Abstract The present study addressed the question of how anticipatory postural adjustments (APA) develop during childhood, in the range from 4 to 8 years, during a bimanual load-lifting task. This task required maintaining the stabilisation of the forearm position despite imposed or voluntary unloading of the forearm. Elbow angle and multiple surface EMG were recorded on the child postural forearm supporting a load. During voluntary unloading, the elbow flexion of the postural forearm was calculated as a percentage of the elbow flexion measured during the imposed situation. Improvement of the forearm stabilisation was observed mainly between 4–6 and 7–8 years of age, but the oldest children did not reach the adult level of stabilisation of the postural forearm. Moreover, a clear developmental sequence in the acquisition of APA was reported: first the selection of an efficient EMG pattern underlying the forearm stabilisation, and second the mastering of timing adjustments. In fact, regression of the co-contraction pattern was observed with age, together with selection of the adult-like reciprocal pattern. Mastering of the timing adjustments of the reciprocal pattern, characterised in adults by a well-synchronised co-ordination between onset of the flexor muscle contraction of the manual arm and onset of the flexor muscle inhibition of the postural forearm, progressively improves during development. Moreover, these results suggest that the internal representation of the consequences of unloading on the forearm stabilisation, underlying anticipatory function during a bimanual co-ordination task, slowly build up during childhood.

Keywords Anticipatory postural adjustments · Bimanual co-ordination · Kinematic · EMG · Children

Introduction

In children, as in adults, co-ordination between posture and movement can be achieved either in a feedback manner, after the initiation of the movement, to correct for the instability caused by the movement, or in a feed-forward manner, prior to or concomitant with the prime mover muscles, in order to compensate in advance for the destabilising effects of the movement. Anticipatory postural adjustments (APA) occur before the onset of disturbance due to voluntary movement, and therefore they prevent the forthcoming disturbance of posture. APA are mostly acquired by learning because their organisation depends on the previous experience of the postural disturbance associated with the movement performance. The general process underlying the acquisition of APA implies the transformation of feedback postural corrections into a feedforward control associated with voluntary movements which are causing the postural disturbance (Massion 1992).

During childhood, it is classically admitted that feedforward control matures later than feedback control (Bernstein 1967; Kelso 1982; Haas et al. 1989). Developmental studies involving postural control of the whole body during various posturokinetic tasks suggest that feedforward control, despite its early emergence, takes time to mature and most of its components do not appear consistently until 4–5 years of age (Haas et al. 1989; Hay and Redon 1999, 2001; Assaiante et al. 2000). Moreover, the expression of anticipatory locomotor adjustments for obstacle avoidance is still maturing during mid-childhood (McFadyen et al. 2001), and similar maturation has been reported in jumping tasks (McKinley and Pedotti 1992). Other developmental studies focusing on manual motor skills also report an anticipatory control strategy that starts to clearly appear in 4-year-old children (Forssberg et al. 1992; Paré and Dugas 1999; Schmitz et al. 1999).

The bimanual load-lifting task is an interesting model for assessing the development of APA. It involves the co-ordination between a manual task, lifting a load, and
a postural task, stabilising the postural forearm, which will be used as a reference frame for the organisation of movement (Massion et al. 1999). To succeed in this task the subject must first control the stabilisation of the forearm and second master the timing adjustment of the two events performed simultaneously by the postural and the manual arms.

Previous studies, in bimanual unloading tasks in adults, suggested that there are two modes for the postural stabilisation, as indicated by muscle activity. The first involves an increase in the joint stiffness (Biryukova et al. 1999), indicated by a co-contraction of antagonist muscles. The second and the most efficient pattern is characterised by a reciprocal activity of antagonist muscles, with a suppression of EMG activity of the load-bearing muscles (Hugon et al. 1982; Kaluzny and Wiesendanger 1992). Studies on motor learning suggested that during ontogenesis, the acquisition of a new sensorimotor skill presents a time course similar to that occurring during the learning of a new skill in adults (Bernstein 1967; Newell and Emmerik 1989; Thelen et al. 1992). First, co-contractions, which are the prevailing EMG pattern commonly found at the beginning of each new acquisition of the child, are used (Gachoud et al. 1983; Forssberg 1985; Hadders-Algra et al. 1992; Assaiante and Amblard 1995; Konczak et al. 1997). Then, subjects learn to reduce the cost in energy by using a selective activation of the muscles involved in the task. That is, skilled subjects would not rely entirely upon muscle stiffness to control their movements, but rather would dynamically control muscle forces taking into account passive mechanical forces to achieve the goal. This style of control requires that skilled subjects can predict the internal and external passive mechanical forces that characterise an action performed in a given environment (Bernstein 1967; Newell and Emmerik 1989; Thelen et al. 1992).

The bimanual load-lifting task also implies a co-ordination between both arms that depends on a central timing signal (Massion et al. 1999). Indeed, a precise timing is required for the fine adjustment of APA. During this task, there is an almost perfect synchronisation between the onset of the EMG burst of the flexors of the arm lifting the load and the onset of the decreased EMG activity of the load-bearing flexors (Hugon et al. 1982; Kaluzny and Wiesendanger 1992). The timing of the adjustments is a parameter to be early affected in various pathologies such as in Parkinson’s disease during a load-lifting task (Viallet et al. 1987). Moreover, the timing of the anticipatory adjustments seems to be the main difficulty to be mastered during childhood and the latest to reach the adult-like precision (Eliasson et al. 1995; Konczak and Dichgans 1997).

This study was mainly focused on the gradual development of feedforward control during childhood. The goal was to investigate accurately the building processes of APA during the bimanual load-lifting task in 4- to 8-year-old children as compared to adults. Our first hypothesis was that feedforward control may be characterised by a progressive removal of the immature co-contraction pattern in favour of the mature reciprocal pattern. This hypothesis is in agreement with developmental theories suggesting that mature and immature patterns are still belonging to an innate repertoire of patterns, and that selection plays a major role during development (Hadders-Algra et al. 1996a; Forssberg 1999). Our second hypothesis concerned the maturation of the timing parameters involved in the bimanual co-ordination between the lifting performed by the right arm and the postural control of the left forearm. There should be a progressive improvement of the mastering of the temporal parameters involved in this co-ordination. Kinematic results concerning the youngest children (3- to 4-year-old) included in this study were presented previously (Schmitz et al. 1999).

Materials and methods

Subjects

Forty-one healthy right-handed children aged from 4 to 8 years, and 8 right-handed adults, participated in this experiment. Four age groups were compared: a group of 12 children aged 4 years (mean ± SD: 4 years ±5 months; 4 girls, 8 boys), a group of 15 children aged from 5 to 6 years (5.3 years ±6 months; 4 girls, 11 boys), a group of 14 children aged from 7 to 8 years (7.3 years ±6 months; 5 girls, 9 boys), and a group of 8 adults aged from 23 to 34 years (27.8±4.4 years; 3 males, 5 females). The children were all at school, and inside each age group they presented similar motor capacities for their upper extremities in their everyday life. For children, all parents gave their informed consent prior to the experiment, which obtained the approval of the local ethics committee.

Experimental set-up

The experimental arrangement was the same as that described in a previous paper (Schmitz et al. 1999), and is shown schematically in Fig. 1A. The subjects were comfortably seated on a hard-back chair, equipped with a support to which the postural arm (chosen as the left for all the subjects) could be fixed vertically just above the elbow. The subjects were asked to place their left forearm horizontal and semiprone during the entire session, without any other specific instruction. The experimenter verified the correct postural position before each recording. The forearm carried a platform equipped with strain gauges, allowing the load to be suspended below it or placed upon it. During imposed unloading, the release of the load suspended below the platform by means of an electromagnet was performed by the experimenter switching off the magnet at unpredictable times. During voluntary unloading, the load was placed onto the platform and voluntarily lifted by the subject with his/her right hand. The weight of the load was chosen, in the children’s group, to maintain a constant ratio between the body weight and the load weight. In agreement with the initial ratio used for adults in previous studies (Dufosse et al. 1985; Ioffé et al. 1996), a 1,000-g load was chosen for the adult group. The load weight was adapted for each age group: a 300-g load for the 4-year-old group, a 350-g load for the 5- to 6-year-old group, and a 400-g load for the 7- to 8-year-old group. The general procedure was as follows: first a session of ten control imposed unloadings, then a session of ten voluntary unloadings, and a last session of ten control imposed unloadings. A 5-min rest period was proposed between each situation. An entire recording usually lasted 1 h.