DEVELOPMENTAL MEDICINE & CHILD NEUROLOGY ORIGINAL ARTICLE

Anticipatory postural adjustments in a bimanual load-lifting task in children with developmental coordination disorder

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LIST OF ABBREVIATIONS

APA	Anticipatory postural adjustment
DCD	Developmental coordination disorder
M-ABC	Movement Assessment Battery for Children
MAA	Maximum angular amplitude

AIM Postural control is a fundamental component of action in which deficits have been shown to contribute to motor difficulties in children with developmental coordination disorder (DCD). The purpose of this study was to examine anticipatory postural adjustments (APAs) in children with DCD in a bimanual load-lifting task.

METHOD Sixteen children with reported motor problems (two females, 14 males; mean age 9y; SD 2y) and 16 typically developing, age-matched children (six females, 10 males; mean age 9y; SD 2y) took part in the study. The task required the children to maintain a stable elbow angle, despite imposed or voluntary unloading of the forearm. APAs were assessed using electromyography and kinematics analysis.

RESULTS Although children with DCD could compensate for the consequences of unloading, the results demonstrated that APAs were less efficient in children with DCD than in typically developing children. A positive and significant coefficient of regression between the flexor inhibition latency and the postural stabilization was only found in typically developing children.

INTERPRETATION The impaired fine-tuning of the muscle contribution and the poor stabilization performances demonstrate poor predictive modelling in DCD.

Developmental coordination disorder (DCD) is the term used to describe marked clumsiness without any sign of neurological injury, pervasive developmental disorder, or learning disability.* Performances on daily activities that require motor coordination are substantially poorer than expected. DCD may manifest itself in considerable delays in achieving motor milestones, poor performance in sports, or poor handwriting.[1] The clinical picture of the motor impairment is very heterogeneous, with some children presenting with poor gross motor coordination whilst demonstrating proficiency in fine coordination, and vice versa.

Postural deficits have been found in children with DCD.[2] It has been demonstrated that static postural control in children with DCD relies on a greater amount and a more variable patterns of muscular activity than it does in typically developing children of a similar age.[3] Studies exploring balance during quiet standing have yielded inconclusive results. Although Geuze et al.[4] failed to find any clear differences between children with and without DCD, other authors have observed a greater centre of pressure sway in children with DCD than in their typically developing peers.[5] It seems that the former are especially prone to difficulties when placed in novel situations.[4]

In more dynamic postural tasks the differences between children with and without DCD in the fine control of postural adjustments become more obvious. By predicting the possible postural disturbance created by movement performance, anticipatory postural adjustments (APAs) allow the body or one of its segments to maintain stability.[6] In a forward- and backward-leaning task, Przysucha et al.[7] observed less efficient postural adaptations in young males with DCD than in males without DCD. Using electromyography (EMG), Johnston et al.[8] showed that children with DCD demonstrate spatial and temporal impairment of APAs in most of the postural muscles that provide a stable basis when performing a rapid voluntary goal-directed arm movement. On the basis of centre of foot pressure displacement and grip force analysis in lifting while standing, Jucaite et al.[9] showed that, although children with DCD initiated postural adjustments before lifting the object, they did so with delayed timing. Further, postural adjustments presented less consistent adaptation to the weight of the lifted object in children with DCD than in non-affected comparison individuals. In other words, it seems that children with DCD encounter difficulties in the predictive modelling of APAs.

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*North American usage: mental retardation.

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Both perceptual and motor processing have been reported to be impaired in children with DCD. However, according to Wilson et al.,[10] DCD originates from a deficit in the *internal modelling* of action, which could explain the reduced ability of these children to produce an accurate forward model for prospective actions and APAs. Forward models use the efference copy to anticipate and cancel the sensory effect of a given movement. They also integrate both sensory and motor information, and, therefore, rely on intersensory integration (visual, tactile, proprioceptive, etc.).

In this study, we investigated APAs in children with DCD by means of a bimanual load-lifting task, which consisted of the unloading of the forearm by a voluntary movement of the child's other arm. The feedforward control of this coordination relies on both accurate representation of the load and coordination between the arm executing the unloading and the forearm position, to minimize the disturbance of the forearm position due to the unloading. In children with DCD a deficit in the internal modelling would then result in imprecise and variable APAs. In addition, the bimanual load-lifting task has the advantage of establishing a clear anatomical distinction between posture and movement (i.e. the 'postural forearm' supporting the load and the arm executing the movement). It also allows the simultaneous study of muscle contribution (EMG) and kinematics, both key indicators of APA.

This paradigm was chosen in an attempt to describe the mechanisms underlying the hypothesized impaired use of APAs in DCD.

METHOD

Sixteen children (two females, 14 males) with reported motor problems and ages ranging from 5 years 10 months to 12 years 7 months (mean 9y; SD 2y) took part in the study at the care units of Timone University Hospital in Marseilles and Toulouse University Hospital. The children's motor performances were assessed by means of motor tests, such as the Lincoln–Oseretsky,[11] the Charlop–Atwell,[12] or the Movement Assessment Battery for Children (M-ABC),[13] all of which have French norms. The children's results were poorer than expected, given their chronological age and intelligence in terms of academic achievement. Furthermore, their coordination problems were serious enough to interfere with academic performance and social integration. All the children also met the DSM-IV criteria for DCD.[1] The M-ABC[13]was used to test the children before administering the bimanual load-lifting task.

Sixteen age-matched children (six females, 10 males) ranging in age from 5 years 11 months to 13 years (mean 9y; SD 2y) constituted the comparison group (typically developing children). All children were receiving normal schooling and there were no reports of motor difficulty. There was no significant difference in age and arm length between the two groups, according to the Wilcoxon signed-rank test; and in sex and handedness, according to Fisher's exact test. All parents and children gave their informed consent before the experiment, which was approved by the local ethics committee.

What this paper adds:

- Defines APA impairments in children with DCD in a bimanual load-lifting task
- Links performance during postural stabilization to muscle inhibition latency
- Is in favour of immature or impaired predictive modelling in children with DCD

The experimental set-up was the same as that described in a previous study.[14] The bimanual load-lifting task consists of a comparison between the imposed and voluntary unloading of a load placed on the participant's forearm. The children were seated on a chair equipped with a support to which the non-preferred arm could be fixed vertically just above the elbow. The load was attached to this 'postural' arm, either below or on top of the forearm, via a metallic wrist band equipped with a strain gauge. Following the scaling determined in previous studies,[14] the weight of the load was 300g for children aged 5 to 6 years, 350g for children aged 7 to 8 years, 400g children aged 9 to 11 years, and 450g for children aged 12 to 13 years. Before each trial, children were asked to place their postural forearm in a horizontal and semi-prone position. In the imposed unloading situation, the load suspended below the postural forearm was unpredictably released by the experimenter by breaking an electromagnetic circuit. The unpredictable load release triggers an elbow flexion accompanied by an unloading reflex on the flexor muscles of the postural forearm. In the voluntary unloading situation, the load placed on the upper part of the postural forearm was lifted by the child using his or her contralateral hand. Reduced elbow flexion and reduced EMG activity on the flexor muscles, starting before the onset of unloading, indicated the use of APA.[14] The procedure consisted of 10 trials in the imposed condition, followed by 10 to 15 trials in the voluntary condition. The effect of order has been tested in this protocol[14] and does not affect comparisons between the two situations.

The force exerted by the load on the postural forearm and the angular postural elbow displacement signals were recorded, digitalized, and stored on a computer disk for analysis, along with the EMG signals (sampling rate 500Hz). Each trial was viewed offline on a monitor screen. Using a semi-automated program that enables visual adjustments, developed in our laboratory (Matlab 5.2, Mathworks), the onset of unloading (t_0) was defined as the time of the first maximal value of the second derivative of the force signal transmitted by the gauge. The upwards movement of the postural forearm was quantified both in the imposed and the voluntary conditions. We measured maximum angular amplitude (MAA), maximum velocity, and their corresponding latencies. In the voluntary unloading session, the MAA and maximum velocity for each trial were expressed as a percentage of the mean value obtained from each child in the imposed unloading session (MAA% and maximum velocity percentage). As such, MAA% and maximum velocity percentage expressed postural stabilization performances during voluntary unloading.

Bipolar surface electrodes (surface area 2.5mm^2) were placed over the surface of the biceps brachii and brachioradialis postural elbow flexors. EMG signals were recorded with a TELEMG multichannel electromyograph (BTS Bioengineering, Padova, Italy), amplified, rectified, filtered (10–200Hz band pass), and integrated with a 10ms time constant. In the imposed unloading condition, the latency and duration of the reflex inhibition were measured. In the voluntary unloading condition, changes in the level of activity occurring at t_0 ±100ms were measured (latency and duration). Within this time window, inhibition and activation occurring before t_0 +50ms were deemed to be anticipated.[14]

Most of the data analysis was performed using the mean value obtained for each child. These mean values were treated as single independent observations. The Wilcoxon signed-rank test was then used to compare performances between the voluntary and imposed unloading conditions and to compare children with and without DCD. Pearson's correlation coefficient was used to measure the correlation between the M-ABC score and postural performances, and between age and postural performances. The analysis of the influence of the flexor inhibition latency on postural stabilization during voluntary unloading (as expressed by MAA%) was completed across the entire set of trials for each child. This data structure, in which several individuals were assessed more than once, required a specific regression procedure. A generalized linear model (Gaussian distribution and identity link function) estimated by a generalized estimating equation procedure with an independent correlation matrix was used.[15] This approach takes the conditional dependencies between observations into account and provides unbiased standard error of the linear regression coefficients. Differences with a p value of <0.05 were considered to be statistically significant.

RESULTS

Postural stabilization and M-ABC impairment score

According to the M-ABC manual,[13] DCD is indicated when the impairment score is at or below the 5th centile, whereas 'borderline DCD' is indicated when the score is between the 5th and 15th centiles. In this study, nine children scored below the 5th centile (S1–S9), three children scored between the 5th and 15th centiles (S10–S12), and four children scored above the 15th centile (S13–S16). Figure 1 shows box plots representing key values of MAA% for each child and his or her age-matched peer. The correlation between the M-ABC score and MAA% was not significant.

The median values and quartiles of the MAA% were 36% (32–42%) in children with confirmed DCD, 22% (20–23%) in children with 'borderline DCD', and 26% (24–27%) in children with reported motor problems but who scored above the 15th centile. The median values and quartiles of their age-matched typically developing peers were 19% (12–27%), 12% (11–17%), and 17% (13–23%) respectively.

Taking into account the large difference between the three groups of children with reported motor problems, and in order to focus on 'children with confirmed DCD', the subsequent analysis was conducted only in children with an M-ABC score below the 5th centile. This group thus comprised the children with a reported motor problem who scored below the 5th centile on the M-ABC (n=9; two females, seven males; age range 5y 10m–12y 4mo) and their age-matched typically developing peers (n=9; four females, five males; age range 5y 11mo–11y 10mo). The mean age of each group was 8 years 5 months. Differences in age, arm length, sex, and handedness between children with and without DCD were not significant.

Imposed unloading

Imposed unloading was followed by an upward flexion of the postural forearm and by an unloading reflex characterized by flexor muscle inhibition. The latency and duration of this inhibition, measured on the biceps brachii and brachioradialis, did not differ significantly between the two groups of children (Table I). The difference between children with DCD and the typically developing children was not significant for the absolute values of MAA and maximum velocity during imposed unloading (Table II).

Voluntary unloading

As observed in typically developing children in a previous study,[14] the elbow rotation following voluntary unloading was smaller than that following imposed unloading in children with DCD. The absolute value of MAA was lower (t=45, p=0.004) and its latency shorter (t=45, p=0.004) during voluntary unloading than during imposed unloading. Maximum

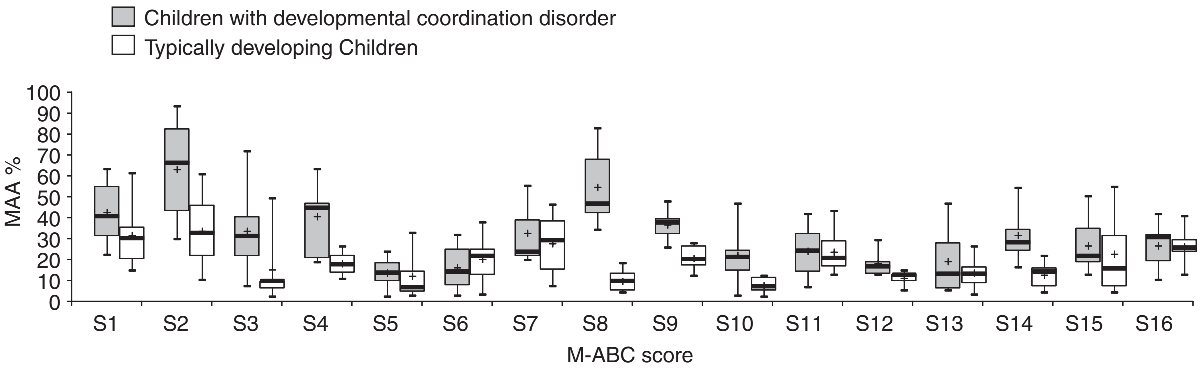

Figure 1: Box plots representing maximum amplitude percentage (MAA%) in children with reported motor problems (grey boxes) and age-matched typically developing children (white boxes) during voluntary unloading: means (cross), medians (bold line), quartiles (box lower and upper side), and extreme values. S1 to S9, Movement Assessment Battery for Children (M-ABC) score below the 5th centile; S10 to S12, M-ABC score between the 5th and 15th centiles; S13 to S16, M-ABC score above the 15th centile. Children were sorted by age within each of the three groups.

Table I: Median values and quartiles of the latency and duration of the inhibitions occurring on the biceps brachii and the brachioradialis during voluntary and imposed unloading in children with developmental coordination disorder (DCD) and typically developing children

	Inhibition latencies (ms)			Inhibition duration (ms)		
	Typically developing children	Children with DCD	Group comparison	Typically developing children	Children with DCD	Group comparison
Biceps brachii						
Imposed unloading	54.3 (52.4, 60.4)	52.8 (50.3, 58.6)	*ns* (t=21, p=0.74)	38.5 (35.8, 41.6)	37 (35.3, 49.5)	*ns* (t=22, p=0.64)
Voluntary unloading	–4.4 (–36.9, 4.6)	–0.2 (–8.8, 17.8)	*ns* (t=24, p=0.46)	71 (61.6, 87.9)	80 (74.6, 82.5)	*ns* (t=21, p=0.74)
Condition comparison	t=36, p=0.01	t=45, p=0.004		t=0, p=0.01	t=3, p=0.02	
Brachioradialis						
Imposed unloading	56.4 (55.2, 60.9)	62.3 (58.3, 63.1)	*ns* (t=16, p=0.31)	55.5 (51.3, 63.0)	45.38 (43.5, 48.53)	*ns* (t=3, p=0.16)
Voluntary unloading	–24.4 (–36.4, 3.2)	22 (0, 36.6)	t=32, p=0.05	73.4 (64.7, 82.8)	64.4 (55.3, 88.6)	*ns* (t=15, p=0.74)
Condition comparison	t=28, p=0.02	t=36, p=0.01		t=2, p=0.05	*ns* (t=12, p=0.46)	

Comparisons were performed using the Wilcoxon signed-rank test. *ns*, not significant.

Table II: Median values and quartiles of maximum angular amplitude (MAA) and maximum velocity (MV; expressed in both absolute values and percentages) of the forearm flexion during voluntary and imposed unloading in children with developmental coordination disorder (DCD) and typically developing children

	Typically developing children	Children with DCD	Group comparison
MAA			
Imposed unloading	7.9 (7.5, 8.9)	6.7 (6.3, 7.1)	*ns* (t=12, p=0.25)
Voluntary unloading	1.4 (1.12)	2.6 (2.3 2.9)	t=40, p=0.04
MAA%	19.9 (15.2, 21.1)	36.5 (32.6, 42.5)	t=43, p=0.01
MV			
Imposed unloading	71 (59.8, 76.9)	55 (50.6, 62.2)	*ns* (t=12, p=0.25)
Voluntary unloading	23.7 (16.4, 30.5)	40.4 (30.5, 43.4)	*ns* (t=38, p=0.07)
MV%	34.3 (29.2, 37.1)	64.9 (44.8, 79.9)	t=42, p=0.02

Comparisons were performed using Wilcoxon signed-rank tests. *ns*, not significant.

velocity was also reduced (t=43, p=0.01) and its latency was longer (t=3, p=0.02) during voluntary unloading than during imposed unloading.

MAA% and maximum velocity percentage were significantly higher in children with DCD than in typically developing children (Table II). MAA and maximum velocity latencies did not significantly differ between the two groups (178ms and 89ms respectively in children with DCD, and 154ms and 91ms respectively in typically developing children).

The activity measured on the biceps brachii decreased either before or concomitantly with the onset of voluntary unloading (Table I). This inhibition started earlier and lasted longer in the voluntary situation than in the imposed one for both groups of children. Neither the latency nor the duration of the biceps brachii inhibition differed significantly between the two groups. The inhibition measured on the brachioradialis started earlier in the voluntary condition than in the imposed one in both groups. However, in children with DCD, inhibition duration was not significantly longer for the voluntary unloading than it was for the imposed unloading. During voluntary unloading, brachioradialis inhibition latency was shorter in typically developing children than in children with DCD.

A previous study had demonstrated that the timing of inhibition is a key factor for APA performance.[14] In this study, we investigated the link between MAA% and the onset of postural flexor inhibition with a generalized estimating equation. For the biceps brachii, the standardized coefficient of regression showed a positive and significant effect of the onset of inhibition on MAA% in typically developing children (β=0.39, p=0.007) but not in children with DCD (β=–0.05, p=0.74). For the brachioradialis, a similar result was found (β=0.38, p<0.001, and β=0.03, p=0.89; Fig. S1, supplementary material published online).

The effect of age was tested in children with and without DCD for each variable using Pearson's correlation coefficient. Despite the participants' broad age range, age was not a contributing factor to any of the results.

DISCUSSION

DCD, M-ABC score, and postural stabilization

In the first part of this study, we showed that the diagnosis of DCD is still problematic.[16] The assessment of DCD relies on an individually administered norm-referenced test. In France, many physiotherapists still refer to French versions of the Lincoln–Oseretsky[11] or of the Charlop–Atwell[12] motor scales. Because the M-ABC[13] has been described as the best instrument and facilitates international communication, we added this test to our protocol and observed that some of the selected children scored above the 15th centile. This phenomenon has been reported previously,[17] and one possible explanation for this may be that none of the existing tests of motor function covers the whole range of motor abilities. It is, however, important to stress that a specific test and a cut-off point for inclusion should always be clearly determined, and that clumsy children scoring above the 15th centile deserve further examination.

Contrary to the findings of Cherng et al.,[5] the correlation between the M-ABC score and postural stabilization was not significant in this study. However, despite the small group size, children scoring between the 5th and the 15th centile tended to present lower values of MAA% than children scoring below the 5th centile. These children with ‘borderline DCD’ also seemed to be more efficient in maintaining postural forearm stability during the task. Further investigations should help researchers and clinicians to explore the status and development of these ‘at risk for DCD’ children.

Unloading reflex in children with DCD

Both kinematic and EMG data indicated that the unloading reflex during imposed unloading was the same in both groups of children. Other studies using this paradigm have found that this reflex is intact in children with Duchenne muscular dystrophy[18] and autism,[19] but not in individuals with deafferentation.[20] This result confirms that the proprioceptive afference and motor efference that constitute the unloading reflex are not impaired in DCD.

Postural anticipation in children with DCD during voluntary unloading

It appears from our study that APAs are present in children with DCD, just as they are in typically developing children.[14] The decrease in both maximum elbow rotation and maximum angular velocity during voluntary unloading compared with imposed unloading indicates the presence of voluntary control of postural stabilization. Further, the early inhibition of the elbow flexors within the anticipatory window (i.e. before t_0 +50ms) confirms that postural stabilization was made possible by the use of an anticipatory mode of control.

However, despite the presence of APAs, forearm stabilization during voluntary unloading was poorer in the DCD group than in the typically developing group. The anticipatory control of posture was not as efficient in children with DCD as it was in typically developing children. This result is in line with other studies exploring APA during arm pointing[8] or in a voluntary load-lifting task while standing.[9]

Under normal circumstances, the initiation of voluntary unloading triggers the onset of a precisely organized sequence of muscle activation and inhibition in the postural forearm.[6] Using the same task, Schmitz et al.[14] demonstrated that precise mastering of timing parameters is one of the key factors in the development of APA during childhood. Our results show that the timing of the muscular events on the brachioradialis, but not on the biceps brachii, was affected in children with DCD compared with typically developing children. This may contribute to the impaired postural stabilization observed in children with DCD. Inconsistent timing of muscle activation sequences and an atypical profile of muscle activation patterns have been reported in children with DCD.[2–4,8,21] Given that development proceeds in a proximodistal manner, the delayed inhibition of the distal muscle (brachioradialis) only, as observed in this study, argues in favour of a maturational delay in the development of APA control in children with DCD.

From flexor inhibition to postural stabilization

The bimanual load-lifting task makes it possible to calculate the coefficient of regression between the onset of flexor’s inhibition and postural stabilization. This effect was positive and significant in typically developing children: the earlier the onset of inhibition, the better the forearm stabilization. Interestingly, we did not find this link for either of the muscles in children with DCD. When Geuze[2] analysed the correlation between EMG activation and ground reaction force in the one-leg stance, he also observed a weaker coupling in children with DCD than in typically developing children. We assume that the poor predictive modelling of force–time parameters of APA lies behind the weak efficiency of postural control in children with DCD.

Returning to the computational approaches to motor control, our results support the *internal modelling deficit* hypothesis of DCD.[10] First, peripheral sensory and motor function appeared to be preserved in children with DCD, in so far as the unloading reflex was similar in typically developing children and in children with DCD. In addition, children with DCD were able to produce APAs and presented anticipatory muscle inhibitions and reduced forearm flexion during voluntary unloading. However, the feedforward planning of the postural component of the action was not as consistent with the task goal in children with DCD as it was in typically developing children. The onset of brachioradialis inhibition was delayed in the former group compared with the latter; there was no link between muscle inhibition onset and forearm stabilization in children with DCD, unlike typically developing children, and forearm stabilization was poorer in the former than in the latter. Poor predictive modelling may have stemmed from the impaired integration of kinaesthetic and visuomotor feedback concerning the object’s weight, the onset of unloading, and the temporal and spatial coordination between both arms. As a result, bimanual coordination during the unloading task appeared imprecise and immature in children with DCD.

CONCLUSION

The bimanual load-lifting task relies on a precise forward model of prospective action coordinating movement and posture, and requires a carefully orchestrated sequence of postural muscle activations and inhibitions.[6] In this study, the impaired fine-tuning of the muscle contribution and the poor performances on postural stabilization argue in favour of impaired predictive modelling in DCD.[10] Note, however, that the children from this study underwent a definite classification of DCD and that a closer look at the individual kinematic data reveals that not all children exhibited an impairment of APA in this task.

The characteristics of APA observed in this study are indicative of an immature anticipatory control of posture in children with DCD scoring below the 5th centile on the M-ABC. The immature aspect of motor coordination or function in children with DCD has already been reported.[22,23] However, in contrast to other neurodevelopmental disorders, spontaneous recovery from DCD may occur during adolescence.[24,25] This study was initially designed to investigate the development of children with DCD, but our results do not yield any developmental conclusion. We believe that longitudinal studies are now needed to track developmental trends in these children. Such research would probably help to understand better the important variability observed in children with DCD.

Finally, APAs should also be investigated in children or adolescents with reported motor difficulties who score above the 5th or 15th centile on the M-ABC.[13] A better understanding of the two DCD developmental pathways (persistence or resolution)[24] should, at last, help us to determine whether DCD results from a maturational delay or from a specific dysfunction of the internal model of the motor system.

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ONLINE MATERIAL

Supporting information for this article is available online:

Figure S1: Graphic representation of maximum amplitude percentage (MAA%) as a function of flexor inhibition latency for each trial.

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