Dynamic control of balance in children with Developmental Coordination Disorder

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Chapter I

General introduction

GENERAL INTRODUCTION

Motor performance is one of the main determinants of the degree in which a child can function efficiently in daily life and at school. Of all children, 5-10% have developmental motor problems that seriously affect their activities of daily living. These children are referred to as children with Developmental Coordination Disorder (DCD) (APA, 2013; Polatajko, Macnab, Anstett, Malloy-Miller, Murphy, & Noh, 1995; Sugden & Chambers, 2005). Around sixty or seventy percent of these children have balance problems (Macnab, Miller, & Polatajko, 2001; Geuze, 2005). This thesis aims to disentangle features of dynamic balance control problems in children with DCD.

Balance is defined as "an even distribution of weight enabling someone or something to remain upright and steady", according to the Oxford Dictionaries. Balance is not a skill, but a basic condition to control the center of mass (CoM) by keeping its projection in or returning it to the base of support (BoS) (Otten, 1999; Shumway-Cook & Woollacott, 2007). An equivalent for balance is equilibrium or postural stability. Posture is defined as "the relative position of parts of the body or of the whole body with respect to a reference frame" (Latash & Hadders-Algra, 2008). Posture includes aligning the body in an upright position, but also the orientation of the body to the environment (Shumway-Cook & Woollacott, 2007, pp. 158). Postural control usually develops according to a predictable sequence of expanding abilities from early childhood to adolescence (Illingworth 1987; Hadders-Algra, 2008). This introduction will start with a brief description of the normal development of balance. This will be followed by some theoretical aspects of motor learning, the role of feedback and feedforward control, and assumed causes of balance problems in children with DCD; it ends with the aims of this study.

Balance: static and dynamic

Postural control can first be observed in the prenatal period after 32 weeks postmenstrual age with some antigravity postural control of the head and trunk (Prechtl, 1977). For a clear description of the sequential development of postural control we refer to Shumway-Cook & Woollacott 2007, chapter 8 in: *Motor Control* and Hadders-Algra, chapter 3 in: *Postural Control: a key issue in developmental disorders*. During development, the CoM of the body moves upwards with each step of gaining a more upright posture and due to the growth of body length.

Two types of balance are usually distinguished. Firstly, *static balance* which is the capacity to maintain the body in a stable position in which the base of support is fixed. Both the person and environment remain" static" (Sugden & Sugden, 1991; Gentile, 1987; Spaeth-Arnold, 1981). Although this type of balance is called static, continuous forces acting upon the body result in movement or sway that needs to be controlled. Quiet standing consists of a relative unstable equilibrium because the upright standing body behaves like an inverted pendulum – any deviance from perfect balance is reinforced by the force of gravity and needs to be counteracted to prevent loss of balance by reactive and prospective control. Secondly, *dynamic balance* is distinguished, which represents the capacity to maintain posture whilst accommodating to a dynamic environment or a task, or both. It is the ability to control while i) intentionally moving in a fixed environment (walking in a room with furniture), but also under more challenging environmental constraints like ii) standing still in a changing environment (bus ride) or iii) intentionally moving through a changing environment (playing games in a schoolyard) (Sugden & Sugden 1991; Gentile 1987; Spaeth-Arnold, 1981). In these situations, one needs to maintain in upright position with dynamic environmental constraints, which threaten the projected Centre of Pressure (CoP) to move beyond the border of the base of support in antero-posterior or lateral direction. After such external perturbations, reactive postural adaptations will generate rapid adjustments to help stabilize the body and prevent bumping into something or falling down. However, when braking is more or less expected, anticipatory postural adjustments (APA's) can counteract predictable forces to prevent loss of balance or prepare an altered posture to remain in balance during a bus ride (Geuze, 2007).

This thesis focuses on dynamic balance tasks in action controlled Virtual Reality (VR) gaming. In these games, intentional weight shifts are used to steer a VR character (a so-called avatar) on a static base of support without losing balance. The tasks require both task control and dynamic balance control. Moreover, dynamic balance control is direction specific.

To control a standing position, muscles are either tonically active, with a great propensity to work, while other muscles are phasically active to oppose and correct posture by fast contractions (Kendal & McCreary, 1983; Basmajian & Deluca, 1985). When a relatively small disturbance occurs in forward direction, small corrections around the ankle axis (ankle strategy) can be used to correct the movement of the body by a muscle synergy in opposite direction (Nashner 1977; Nashner, 1989). Contrary, a hip strategy is usually used after large perturbations in anterior-posterior direction, characterized by large and rapid corrective motion at the hip joints in the backward or forward direction to counteract the external forces with simultaneous compensatory motion in the ankles. On the other hand, in case of backward loss of balance, activity of the muscles at the frontal side of the body will correct the perturbation, but then needs control not to overreact. In case of loss of balance in forward direction, the backside of the body will initiate the body to go backwards (Horak & Nashner 1986). Head movements take place in the opposite direction of the movements of the hip and ankle (Lekhel, Marchand, Assaiante, Cremieux & Amblard, 1994). When abovementioned strategies are not sufficient and threaten balance, a reach or a step leads to a changed or enlarged base of support in order to regain control of the COM and prevent a fall (Shumway-Cook & Woollacott, 2007).

When the loss of weight is in medio-lateral or sideways direction, a different strategy is seen by the muscles around the ankle to correct a small loss of balance, and for recovering larger balance disturbances upper leg and hip muscles are involved. (Maki, McIlroy, & Perry, 1994; Winter Prince, Steriou, & Powell, 1993; Horak, & Moore, 1989). Children at the age of 4-6 years usually present mature control, adaptability and APA's in quiet, unthreatened stance (Newell, 1997; Nashner, Shumway-Cook, &Marin, 1983; Woollacott & Shumway-Cook, 1986). Consistent active control of balance after balance perturbation is only present in children who are 7-10 years old, characterized by high levels of abdominal muscle activity and refined response patterns (Woollacott et al. 1998; Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985).

Motor learning of postural control

The musculoskeletal system is redundant in its degrees of freedom. This implies that there are usually many solutions for a movement or control problem. Musculoskeletal components, like range of motion of joints and the viscoelastic properties of muscle fibers and tendons, play a role in holding balance. Changes in co-contraction level in muscles are an effective mechanism to prepare for an expected perturbation or in learning a new skill. Bernstein (1967) describes motor learning as controlling degrees of freedom as an essential characteristic of learning a new movement task. By freezing redundant degrees of freedom by co-contraction, the task becomes easier to perform. This stage is known as the novice stage (Vereijken, Emmerik, Whiting, & Newell, 1992). A higher level of performance, also called the advanced stage, is reached when more joints are allowed to participate in the movement while maintaining body posture. Co-contraction of agonist and antagonist muscles will be reduced and replaced by muscle synergies across a number of joints in order to perform a well-coordinated movement. The expert stage is recognized by a release of all those degrees of freedom that are needed in the task to execute an efficient well-coordinated movement, making use of mechanical and inertial characteristics of the limbs to speed up the adaptation and reduce energy costs (Schmidt & Lee, 2005; Vereijken et al., 1992).

Another traditional motor learning theory of Fitts and Posner (1967) emerged in the same period. It describes the progress of skill through a cognitive, associative and autonomous stage. This theory is still the base of more current psychological skill acquisition approaches in which reflective action or conscious awareness of bodily movement plays a functional role and results in an effective way to learn at the novice level (Shusterman, 2008; Toner & Moran, 2015). This may even help athletes to identify inefficient movement pattern and then help to consciously attend to alter and refine the proficiency towards an expert level (Toner & Moran, 2015). However, these theories concentrate on motor skill learning, which appear to be different from postural control in a dynamic balance task, but the one cannot progress without the other.

The third contemporary theory of motor learning describes two stages of motor skill acquisition of which the first stage consists of an explorative understanding of the task and its dynamics displayed by different movement strategies (Gentile, 1987). In the second stage, the movement is refined, characterized by a more consistent and efficient performance. During the first stage of learning task, performance improves fast, while in the second stage the improvement will be more gradually which may continue for a long period of time (Schmidt & Lee 2005). For adequate motor performance, one needs besides normal maturation of the nervous system the opportunity to practice skills and motor learning ability.

Feedback and feedforward control

The sensory information is essential for motor learning. Sensory endings in muscle spindles, tendons and joints inform the central nervous system on the position of the limbs and their position related to the trunk (Roll & Vedel 1982; Cordo, Burke, Gandevia, & Hales, 1998). The youngest children have the least control over their movements (Austad & van der Meer, 2007). Visual input is usually initially dominant when learning a new motor task or skill, while its relative importance decreases as soon as the task becomes more automatic and thus relies more on somatosensory input (Lee & Aronson 1974; Lee & Lishman, 1975). The adjustment of posture during movements is not only due to the reactive control after perturbing forces of the motor system, but also to predictive control, which increases in skilled movements. Internal models for action are built using sensorimotor feedback loops, and appear to be stored in the cerebellum (Miall & Wolpert, 1996; Imamizu, Kuroda, Yoshioka & Kawato, 2004; Imamizu et al. 2000). The forward model exists of a 'blue-print' of the motor command signals, which predicts the future position of the moving parts of the body, while the inverse model generates the necessary motor output signals needed to execute the planned action (Wolpert, 1997; Wolpert & Flanagan, 2001; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank. 2013). In the novice or first stage of motor learning, exploration of solutions of movement challenges takes place, making use of online control using sensorimotor feedback. Through experience, this usually results in successful internal models of each task. Most motor tasks require shifts of weight of body parts or the complete body that are controlled by anticipation and restoring loss of posture or balance, which depend on efficiently coordinated visual, vestibular and proprioceptive systems (Assaiante & Amblard, 1995). The internal model offers the advantage of making use of faster internal feedback loops by comparing sensorimotor feedback directly with the predicted status.

Statement of the problem

The reason why a considerable proportion of children with DCD show problems with postural control and perform worse during skills requiring high levels of balance like hopping, running or jumping is not fully understood. Children with DCD perform worse in these tasks and respond slower during variable balance challenges compared to typically developing children (Kalverboer 1996; Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). Geuze and Wilson conclude that children with Developmental Coordination Disorder (DCD) show problems in postural control at both the neuromuscular level, like increased amount of co-contraction or decreased muscle tone and the behavioral level, like more postural sway, slower adaptation to perturbation and instability (Geuze & Wilson, 2008). Postural sway in stance is larger during challenging conditions such as standing on one leg, with eyes closed or during unexpected perturbation in children with DCD compared to TD children (Cherng, Hsu, Chen, & Chen, 2007; Geuze, 2003; Grove & Lazarus, 2007). Moreover, in dynamic balance tasks such as gait under challenging circumstances or when crossing obstacles, children with DCD exhibit more sway (Deconinck, De Clercq, Savelsbergh, Van Coster, Oostra, & Dewitte, 2006; Deconinck, Savelsbergh, Clercq, & De Lenoir, 2010). Besides differences in sway, higher levels of co-activation and more variable movement patterns are found during walking or running (Raynor, 2001; Rosengren et al., 2009; Chia, Licari, Guelfi, & Reid, 2013).

How can these characteristics of balance problems in children with DCD be explained? There are different theories, sometimes overlapping, that might explain poorer balance in children with DCD. Firstly, explanations have been proposed at the neuromuscular level, i.e. a 'low muscle tone' (Ball, 2002) which represents a lack of force in peak contractions and 'pathological freezing' through increased co-activation (Raynor 2001; Johnston, Burns, Brauer, & Richardson, 2002). Secondly, explanations have been put forward at the neural level resulting in delayed response times which makes posture and balance control more difficult. Control of balance requires cerebellar involvement. DCD characteristics such as poor coincidence timing and more variability of rhythmic coordination also suggest the involvement of the cerebellum (Lundy-Ekham, Ivry, Keele, & Woollacott, 1991; Mackenzie, Getchell, Deutsch, Wilms-Floet, Clark, & Whitall, 2008; Hadders-Algra 2002). The cerebellum is also involved in motor learning (Biotteau, Peran, Vayssiere, Tallet, Albaret, & Chaix, 2016). The less efficient APA's in children with DCD as compared to their peers (Jucaite, Fernell, Forssberg, & Hadders-Algra, 2003; Jover Schmitz, Centelles, Chabrol, & Assaiante, 2010), suggest difficulties with forward modeling of postural adjustments and implementing predictive models of action, also called internal model deficit (Wilson & McKenzie, 1998; Wilson & Butson, 2007; Wilson et al. 2013). Since the internal model can only be built by learning from sensorimotor feedback providing internal feedback loops, a motor learning deficit would lead to poorer predictive functioning. Impaired visual-motor integration (Wilson & McKenzie, 1998) and reduced ability to automate motor skills (Nicolson, Fawcett, & Dean, 2001) may limit adequate motor learning. So far no studies have looked into the learning of balance tasks of children with DCD.

Besides these theories, it is known that children with DCD dislike physical activities and their motivation to become more physically active is poor (Kwan, Cairney, Hay, & Faught, 2013). At school age, children become aware of their poor performance in sports compared to their peers (Cairney, Hay, Faught, Wade, Corna, & Flouris, 2005; Schoemaker & Kalverboer 1994; Cantell, Smyth, & Ahonen, 1994), which makes them less popular and which increases withdrawal of adequate practice (Causgrove Dunn, & Watkinson, 2006), becoming physically unfit and experience more loneliness as they participate less in sports or playground games (Cairney & Veldhuizen, 2013; Schoemaker & Smits-Engelsman, 2015). Lack of practice limits motor learning and formation of internal models and increases a delay in motor performance even further.

Based on the conclusions of the reviews of Wilson et al. (2013) and Adams et al. (2014), we consider the balance problems of children with DCD to originate in a deficit in predictive control (internal model deficit) and in learning new coordinated movement patterns. Based on these theories the initial levels of performance on a dynamic balance task is expected to differ between children with and without DCD and children with DCD are expected to progress less in training than TD. The present thesis will focus on differences between children with DCD and typically developing children in motor performance, and in motor learning, retention and transfer. Dynamic postural control tasks will be used that challenge coordination and timing to study these group differences in performance and learning.

Aims

The main aim of this thesis is threefold:

- to determine which aspects of dynamic balance control differ between children with and without DCD
- to investigate whether motor learning through intervention differs between children with and without DCD in a task that requires dynamic balance control
- to determine whether children with DCD show transfer of the training to other skills.

The groups of children were aged between 6-12 years. Children with balance problems fulfilling the Diagnostic Criteria for DCD (DSM-5, APA 2013)[1] were compared to groups of matched control children, selected according to low scores on the MABC-2 test (for criteria see Table 1.1). Studies were conducted with a group of children with DCD and typically developing children as controls in the Netherlands as well as in South Africa in order to examine cultural differences.

Dynamic balance control was studied using a Nintendo© Wii Fit system with a Wii Balance Board (WBB). The Wii ski-slalom game was the target game, used to measure change due to learning or training. Ten other Wii balance games were used for Wii Fit training (also referred to as Virtual Reality (VR) training or variable training schedule). By shifting weight on the WBB, the child can control these games and can observe the results of these weight shifts directly on a TV screen. In part of the study, the WBB was put on force plate sensors to detect the players Centre of Pressure (CoP) displacements. The specific game used to measure dynamic balance is the ski slalom game. This task requires both dynamic adaptation of posture to control the avatar and dynamic control of balance.

Table 1.1 DSM-5* Diagnostic Criteria for Developmental Coordination Disorder (APA, 2013)

A	The acquisition and execution of coordinated motor skills is substantially below that expected given the individual's chronological age and opportunity for skill learning and use. Difficulties are manifested as clumsiness (e.g., dropping or bumping into objects) as well as slowness and inaccuracy of performance of motor skills (e.g., catching an object, using scissors or cutlery, handwriting, riding a bike, or participating in sports).
B	The motor skills deficit in Criterion A significantly and persistently interferes with activities of daily living appropriate to chronological age (e.g., self-care and self-maintenance) and impacts academic/school productivity, prevocational and vocational activities, leisure, and play.
C	Onset of symptoms is in the early developmental period
D	The motor skills deficits are not better explained by intellectual disability (intellectual developmental disorder) or visual impairment and are not attributable to a neurological condition affecting movement (e.g., cerebral palsy, muscular dystrophy, degenerative disorder).

*DSM-5: Diagnostic and Statistical Manual of Mental Disorders Fifth edition

1 Children who met the criteria for DCD were referred to as probable DCD (p-DCD) in chapter 2 and 3 and, with advancing insight as presented in Smits-Engelsman et al. 2015, as children with DCD in chapter 4-8.

The control of dynamic balance was measured at different levels. Firstly, performance was measured as the scores (speed and accuracy) in a chosen test game (Wii ski-slalom). Secondly, we studied dynamic balance control at the level of shifting weight by placing the WBB on an AMTI force plate by calculating the trajectories of the CoP of the child during the ski slalom. Lastly, differences between groups and change over time were evaluated using standardized tests.

In the chapters of the thesis we address the following specific questions:

Chapter 2: Does task performance in the dynamic balance control task differ between children with DCD compared to children with typical balance control (TD-group)? Does dynamic balance control and task efficiency improve after Wii Fit intervention such that change due to intervention is significantly larger than a change over a similar non-intervention period?

Chapter 3: Do children with and without DCD differ in dynamic control of balance in anterior-posterior (AP) and lateral directions as displayed in variability and path length of the Center of Pressure (CoP); and do they change control over time or after VR intervention?

Chapter 4: Is the rate of short-term learning a dynamic balance task different between children with DCD and their TD peers? Does the rate of motor learning differ between children with DCD from The Netherlands and South Africa, the latter being novice towards motion steered computer gaming? What is the retention effect after a period of no intervention?

Chapter 5: Is the rate of learning over a longer period and the retention different between DCD and control groups? Does the rate of learning depend on the level of the game? Do the groups differ in transfer to other balance tasks?

Chapter 6: Does variable training lead to better motor learning compared to repetitive training in children with and without DCD when exposed to active VR training? Are there differences in improvement during training, retention, and performance after the training and amount of transfer? Is the level of motor competence (children with DCD and their TD peers) a mediating factor in the rate of learning and the amount of transfer?

Chapter 7: Does improvement in games score after VR training lead to transfer to other skills like running, jumping, stair climbing? What is the effect of type of practice (variable and repetitive)?

Chapter 8: General discussion.

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