline (T0) performance. Six weeks later (T1) half of the DCD group (referred to as DCDB) and the TD group minus one child who fell ill, repeated the test. This was followed by 6 weeks of intervention in the DCDB group, concluded (T2) with a third Wii-Fit test for this subgroup (Fig. 1).

The intervention (Jelsma et al., 2014) took place in half-hour sessions, three times a week for 6 weeks. During these sessions the children played each of the available Wii-Fit balance games, except for the ski slalom game, twice before moving on to the next game. The first author coordinated and supervised the intervention, which was performed by specially trained PE, PT and education students.

2.4. Analyses

The standard deviations of the signals were calculated over the period of 2 s before passage of the first gate until 1 s after passage of the last gate. The position of the center of pressure (CoP) relative to the origin of the force plate, corrected for the thickness of the Wii board (5 cm), was calculated by the formulas (Michalski et al., 2012):

$$\text{CoPx} = -(My + Fx * 0.05)/Fz \text{ and}$$

$$\text{CoPy} = (Mx - Fy * 0.05)/Fz$$

SDCoPx represents variation of displacement in anterior-posterior (AP) direction, used for speed control, and SDCoPy indicates variation of displacement in lateral direction, used for directional control in the ski slalom game. The total trajectory of the child's CoP during the game, referred to as path length, was calculated as $\sqrt{(\text{CoPx})^2 + (\text{CoPy})^2}$ in cm. Fig. 2 shows CoP signals for a single run by a child with DCD.

The basic swing of the task, passing 19 gates in about 38 s, is about 0.5 Hz; the median frequency in static balance in children ranges from 0.8 to 1.3 Hz (Cherng, Lee, & Su, 2003). CoP values were smoothed (half width 24 points) to suppress the higher frequency corrections related to balance control, thereby placing more emphasis in the analysis on the control of the avatar. Active control was qualified as directional reversals in the smoothed CoPx and CoPy signals. The total number of reversals divided by the path length led to the number of reversals per cm.

the essential differences in kinetics between DCD and control children that were independent of the performance level of the child. Therefore we corrected the model for the level of performance (number of passed gates). Furthermore we corrected for age since the range was large (5–11 years).

First, differences between groups were tested (TD, DCD) at baseline (T0). Second, we tested differences in changes after six weeks of nonintervention (T1) between the TD group and the DCDB group (Time x Group effect). Third, it was tested within the DCDB group if the effect of intervention was larger than the change after the period of nonintervention. Fourth, to support interpretation, we tested the relation between number of passed gates and path length with Pearson correlation. Finally, perfect runs were selected of TD children at T1-defined as runs in which a child passed all gates and finished within 40 s – for which we calculated SDCoPx, SDCoPy, mean path length and mean number of reversals per cm in AP and lateral directions as a 'golden standard'. Based on the perfect runs a 95% confidence interval (CI) was calculated for the path length. This CI was compared to the outcomes of the TD and DCD groups: the number of runs that fell outside the 95% CI of the golden standard was counted in the TD group and the DCDB group after six weeks of nonintervention and for the latter also after intervention. Finally, we ranked the individual changes in lateral sway for T1-T0 and T2-T1 as follows: a difference of lateral displacement (SDCoPy) of each run at T1-T0 or T2-T1 of >0.10 cm as increase, between 0.10 and –0.10 cm as no change and <–0.10 cm as decrease per child. We classified a pattern as i) increase if the number of increases of the ten consecutive changes per child exceeded twice or more compared to no change or minus the number of decreases; ii) decrease if the number of decreases exceeded twice or more compared to no change or minus the number of increases. The proportion of the children showing the described patterns was reported.

3. Results

3.1. Group differences at baseline

The performance of the TD group (mean number of gates passed = 13.9 (3.4)) was superior to that of the DCD (9.3 (3.7)) (see Jelsma et al., 2014). Table 1 reveals the difference in kinetic variables at baseline measurement between the DCD group and TD group after correction for age and number of passed gates. The DCD group had less variation in lateral displacement, a shorter path length, but more reversals per cm in both AP and lateral directions. However, only the path length differed significantly ($b = -12.2$, $p = 0.004$). The covariates age and passed gates had no significant influence on the outcome of path length and number of reversals per cm. However, older children showed more variation in lateral displacement ($b = 0.002$, $p = 0.04$); and number of passed gates was related to the displacements, with more passed gates corresponding with a decrease in displacements in AP ($b = -0.002$) and lateral ($b = -0.003$) directions.

3.2. Changes after six weeks of nonintervention

The mean number of gates passed improved after the nonintervention period from 13.9 to 15.5 in the TD group and from 8.5 to 10.2 in the DCDB group (Jelsma et al., 2014). Table 2 shows the group means of the five force plate variables at the two time points. Significant group differences were found for variation of lateral displacement and path length. The group by time interaction for path length (Fig. 3) indicates that whereas in the TD group the path length decreased, in the DCDB group the path length increased over time.

Age was related to the variation in AP direction: older children used more variation in speed control ($b = 0.001$, $p = 0.05$).

The number of passed gates was associated with variation in AP ($b = -0.003$, $p = 0.0001$) and lateral ($b = -0.004$, $p = 0.0001$) directions; more passed gates corresponded with less variance.

Table 1

Differences in kinetic measures between groups at baseline: mean values (SD) of the variation of AP and lateral displacement, path length and number of reversals per cm in AP and lateral directions; and the results of the linear mixed model analysis.

	TD (n = 21)	DCD (n = 28)	Group difference <i>b</i> , (<i>p</i>) and CI ^a	Co-variate age <i>b</i> , (<i>p</i>) and CI	Co-variate passed gates <i>b</i> , (<i>p</i>) and CI
SD CoPx	0.16 (0.05)	0.16 (0.06)	–0.014 (0.31) –0.04; 0.01	0.0005 (0.196) –0.0003; 0.001	–0.002 (0.0001) –0.003; –0.001
SD CoPy	0.35 (0.09)	0.30 (0.10)	–0.05 (0.06) –0.10; 0.003	0.002 (0.04) 0.00004; 0.003	–0.003 (0.0003) –0.005; –0.002
Path length cm	50.7 (17.3)	37.0 (15.3)	–12.2 (0.004) –20.1; –4.22	0.11 (0.39) –0.14; 0.35	–0.07 (0.67) –0.40; 0.26
Nr. of reversals in AP direction	0.86 (0.26)	1.02 (0.45)	0.16 (0.09) –0.02; 0.34	–0.004 (0.17) –0.01; 0.002	0.005 (0.21) –0.003; 0.014
Nr. of reversals in lateral direction	0.70 (0.22)	0.90 (0.46)	0.14 (0.09) –0.02; 0.30	–0.003 (0.24) –0.008; 0.002	0.004 (0.41) –0.005; 0.012

Bold values represent significance <0.05.

^a Corrected for age and missed gates.

Table 2

Differences in kinetic measures between the TD group and the DCDB group at baseline and six weeks later: mean values (SD) of the variation of AP and lateral displacement, path length (cm) and number of reversals per cm in AP and lateral direction at first measurement and six weeks later of the TD and DCDB group and the results of the linear mixed model analysis corrected for age and number of passed gates.

	TD (n = 21) T0	TD (n = 20) T1	DCDB (n = 14) T0	DCDB (n = 14) T1	Group difference (p) and CI ^a	T0 vs T1 difference (p) and CI ^a	Group x Time (p) and CI ^a
SD CoPx	0.16 (0.05)	0.17 (0.05)	0.15 (0.06)	0.15 (0.04)	−0.02 (0.11) −0.05; 0.006	0.006 (0.20) −0.004; 0.016	0.002 (0.83) −0.01; 0.017
SD CoPy	0.35 (0.09)	0.33 (0.07)	0.28 (0.11)	0.32 (0.11)	−0.06 (0.04) −0.11; −0.003	0.006 (0.53) −0.013; 0.025	0.019 (0.20) −0.01; 0.05
Path length cm	50.7 (17.3)	46.0 (14.7)	35.8 (16.0)	40.0 (13.9)	−14.9 (0.002) −23.9; −5.82	−2.5 (0.14) −5.8; 0.81	6.00(0.02) 0.84; 11.2
Nr. of reversals in AP direction	0.86 (0.26)	0.85 (0.21)	1.1 (0.53)	0.92 (0.38)	0.16 (0.12) −0.04; 0.37	−0.02 (0.58) −0.10; 0.06	−0.05 (0.44) −0.17; 0.07
Nr. of reversals in lateral direction	0.70 (0.22)	0.71 (0.19)	0.98 (0.53)	0.81 (0.40)	0.07 (0.46) −0.12; 0.26	0.01 (0.75) −0.07; 0.09	0.01 (0.83) −0.11; 0.14

Bold values represent significance <0.05.

^a Corrected for age and missed gates.

Fig. 3. Differential change of path length over six weeks of nonintervention of the TD group and the DCDB group.

3.3. Changes within the DCDB group

After six weeks of nonintervention within the DCD group lateral displacement and path length increased and the number of reversals decreased significantly (Table 3). Intervention did not lead to further significant change in the force plate variables. The change in these variables after the intervention period (T2–T1) was not significant, and compared to the first

Table 3

Differences in force plate variables of the DCDB group after 6 weeks of nonintervention and after 6 weeks intervention: mean values (SD) of the variation of AP (SDCoPx) and lateral displacements (SDCoPy), path length and numbers of reversals per cm in AP and lateral directions; and the results of the linear mixed model analysis, corrected for age and number of passed gates.

	DCDB (n = 14); T0	DCDB (n = 14); T1	DCDB (n = 14); T2	Difference T1 vs T0 b, (p) and CI ^a	Difference T2 vs T1 b, (p) and CI ^a	Difference T2–T1 vs T1–T0 b, (p) and CI ^a
SD CoPx	0.15 (0.06)	0.15 (0.04)	0.15 (0.04)	0.01 (0.008) 0.003; 0.02	0.003 (0.46) −0.006; 0.01	−0.02 (0.04) −0.03; −0.0005
SD CoPy	0.28 (0.11)	0.32 (0.11)	0.33 (0.09)	0.05 (0.0001) 0.03; 0.07	0.01 (0.28) −0.01; 0.03	−0.04(0.007) −0.07; −0.01
Path length in cm	35.8 (16.0)	40.0 (13.9)	38.6 (10.9)	3.74 (0.01) 0.84; 6.64	−1.88 (0.20) −4.73; 0.97	−5.62 (0.02) −10.44; −0.80
Nr. of reversals in AP direction	1.1 (0.53)	0.92 (0.38)	0.86 (0.23)	−0.18 (0.0001) −0.26; −0.10	−0.06 (0.12) −0.14; 0.02	0.12 (0.09) −0.02; 0.25
Nr. of reversals in lateral direction	0.98 (0.53)	0.81 (0.40)	0.75 (0.28)	−0.16 (0.0002) −0.25; −0.08	−0.06 (0.19) −0.14; 0.03	0.11 (0.14) −0.04; 0.25

Bold values represent significance <0.05.

^a Corrected for age and missed gates.

change (T1-T0) significantly smaller (even negative for the variation in AP and lateral displacement and path length) (Table 3). Apart from the force plate variables, the number of passed gates improved non-significantly between T0 and T1 and between T1 and T2 (respectively 8.5, 10.2, 11.9 as reported in Jelsma et al., 2014).

Age had no influence on the force plate variables. The covariate passed gates was associated with variation in AP ($b = -0.002$, $p = 0.0004$) and lateral ($b = -0.003$, $p = 0.018$) displacement; more passed gates corresponded with less variance.

3.4. Relation between path length and passed gates

The factor passed gates explained, as reported in all three analyses, a significant amount of variance. An increase of this factor was significantly associated with a decrease in displacement in both AP and lateral directions. Within the TD group, a negative correlation was found between the number of passed gates and the path length at both T0 and T1 (respectively $r_p = -0.17$, $p = 0.01$; $r_p = -0.23$, $p = 0.001$). In the DCDB group a positive correlation was found at T0 ($r_p = 0.20$, $p = 0.02$), whereas after six weeks of nonintervention a longer path length corresponded with fewer passed gates ($r_p = -0.18$, $p = 0.04$), and after intervention no relation was found.

3.5. Performance in faultless runs

Seven children (33%) in the TD group produced 12 faultless runs at T1 in a perfect controlled way with all gates passed within 40 s ('golden standard'), whereas none of the DCDB children did. After the intervention four children in the DCDB group produced eight faultless runs (5.7%). The force plate variables of these faultless runs are presented in Table 4.

3.6. Individual differences

The path length of each run (T0, T1, T2) was classified as shorter, within or longer than the CI of the golden standard. At T0 the TD group had no runs with a path length shorter than the CI, and 43% of the runs had a longer path length, exceeding the CI. When the TD children performed the ten runs for the second time after six weeks 78.9% of the runs had a path length within the CI of the golden standard.

At T0 in the DCD group 63.2% of the runs had path lengths that fell within the CI, 18.4% of runs fell below and 18.4% above the CI. After six weeks of nonintervention 75% of the runs of the children with DCD had a path length within the CI of the golden standard, fewer runs were below (6.4%) the CI and a similar frequency above the CI (18.6%). After intervention a further decrease was seen in the number of runs with a shorter (5%) and longer path length (8.6%) than the CI. With regard to success, it was clear that in the TD group runs with a path length within the CI were on average more successful than runs with a path length outside the CI both at T0 (14.3 versus 13.5 gates passed) and T1 (15.8 versus 14.4 gates passed). In the DCDB group the runs with a path length within the CI were more successful only at T1 (Table 5).

In the TD group 20% of the children showed a pattern of decreased lateral sway and only 10% a pattern of increased lateral sway between T1 and T0. This pattern was different within the DCD group, in which 29% of the children showed a pattern of increased lateral sway between T1 and T0, while after intervention most of the children showed no further change in lateral sway (93%).

Table 4

The mean force plate variables of the 'golden standard' of controlled successful games compared to the faultless runs of the DCDB group after intervention.

Force plate variables	Golden standard of 7 TD children at T1 with all gates passed in 12 runs	Mean values of 4 children of the DCDB group in 8 runs with all gates passed
Variance in speed (SD)	0.18 (0.05)	0.12 (0.04)
Variance in lateral trajectory (SD)	0.29 (0.04)	0.28 (0.03)
Path length (SD)	36.5 (8.8)	38.4 (8.7)
Nr. of reversals in AP direction per cm (SD)	0.94 (0.31)	0.92 (0.15)
Nr. of reversals in lateral direction per cm (SD)	0.74 (0.13)	0.81 (0.20)

Table 5

Percentage of runs (mean number of successfully passed gates) that had a path length in- or outside the Confidence Interval of the 'golden standard' of the TD group (T0, T1) and DCDB group (T0, T1 and T2).

Groups	Pathlength	T0	T1	T2
TD group	<CI	0	0	No data
	Within CI	57.0 (14.3)	78.9 (15.8)	
	>CI	43.0 (13.5)	21.1 (14.4)	
DCDB group	<CI	18.4 (6.4)	6.4 (7.9)	5.0 (11.7)
	Within CI	63.2 (8.9)	75.0 (11.1)	86.4 (11.8)
	>CI	18.4 (8.8)	18.6 (7.3)	8.6 (12.8)

4. Discussion

This is the first study that gives insight into the kinetics of active dynamic balance control by children with and without balance problems during gaming. We found clear differences in force plate variables between DCD and TD children: the TD group initially used a longer path length for the ski slope descent and showed a trend toward more CoP displacements in lateral direction and a trend toward fewer reversals in both AP and lateral directions as compared to the children with DCD. These differences are genuine group differences in force plate variables independent of the level of performance of the child, which obviously was significantly worse in the children with DCD (Jelsma et al., 2014). After six weeks of nonintervention period both groups improved when doing the 10 runs of the Wii test again. Improvement in performance corresponded with a difference in change of kinetic features in opposite direction: the improvement in performance in the TD group was associated with a decrease in path length and a slight decrease of the CoP displacements in lateral direction, whereas the improvement in the DCD group was associated with an increase in path length and greater displacement in lateral direction. Additionally, a decrease in the number of reversals in AP and lateral directions was found in the DCD group, a sign of better control. Remarkably, after intervention the expected change in force plate variables was absent, even though the performance improved. Over time in both groups the path length of the individual runs fell more often within the CI range of the faultless runs. This indicates that both groups of children modified their force plate variables in the direction of optimal trajectory, facilitating conditions for better performance.

4.1. Difference in force plate variables between groups at baseline

At baseline measurement the groups clearly differed. As a general feature it was found that older children showed larger lateral displacement, indicating more exploration of the base of support during the weight shifts from one side to the other. Irrespective of level of performance or age the larger path length and lateral sway and the better performance in the TD group imply a more appropriate lateral displacement with better timing in this group. These results are not attributable to age, since we corrected for this. The shorter path length and smaller lateral displacement of the DCD group seem at odds with studies that found larger sway during standing in children with DCD (Cherng et al., 2007; Geuze, 2003; Grove & Lazarus, 2007) and during complex gait conditions or obstacle crossing (Deconinck et al., 2006, 2010). However, our task is different because of the specific task constraints: it requires goal directed lateral displacement to pass the gates. The present findings point to less efficient lateral displacement in the DCD group that falls short in amplitude, resulting in poorer performance. The ski slalom game requires both controlling body balance within the base of support and controlling the avatar in goal-directed weight shifts. Obviously, anticipating the moments of weight shift is an important factor to be successful in this game. The poorer dynamic balance control of the children with DCD thus may result from difficulties in keeping their balance within the base of support and/or inaccuracy in weight shifting that directs the avatar to ski in the direction of the next gate within the available time frame.

One explanation for the shorter path length might be that children with DCD avoid the boundaries of the base of support (BoS). It is known that for unexpected loss of balance the effective BoS is considerably smaller than the area between the feet, because of the delay time of detection between loss of balance and reactive forces generated (Hof & Curtze, 2016). With this in mind and the fact that children with DCD are slow in responding with reactive postural muscle contraction (Geuze & Wilson, 2008, Chap. 11) and have poorer visual and vestibular sensory organization (Fong, Ng, & Yiu, 2013), a plausible explanation for the initial shorter path length is that the children use a safety strategy to avoid the boundaries of their BoS, causing more gates being missed.

Other explanations suggest a delay in anticipatory or predictive control (for example see Hyde & Wilson, 2011a), or in processing of visual (Hyde & Wilson, 2011b) or proprioceptive input needed for rapid online control (Desmurget & Grafton, 2003). Obviously, playing the Wii ski slalom game requires lateral displacement by weight shift adapted to the varied distances of the gates from the midline. Playing the game successfully requires control not only with spatial but also temporal accuracy; the avatar needs to be on the right spot at the right time within a limited amount of time. This requires forward estimate of weight shifts that need to be corrected by an intact internal feedback loop in case of movement errors, integrating efferent and afferent signals (Miall & King, 2008; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). The less efficient lateral displacement in the DCD group may be caused by a delayed preparation of the movement, in agreement with the fact that anticipatory postural adjustments in children with DCD have later onsets in abdominal and distal muscles (Kane & Barden, 2012). These problems with rapid online corrections may be caused by the lower sensitivity in children with DCD to pick up from the display those visual cues that can be used to correct ongoing control.

Interestingly, in contrast to the smaller amplitudes of displacements, the opposite phenomenon was shown in the number of reversals in AP and lateral directions during the game. The children with DCD had a tendency to make more reversals during the game compared to the TD group, which suggests poorer goal-directed control. The increased number of reversals in our study did not lead to a longer path length, but rather to erratic weight shifts that were ineffective for successful passage of the gate. "Inconsistency is a general characteristic of children with DCD" (Sugden, Chambers, & Utley, 2006, p12). This characteristic is also supported by studies of a fine motor task (drawing a line between targets), during which children with DCD made more spatial errors, especially in a cyclic task, and were more erratic in pen pressure: all attributed to problems in anticipatory adjustments towards the target (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003;

Smits-Engelsman, Bloem-van der Wel, & Duysens, 2006; Ruddock et al., 2015). It seems as though children with DCD have inconsistent predictive control that leads to high demands for error correction as reflected in more frequent reversals.

One may distinguish between forward and inverse models, both of which are used to control the movement. The inverse model transforms the desired sensory states into a motor command. The forward model predicts the sensory outcome based on an efferent copy of a motor command. The output of this forward model can then be used in the online control of movement by anticipating the errors (Geuze & Wilson, 2008, Chap. 11; Johnston, Burns, Brauer, & Richardson, 2002; Jucaite, Fernell, Forssberg, & Hadders-Algra, 2003). In our study it seems that children with DCD need more corrections, which due to the timing problems may be too late or too large, resulting in more corrections depicted in erratic reversals. This phenomenon corresponds with the cerebellar hypothesis. The cerebellar hypothesis states that motor difficulties in DCD are due to dysfunction of the cerebellum, resulting in delayed response times, poor coincidence timing, poor anticipation of forthcoming disturbances, dysmetria, mirror movements and large within-child variability over learning trials (Jucaite et al., 2003; Kandel, Schwarz & Jessell, 2000; Visser, 2003). For the predictive, feedforward part of the movement the cerebellar adaptive mechanism is important. It is known that patients with cerebellar damage have difficulty to adapt to and anticipate new circumstances (Bastian, 2006) and so far, there is indirect evidence from behavioral studies that a dysfunction of the cerebellum might play a role in the difficulties that children with DCD show in motor adaptation (Hyde & Wilson, 2011b; Cantin, Polatajko, Thach, & Jaglal, 2007; Wilmut, Wann, & Brown, 2006). More direct evidence shows that this may be due to underactivation of cerebellar-parietal and cerebellar-frontal networks as found in a small fMRI study of Zwicker, Missiuna, Harris, and Boyd (2011) in children with DCD performing a trail-tracing task.

4.2. Changes after six weeks

After the six weeks of nonintervention we found significant change in all five forceplate variables and a significant interaction of group and time for path length. As the number of passed gates increased after the nonintervention period by just playing the game ten times at two occasions (Jelsma et al., 2014), this result reveals that children with DCD, like the TD children, do have potential for spontaneous learning at the level of kinetic control to reach a higher level of accuracy. Remarkably, the groups changed the path length in opposite direction. The TD group seems to have shifted their weight more efficiently leading to a decrease of path length by staying closer to the gates and improvement on the Wii Fit test score. In the DCD group an increase of path length was seen. Initially, children can be considered novices in learning the ski slalom game and it is known that inexperienced performers initially reduce the skill complexity by restraining degrees of freedom (Anderson & Sidaway, 1994; Stergiou & Decker, 2011). When the task becomes more familiar gradually more degrees of freedom are explored (unfreezing) to find alternative solutions for mastering the task (Gentile, 2000; Newell, Deutsch, Sosnoff & Mayor-Kress, 2006). Apparently, the inefficient timing and persistent coactivation fitting with novel actions that initially led to freezing, moves to a next stage allowing more degrees of freedom and providing more adapted coordination. The increase of the lateral displacement and path length also points to improvement of lateral amplitude that initially fell short to pass the gates. Additionally the DCD group, but not the TD group, decreased the number of reversals when playing the game ten times at the second occasion. This points to greater accuracy of the goal-directed weight shifts in the DCD group. However, the children in the DCD group did not reach the level of accuracy of the TD group. The TD group may have reached a mean optimal level of number of reversals in the first ten runs.

4.3. The effect of intervention

As reported in Jelsma et al. (2014) Wii Fit intervention consistently improved motor performance on tests related to dynamic control of balance, compared to change after a similar nonintervention period. However, the improvement in Wii game scores due to intervention was comparable to the spontaneous improvement after the nonintervention period. Likewise, in this study at the level of kinetic behavior no improvement was found that exceeded the change after the period of nonintervention if corrected for game performance. In fact, none of the five kinetic variables were affected by the intervention during which the ski game was not played. Given the lack of change the intervention may not have lead to transfer in a game not played. Apparently, the intervention consisting of many different Wii Fit games challenging balance control, did not meet the task specificity criteria needed for changes in force plate variables in the ski slalom game.

After the nonintervention period both groups adapted their kinetic behavior during the second series of ten runs with more runs approaching the CI of the golden standard. After intervention, a further increase in the number of runs that fell within the CI of the golden standard was seen. The slightly longer path length after intervention and fewer reversals may have facilitated this, offering better opportunity for and actually resulting in passing more gates. However, it is unclear whether the conditions for better performance matched with a better timing, necessary to pass the gates successfully.

Performance was related to the variation of displacement since the passed gates corresponded with a decreased variation of displacement in AP (more consistent speed) and lateral direction. Within the groups the correlation between numbers of passed gates and path length was consistently negative in the TD group (shorter trajectory; more passed gates), whereas the DCDB group was less consistent in this relation.

The Wii Fit test consisted of a repetition of ten runs of the ski slalom game, which gives opportunity to learn within the ten runs. Given that the children with DCD show poorer performance and different kinetics an interesting question is whether they can reach the level of TD children by learning (Jelsma, Ferguson, Smits-Engelsman, & Geuze, 2015;

Smits-Engelsman, Jelsma et al., 2015; Smits-Engelsman, Schoemaker et al., 2015). For this, task-specific training and experience over a longer period seems essential, to analyze whether level of performance and kinetics can converge those of TD children through more practice.

5. Strengths and limitations of the study

A strength of the present study is that we used a force plate to study the underlying kinetics of dynamic balance control during a ski slalom game – a virtual reality game which is attractive to children and which has potential as a tool for intervention. However, it is hard to disentangle control of balance within the limits of stability from goal-directed control of the avatar through dynamic balance. The force plate data on their own do not differentiate between these efficient and inefficient solutions for controlling balance and the avatar. We have used a low pass filter that partly suppresses the frequencies used for standing balance control (Cherng et al., 2003). With 19 gates spread alternately left and right over the ski slope and an average duration of the run of 38 s the optimal frequency for task control would be about 0.5 Hz. For the number of reversals we have used a low pass filter that partly suppresses the higher frequencies used for standing balance control. Thus the emphasis of the reversals analysis is more on goal directed control than on standing balance control. Future studies might try to find optimal separation of the two types of control at the individual rather than the group level, and/or by additional measurement of sway characteristics in a static balance task and use these as covariates in the analysis of the dynamic balance task. Even manipulating the task by light touch or full support compared to no support may clarify the impact of goal directed control without standing balance control and the corrective sways.

Since the size of the group was limited and the range of age was large (5–11 years), we corrected for age. To gain more insight into the changes between younger and older children with (and without) DCD the best design would be a longitudinal follow up study. Given the difficulties doing that kind of study, comparison of several cross sectional groups with sufficient sample sizes would be a good start to test the changes in dynamic balance in these or comparable tasks, to see how the patterns of adjustments of CoP change over the full age range.

It is also important to consider that children may use ineffective strategies that are not detected by force plate measurements, such as simultaneous opposite lateral displacements of their lower and upper body, or head and arms. Video observation and scoring of the various strategies of control may offer additional insights, both to researchers and clinicians.

6. Conclusion

Children with DCD differed from TD children at the level of displacement of the center of pressure in the Wii Fit ski slalom game, a task that requires dynamic control of the avatar and their own balance. This study shows that both TD and DCD children change the underlying CoP variables of their dynamic balance control, but in different ways that both lead to better performance. This change seems more driven by a task-specific learning process than by transfer from the different tasks used in the intervention.

Competing interest

The authors declare that they have no competing interests.

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