Exp Brain Res (1998) 120:85–94 © Springer-Verlag 1998

RESEARCH ARTICLE

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Scaling anticipatory postural adjustments dependent on confidence of load estimation in a bi-manual whole-body lifting task

Received: 30 October 1995 / Accepted: 10 September 1997

Abstract Anticipatory control of motor output enables fast and fluent execution of movement. This applies also to motor tasks in which the performance of movement brings about a disturbance to balance that is not completely predictable. For example, in bi-manual lifting the pick-up of a load causes a forward shift of the centre of mass with consequent disturbance of posture. Anticipatory postural adjustments are scaled to the expected magnitude of the perturbation and are initiated well before the availability of sensory information characterising the full nature of the postural disturbance. However, when the postural disturbance unexpectedly changes, the anticipatory adjustment of joint torques is not equilibrated and may result in a disturbance to balance. In a previous study, it was demonstrated that apart from anticipatory postural adjustments, corrective responses after load pick-up are used to further compensate the postural disturbance. In this study it was examined whether the central nervous system (CNS) assembles a strategy that incorporates both anticipatory control and corrective responses, in which the magnitude of the anticipatory postural adjustments depends on the perceived level of predictability of the postural disturbance. Subjects performed series of lifts in which the magnitude of the load was never revealed to the subject. Two boxes equal in size and colour, but different in mass (6 and 16 kg), were used. Differences in expectation were created by several lifts with the 16-kg load before the 6-kg box was presented. It was observed that the number of strong corrective responses (stepping) varied with the number of 16-kg trials that formed the prior experience when the final 6-kg trial was presented. The follow-up question was whether control relied more on anticipation in the stepping trials, compared with trials in which such gross signs of imbalance were absent. In this study it was shown that subjects when stepping (i) exhibited differential anticipatory postural adjustments in comparison with 6-kg trials in which expectation was not shaped by preceding 16-kg trials, and (ii) scaled the anticipatory postural adjustments similar to those preceding lift-off of the 16-kg trial preceding it. These findings emphasise the programmed nature of the anticipatory postural adjustments and the ability of the CNS to selectively tune the anticipatory postural adjustments to stored information gained during the previous lift(s).

Key words Postural control · Lifting · Balance
Anticipatory postural adjustments · Stepping response

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Introduction

The execution of fast, smooth, accurate movements is thought to rely on the anticipatory control of motor output, because of the long delay between the release of muscle commands and feedback (Rack 1981). This type of control is proposed as a prerequisite for well-coordinated transitions between movement phases (Forssberg et al. 1992). For example, lifting an object from the ground involves forward bending of the trunk while reaching for the load (reaching phase), grasping the load (grasping phase), lifting the load to a desired end position (lifting phase) and, finally, establishing a new static equilibrium. When the load is grasped in front of the body, the mass of the load is added to the lifter. Consequently the position of the centre of mass (CoM) of the system of lifter plus load will shift forward in the grasping phase (Toussaint et al. 1997b). This shift in position of the CoM relative to the support surface disturbs equilibrium. The adverse effects of the disturbance are, however, limited in anticipatory fashion (Belen'kii et al. 1967; Crenna et al. 1987; Massion 1992; Commissaris and Toussaint 1997; Toussaint et al. 1997b). Furthermore, for a smooth lifting movement of the load, it will be necessary to scale the vertical lift force exerted on the load in accordance with its mass. Since the mass of the load can only be determined with certainty at the start of its movement, the motor program parameters must be set in advance of the lifting movement, taking into account the relevant mechanical control requirements.

In previous studies the mechanical constraints on dynamic balance during lifting were examined (Toussaint et al. 1995). It was demonstrated that anticipatory postural adjustments specific to lifting technique are present prior to pick-up of a known load in bi-manual lifting (Commissaris and Toussaint 1997; Toussaint et al. 1997a; Toussaint et al. 1997b). These adjustments were characterised by an increased backwards-directed horizontal momentum and an increased angular momentum of the lifter (Toussaint et al. 1997b), presumably to compensate for the mechanical effect of picking up the load on the dynamics of the body. However, it was also demonstrated that apart from anticipatory postural adjustments, subjects relied on corrective responses after load pick-up to compensate for the disturbance in the position of the CoM (Toussaint et al. 1997b). This suggests that the central nervous system (CNS) can combine different approaches to counteract predictable postural disturbances. In this context the recent work of Latash and co-workers is noteworthy. They investigated anticipatory postural adjustments in patients with Parkinson's disease (Latash et al. 1995). One of the major symptoms of Parkinson's disease is the deficit in postural reactions (Bouisset and Zattara 1990). However, Latash and co-workers demonstrated that in patients with Parkinson's disease the general mechanism of feedforward postural programming is intact (Latash et al. 1995). They suggested that the lack of anticipatory postural adjustments to counteract predictable disturbances may represent a deliberate choice by the CNS. This deliberate omission of anticipatory control could be understood given the slowness of voluntary movement that characterises these patients. If the prediction of the disturbance and consequently the anticipatory postural adjustments are incorrect, the patient lacks the necessary speedy responses to correct the error. Thus the system may prefer to function suboptimally (but relatively reliably) rather than risk total failure (Latash and Anson 1996).

When lifting a box from the floor, a correct estimation of the object's mass will be rather important for adequate programming of the anticipatory postural adjustments. If successful, this will enable smooth and accurate performance of this task, but if the predictions fail, this could cause loss of balance and consequent falls that sometimes lead to injuries (Pope 1987). It can be expected that the CNS will assess the level of predictability of the postural disturbance caused by the pick-up of the load. Depending on this assessment the CNS could assemble a strategy that incorporates both anticipatory control and corrective responses, in which the relative importance of the anticipatory control depends on the level of subjective predictability. If this hypothesis is true, it suggests that in trials in which subjects showed gross signs of imbalance (i.e. a backward stepping response) after picking up a load of unexpectedly reduced mass, control relied more on anticipation compared with trials in which such gross signs of imbalance were absent.

To investigate the hypothesis that the CNS uses a dual approach in which the weighting of the anticipatory postural adjustments and corrective responses after load pick-up depends on the expected correctness of the subjective estimation of the load to be lifted, we studied a bi-manual whole-body lifting task in which this expectation was manipulated. Subjects performed series of lifts in which the magnitude of the load was never revealed to the subject. Two boxes equal in size and colour, but different in mass (6 and 16 kg), were used. Three conditions were compared. In condition A the subject picked up just the 6-kg box. In series B the 6-kg box replaced the 16-kg box after two lifts. In series C the 16-kg box was presented four times followed by the 6-kg box. It was conjectured that depending on the number of 16-kg trials, the subject would be more inclined to expect another 16-kg box in the following trial, with consequent stronger tuning of the anticipatory postural adjustments to a 16-kg load. Consequently, it was expected that the incidence of stepping would increase with the number of 16-kg trials (i.e. no. of steps A < B < C). Trials of subjects who exhibited a backward stepping response lifting the 6-kg box in series C but not in B were selected for comparison with the 6-kg box lifted under condition A, enabling a within-subject approach. The metrics of the movement prior to the subject grasping the box were analysed to determine differences in anticipatory postural adjustments. The mechanics of the subsequent corrective responses, especially when the anticipation was in error, were analysed in the grasping and lifting phase.

Material and methods

Twenty-five healthy male subjects (age 22.8 ± 2.0 years., height 1.85 ± 0.09 m, body mass 74.1 ± 9.5 kg) participated in this study. All subjects were informed that they were to perform a series of lifting tasks, in which a box (mass ranging from 6 to 16 kg) was to be lifted. The true purpose of the experiment, however, was not revealed to the subjects. They all provided written consent prior to the experiment. The institute's ethics committee approved the experimental procedures. None of the subjects reported a history of low-back disorders or other motor impairments.

Two black PVC boxes of equal size (0.24 × 0.34 × 0.42 m) but different mass (6 kg vs 16 kg) were used. Three retro-reflective markers (diameter 2.54 cm) were placed on one side of each box indicating the box's centre of mass.

Experimental procedures

The subject stood in front of a box and upon a sign from one the authors flexed forward, grasped the box, and lifted it to return to an upright position with the box held aloft at breast height (Fig. 1). The centre of mass of the box was placed 0.30 m in front of the subject's toes. Subjects were further instructed (i) to perform a fast lifting movement, (ii) to keep the heels on the ground while picking up the box, (iii) to perform the lift as sagittally symmetrically as possible and, last but not least, (iv) to guard their balance throughout the movement. No specific instructions were given regarding lifting technique. The subjects performed practice trials using the 16-kg box to familiarise themselves with the experimental task. It was recorded whether subjects were able to guard their balance in the 6-kg trials or whether they had to make a compensatory backward step.

Each subject performed in random order three series of lifts in which we tried to manipulate the expectation of the load of the box. In none of the trials was the load of the box revealed to the subject. Upon completion of each trial, the subject was asked to turn 180°. The box was moved behind a screen. After a fixed time interval the box to be lifted was again placed in position, after which the subject was instructed to turn around again. In series A, the subject had to lift the 6-kg box, without prior lifting of the 16-kg box. In series B, the 6-kg box was lifted after two trials of lifting the 16-kg box. In series C the 6-kg box was presented after lifting the 16-kg box four times. Between series subjects were first allowed to rest for 5 min. Then they performed five lifting movements in which a separate 11-kg box was lifted to prevent any prior experience of the preceding series affecting the following one. The kinematics and the ground reaction forces of each experimental trial were recorded.

Anthropometry

Retro-reflective markers (diameter 2.54 cm) were placed on the skin to indicate the location of the fifth metatarsophalangeal joint, the ankle joint (the distal part of the lateral malleolus), the knee joint (epicondylus lateralis), the greater trochanter, lumbo-sacral joint (L5–S1) (as in Looze et al. 1992), the spinous process of the first thoracic vertebra, caput mandibula (head), the lateral border of the acromion, the elbow joint (lateral epicondyle) and the wrist joint (ulnar styloid). The coordinates of the acromion marker were used to determine the position of the shoulder joint. The coordinates of the joint positions defined eight body segments: the feet, lower legs, upper legs, pelvis, upper trunk/head, upper arms, forearms and hands(/load). Anthropometric data (standing height, total body mass, length of segments) were measured. The mass of each segment, and the positions of segmental centres of mass (except for the trunk) and moments of inertia were calculated according to Plagenhoef et al. (1983). Data from Liu et al. (1971) on the segment inertial parameters of the lumbar segments were scaled to the height of the subject and used to recalculate the parameters of the trunk and the pelvis such that their "joint" was at the lumbo-sacral level (L5–S1). The mass and location of the CoM of the hands(/load) segment were linearly adapted starting two samples after the hands first touched the box and ending at box lift-off. The coordinates of the marker on the spinous process of the first thoracic vertebra, L5–S1, hip and acromion were used to determine the positions of the CoM of the trunk during the movement according to Kingma et al. (1995). Prior to the actual experiment the subjects were asked to adopt three postures (trunk straight up, 45° and 90° flexed forward) on the force platform, while the position of body segments and the centre of pressure of the ground reaction force was determined. An optimisation procedure yielded the algorithm to calculate the trunk's CoM dependent on the angle of the trunk.

Kinematics and kinetics

During the lifting movement the positions of the markers were recorded at a rate of 60 frames/s using a three-dimensional semi-automatic video-based motion registration system (VICON, Oxford Metrics; four-camera set-up). With this system the coordinates of the anatomical landmarks in the sagittal plane were determined. For each trial, data collection started ± 0.5 s prior to the start of the movement and lasted until the subject was standing erect again. The raw data were low-pass filtered with a digital filter (zero phase lag, bi-directional application of a fifth-approximation, second-order Butterworth filter with an effective cut-off frequency of 6 Hz). The angles of each segment were calculated relative to the horizontal. Numerical differentiation of the time histories of the angles and the positions of the segments' CoMs (Lanczos five-point differentiation filter; see Lees 1980) yielded (angular) velocities and accelerations.

Vertical ($\mathbf{F}_{ver}$) and fore-aft ($\mathbf{F}_{hor}$) components of the ground reaction forces ($\mathbf{F}_g$) were recorded by means of a strain gauge force platform. The analogue force signals were amplified, low-pass filtered (30 Hz, fourth-order at 24 dB/oct), sampled (60 Hz, 12 bits) and stored synchronously with the movement registration by the VICON system. From the distribution of the force components, the centre of pressure (CoP) of the force vector was calculated in the anteror-posterior and medio-lateral direction.

Biomechanical analysis

The nature of the mechanical control requirements was assessed using a global mechanical analysis of the movement. The approach adopted was based on the interdependency of local and global mechanics: Locally, muscle contractions result in changes in the linear and angular accelerations of body segments that collectively determine the linear acceleration of the CoM and the angular acceleration of the system and hence the $\mathbf{F}_g$. At the same time, each muscle contraction directly affects the torque of the joints it crosses, whereas the distribution of torques across all joints involved in the movement determines the direction of $\mathbf{F}_g$ relative to the CoM. From a global point of view, in which the body is considered as a single free body, the external ground *reaction* force given gravity determines the movement of the CoM and the rotation of the entire system. At the same time, this external force is controlled by the actor by adequately distributing torques across joints (Ingen Schenau et al. 1992; Toussaint et al. 1992).

The instantaneous location and horizontal momentum ($\mathbf{p}_{hor}$) of the CoM of the whole body was calculated from the location and horizontal momentum of the CoM of the segments.

The instantaneous angular momentum of the whole body ($\mathbf{L}$) was calculated according to Toussaint et al. (1995) as

$$\mathbf{L} = \sum_{j=1}^{8} I_j\omega_j + m_j r_j \times \mathbf{v}_j \quad (j = 1, \ldots, 8) \tag{1}$$

where I_j is the moment of inertia of the jth segment relative to its CoM, ω_j the angular velocity of the jth segment, $\mathbf{r}_j$ is the position vector of the segment CoM m_j relative to the position of the body CoM and $\mathbf{v}_j$ is the velocity of the segment CoM m_j relative to the body CoM.

During movement $\mathbf{L}$ will change. This requires an external moment ($\mathbf{M}_{ext}$) that equals the rate of change of the angular momentum (Beer and Johnson 1972):

$$\mathbf{M}_{ext} = \dot{\mathbf{L}}_{total} \tag{2}$$

This external moment must be provided by $\mathbf{F}_g$ according to

$$\mathbf{M}_{ext} = \mathbf{a} \times \mathbf{F}_g \tag{3}$$

where $\mathbf{a}$ is the smallest distance between the line of action of $\mathbf{F}_g$ and the location of the CoM of the entire system (Toussaint et al. 1995).

Data analysis

Data from eight subjects who exhibited a stepping response in series C but not in series B were analysed. To permit averaging of trials, each trial was synchronised in time to the moment ($t = 0$ s) the hands first touched the box (start of grasping phase). Lift-off of the box was determined manually by visual inspection of the time traces of the three box-markers. The stepping response in C was considered to begin at the first onset of deflection of the CoP in the medio-lateral direction. The threshold for identifying the onset of deflection was a medio-lateral divergence of the CoP greater than 0.25 cm. For all trials, the mean time histories and standard error of the mean were computed for the biomechanical parameters.

Statistical analysis

First, the Cochran's Q-test was used to test whether the observed corrective response (stepping vs no-stepping) after grasping the 6-kg box differed for all 25 subjects in A, B and C.

For the selected trials, the anticipatory phases of the three 6-kg trials of series A, B and C were compared. It was hypothesised that the CNS would assemble a strategy to counteract postural disturbances relying more on anticpatory control rather than corrective responses, depending on the expected ability to estimate the load to be lifted correctly. To compare the time histories of the kinematic properties just prior to grasping the box of the movements performed under the experimental conditions, first a multivariate analysis was performed with "expectation" (A vs B vs C) and time as treatments to determine the existence of an overall effect for the variables **L**, horizontal position of the CoM and CoP, $\mathbf{M}_{ext}$, $\mathbf{F}_{hor}$, $\mathbf{F}_{ver}$, and $\mathbf{p}_{hor}$. Six samples prior to grasping the box (100 ms) were included in the analysis. To further establish which variables showed a significant effect, separate ANOVAs were performed for each variable. If an effect of condition on degree of anticipatory control is found, it was expected that in trials in which subjects showed stepping (C), anticipation is stronger compared with the trials in which no estimation of the load could be based on the experience obtained in preceding lifts (A). Therefore, variables for which a significant overall effect was found were further examined to determine whether the stepping response (C) was preceded by a significantly different anticipatory phase prior to grasping the 6-kg box when compared with A. At each point in time, paired-sample t-tests were applied to determine the onset of significant differences between the parameter curves A and C. If P values were less than 0.05, the differences were considered as statistically significant. Finally, the 6-kg trial of series C in which a stepping response occurred was matched with the 16-kg trial preceding it, to verify that the metrics prior to picking up the 6-kg box in C were indeed similar to the metrics when lifting a 16-kg box and thus anticipatory in nature.

The grasping and lifting phase of the two 6-kg trials of series A and C were compared to analyse how the metrics of the stepping response corrected the error in the anticipatory postural adjustments. The same statistical procedure was applied to the time traces of the kinematic properties in the grasping and lifting phase.

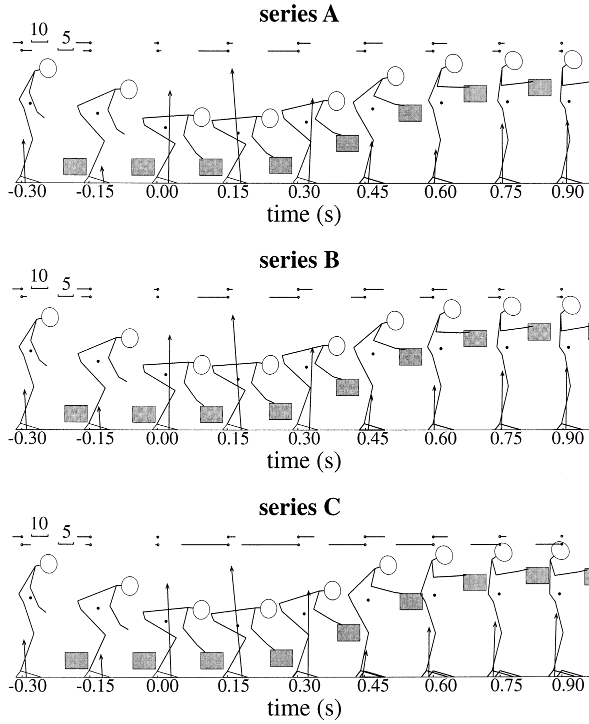


Fig. 1 Sequences of stick-figures representing eight averaged 6-kg trials. The first stick-figure corresponds to 18 samples before the moment of grasping (–300 ms). The time interval between two adjacent stick-figures is 150 ms (9 samples). In every stick-figure $\mathbf{F}_g$ indicated relative to the centre of mass (CoM; *black dot*). Above each stick-figure the magnitude of the angular momentum (*upper indicator*, kg m^2 s^{-1}) and horizontal linear momentum of the lifter (*lower indicator*, kg m s^{-1}), both including the mechanical effect of the box after box-grasp, are indicated. *Lines pointing to the right* from the zero position (represented with a *dot*) indicate a positive value directed counter clockwise (angular momentum) and anteriorly (horizontal linear momentum). The scale of these indicators is given above the first stick-figure. For further explanation the reader is referred to the text

Results

Movement characteristics

All 25 subjects were able to lift the 6-kg box without signs of imbalance when no 16-kg trials directly preceded the lift (condition A). Eight subjects made a compensatory step lifting the 6-kg box in condition C but not in B. Four subjects showed a stepping response in both conditions whereas one subject stepped in B but not in C. The remaining 12 subjects did not show a stepping response at all. The Cochran's Q-test was applied to the results of the qualitative evaluation of all trials (stepping vs no stepping). This resulted for the 25 subjects in a Q value of 16.77, $df = 2$, $P = 0.00023$. Post-hoc analysis of the results using a McNemar test for the significance of changes (Siegel 1956) revealed that the number of stepping responses in series B was *not* significantly larger than in A (P = 0.0625), while the number of responses in C was larger than in B (P = 0.039). The eight subjects (age 22 ± 1.5 years, height 1.84 ± 0.08 m, body mass 73.4 ± 8.8 kg) who exhibited stepping in C but not in B were included in the analysis that followed.

To give a global impression of the experimental task, sequences of stick-figures representing the eight averaged 6 kg trials under condition A, B and C are presented in Fig. 1. In all sequences the subject picks up the box in a continuous movement and lifts it to breast height. Above each stick-figure the magnitude of the angular momentum (upper indicator; see also Fig. 4, right panel) and the linear horizontal momentum of the whole body (including the load after pick-up; Fig. 4, left panel) are indicated. The sequence (condition A) starts 300 ms before grasping the box, showing the subject during the reaching phase. The CoM of the subject moves forward (positive linear momentum) while the subject rotates forward (clockwise, i.e. negative angular momentum). In the final part of the reaching phase both momenta are reduced to approximately zero at box-grasp (t = 0). At box-grasp $\mathbf{F}_g$ runs in front of the CoM leading to a positive $\mathbf{M}_{ext}$ (see also Fig. 2) that will induce a rearward (counterclockwise) rotation of the system (subject plus box). Just after grasping the load (t = 150 ms), $\mathbf{F}_g$ points slightly to the rear, thereby increasing a backward-directed $\mathbf{p}_{hor}$. $\mathbf{F}_g$ also runs behind the CoM, despite a forward shift in the CoP, resulting in a slightly negative $\mathbf{M}_{ext}$ with a conse-

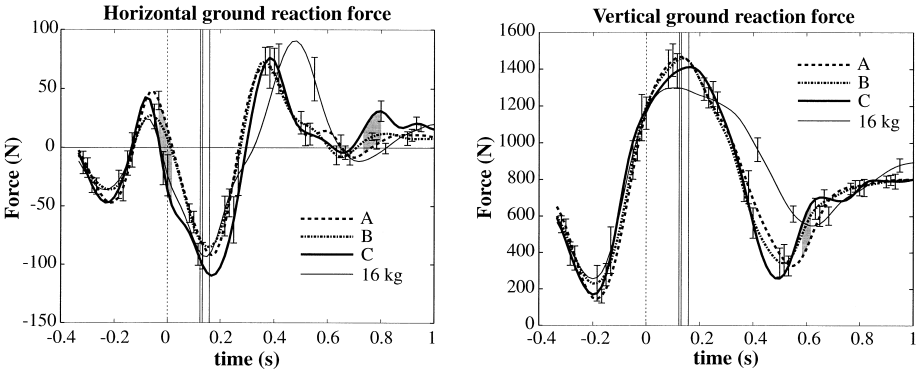


Fig. 2 Mean and standard error of the mean of the horizontal (*left panel*) and vertical (*right panel*) ground reaction force during eight matched 6-kg trials in series A, B and C and the 16-kg trial preceding the 6-kg trial in series C. The *dotted vertical line* indicates the hand-box contact ($t = 0$). The three *continuous vertical lines* indicate box lift-off (C, A, 16 kg). The *shaded areas* between time traces indicate significant differences (paired-sample *t*-test, $P < 0.05$) between series A and C

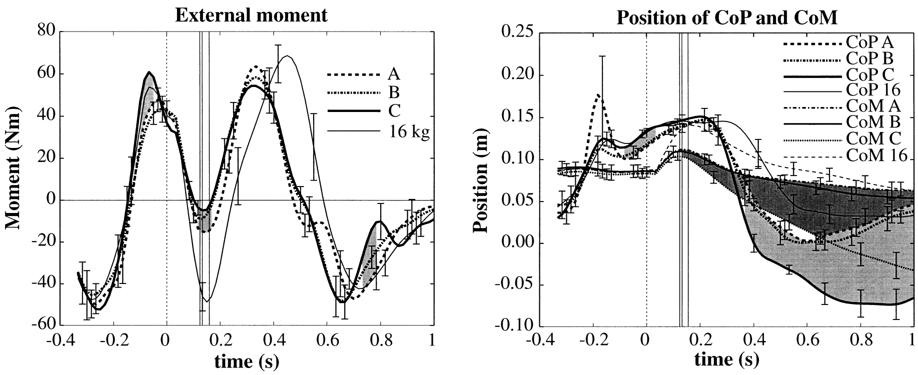


Fig. 3 Mean and standard error of the mean of the external moment (*left panel*) and the centre of pressure (*CoP*) together with the fore-aft position of the centre of mass (*com*, right panel). *Conventions* are the same as those of Fig. 2

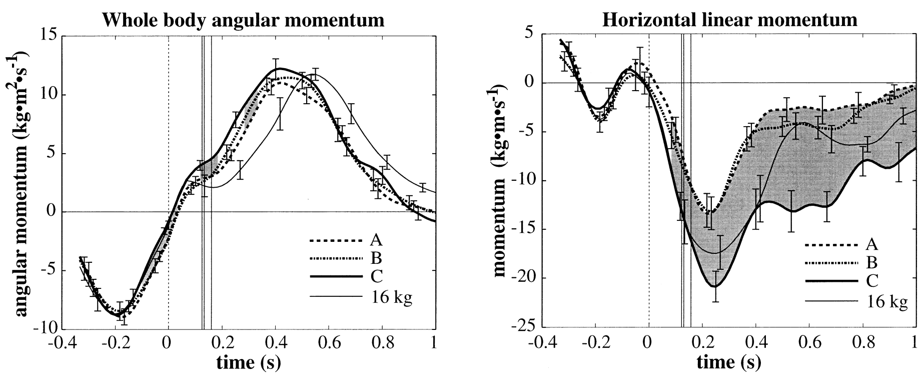


Fig. 4 Mean and standard error of the mean of the angular momentum (*left panel*) and horizontal linear momentum (*right panel*), both including the mechanical effect of the box after box-grasp. A positive value implies a counter-clockwise (angular momentum) and anterior (horizontal linear momentum) direction. *Conventions* are the same as those of Fig. 2

quent decrease of the rearward angular momentum (**L**). The next stick-figure shows $\mathbf{F}_g$ pointing forward braking the negative $\mathbf{p}_{hor}$, while running in front of the CoM. Consequently, $\mathbf{M}_{ext}$ is positive thereby increasing **L**. In the middle part of the movement (t = 300–600 ms) the counter-clockwise rotation of the system is braked by shifting the CoP and thus $\mathbf{F}_g$ to the rear (inducing a negative $\mathbf{M}_{ext}$), while the slightly positive $\mathbf{F}_g$ brakes the still negative $\mathbf{p}_{hor}$. In the last part (t = 600–900 ms) "static". equilibrium is established when the (vertical) lift is completed and $\mathbf{F}_g$ and CoM are aligned. The subject comes to a full stop.

At first glance the sequences of stick-figures representing the movements under the three conditions look rather similar. In particular, series B seems to be a duplicate of series A despite the two 16-kg box lifts preceding it. However, in series C (stepping response) some differences can be observed: At box-grasp ($t = 0$) $\mathbf{F}_g$ already points to the rear, inducing a negative $\mathbf{p}_{hor}$. This backward-directed thrust is apparently not appropriately scaled for the load that is actually lifted. The expected 16-kg load was, without the subject's knowledge, replaced by a 6-kg box and the reactive impulse exerted by the box on the lifter is too small to decrease the backward-directed impulse, as can be observed from the rather large negative $\mathbf{p}_{hor}$ that evolves after grasping the load (see also Fig. 4). The unexpectedly larger rearward-directed $\mathbf{p}_{hor}$ will require some adjustment to avoid a rearward shift of the CoM beyond the limits of the area of support. To counterbalance this unwanted $\mathbf{p}_{hor}$, the horizontal component of $\mathbf{F}_g$ must become positive. This in turn threatens to increase $\mathbf{M}_{ext}$, which is undesirable given the necessity to decrease **L**. To accommodate this "conflict" (see Toussaint et al. 1995), the point of application (CoP) of $\mathbf{F}_g$ shifts backwards such that $\mathbf{F}_g$ points behind the CoM

Table 1 Multivariate analysis on the variables $\mathbf{F}_{hor}$, $\mathbf{F}_{ver}$, $\mathbf{M}_{ext}$, $\mathbf{p}_{hor}$, **L**, CoP, CoM_{hor} for conditions A, B and C

Treatment:	Wilk's lambda	Hypoth. *df*	Error *df*	*F*-value	*P*
Expectation	0.0985	14	16	2.498	0.041
Time	0.0119	35	124.4	6.637	0.000
Expectation×Time	0.1476	70	380	2.108	0.000

Table 2 ANOVA on the variables $\mathbf{F}_{hor}$, $\mathbf{F}_{ver}$, $\mathbf{M}_{ext}$, $\mathbf{p}_{hor}$, **L**, CoP, CoM_{hor} for conditions A, B and C

Variable	Expectation		Time		Expectation×Time	
	$F_{(2, 14)}$	*P*	$F_{(5, 35)}$	*P*	$F_{(10, 70)}$	*P*
L	12.75	0.001	89.54	0.000	8.25	0.000
CoM_{hor}	0.39	0.685	1.16	0.349	0.66	0.756
CoP	11.35	0.001	17.25	0.000	2.58	0.010
$\mathbf{M}_{ext}$	8.07	0.005	1.58	0.191	2.89	0.004
$\mathbf{F}_{hor}$	5.60	0.016	1.77	0.144	3.62	0.001
$\mathbf{F}_{ver}$	1.20	0.332	40.00	0.000	1.08	0.388
$\mathbf{p}_{hor}$	0.69	0.517	0.54	0.747	0.94	0.506

(leading to the desired negative $\mathbf{M}_{ext}$; see Fig. 3). In series C this could apparently only be achieved with a backward stepping response. Three of the eight subjects stepped with the right foot, the others with the left foot. Therefore, the length of the corrective step could not be determined for all subjects, because markers were only attatched to the right side of the body. Consequently, the length of the step is only partially indicated in the last five stick-figures by a backward shift of the right foot relative to the foot's original position.

Differences in anticipation prior to grasping of the load

To examine whether there were differences in anticipation prior to pick-up of the load, a multivariate analysis was performed with "expectation" and time (6 samples, 100 ms prior to box-grasp) as treatments. The multivariate analysis revealed significant main effects for the factors expectation and time, while the interaction between expectation and time was also significant (Table 1). To further establish which variables showed a significant effect, separate ANOVAs were performed for each variable. Results showed significant effects for the treatment Expectation and the interaction of Expectation and Time on **L**, CoP, $\mathbf{M}_{ext}$ and $\mathbf{F}_{hor}$ (Table 2).

The latter variables (**L**, CoP, $\mathbf{M}_{ext}$ and $\mathbf{F}_{hor}$) were further examined to determine the occurrence of significant differences in anticipation prior to grasping the 6-kg box in conditions A and C. At each point in time, paired-sample *t*-tests were applied to determine where the time traces of A and C significantly differed. These significant differences are indicated by shaded areas between the respective time traces in Figs. 2, 3 and 4. Although signs of imbalance were recorded in series B (lifting of the forefoot), it is remarkable that the time traces in A and B are in general rather similar. Apparently, two lifts of the 16-kg box were not sufficient to lure the CNS to rely more on anticipation to counteract the postural disturbance.

The difference in anticipation in $\mathbf{F}_{hor}$ was a much earlier decrease in series C, leading to a negative value at box-grasp, whereas $\mathbf{F}_{hor}$ was still positive in series A (see Fig. 1 also). $\mathbf{M}_{ext}$ exhibited a larger peak in C, while the CoP was shifted more to the front of the feet. Finally, **L** was significantly less negative in C compared with A.

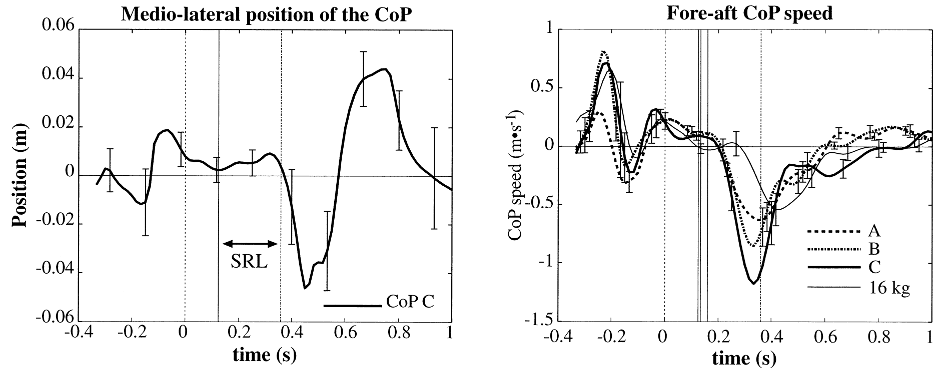
To put the observed differences in anticipation in perspective, the time traces of the 16-kg trial preceding the 6-kg trial in series C are presented in Figs. 2, 3 and 4. It should be noted that grasping and lift-off of the 16-kg box affects the mechanics of the movement in several ways: the addition of mass to the system induces a sharp forward shift of the CoM. To prevent a forward shift of the CoM beyond the boundaries of the area of support, the lifter develops a rather large negative $\mathbf{p}_{hor}$ immediately after the first touch with the box. The reactive impulse exerted by the 16-kg box on the lifter will help to reduce this negative $\mathbf{p}_{hor}$ (see Fig. 4). Furthermore, grasping the load has a breaking effect on the rearward rotation of the system: a rather strong reduction in **L** can be observed immediately after pick-up of the 16-kg box.

Apparently, the observed differences in anticipation between conditions C and A can be understood as an augmentation of the anticipatory postural adjustments to counteract the effect of adding the 16-kg versus the 6-kg load in front of the body: the increased value for $\mathbf{M}_{ext}$ and the less negative value for **L** could be conceived as counteractive to the expected hindrance of the backward rotation towards an erect posture, while the negative $\mathbf{F}_{hor}$ induces the negative $\mathbf{p}_{hor}$ that during the grasping phase will counteract the forward shift of the CoM when the mass of the load is added to the lifter.

Grasping phase

After the first touch with the box, subjects grasped the load and increased the vertical upward force on the box. When this force exceeds the weight of the box it starts to move and the box is lifted from the ground. It is at this

Fig. 5 Mean and standard error of the mean of the medio-lateral position of the centre of pressure (*left panel*) and the fore-aft speed of the centre of pressure (*right panel*). The *vertical dash-dotted line* indicates the onset of the stepping response. *SRL* indicates stepping response latency. *Conventions* are the same as those of Fig. 2



instant that sensory feedback signals the exact load of the box. Box lift-off occurred on average 133 ms (SD 32) after hand-box contact in A, after 125 ms (SD 33) in B and after 123 ms (SD 29) in C. The grasping phase for the 16-kg box was 158 ms (SD 30). This was significantly longer than the duration of the grasping phase for B (*t*-value 2.94, $P = 0.022$) and C (*t*-value 6.06, $P = 0.001$).

During the grasping phase and still before sensory feedback is available regarding the exact load of the box, different preparations for lift-off between A and C can be observed for $\mathbf{p}_{hor}$. A stronger rearward momentum is developed in C, the time trace mimicking the preceding 16-kg condition until lift-off.

Corrective responses in the lifting phase: rearward CoP shift

The lifting phase started at box lift-off. If the expected and actual load of the box are at variance, this will initially induce a deviation from the expected time history of the CoM. During the grasping phase, the mass of the box, positioned in front of the body, is added to the system. Consequently, the CoM shifts forward. This effect is, of course, more pronounced when the 16-kg box is grasped, as compared with the trials in which a mass addition of 6 kg occurs. Figure 3 (right panel) shows the time traces of the horizontal position of the CoM and of the CoP for condition A, B, C and, for C, the preceding 16-kg box-lift. In the reaching phase the CoP is anterior to the CoM. Especially in condition C the distance between CoP and the horizontal position of the CoM is unexpectedly larger (compared with the 16-kg lift) resulting in an increased moment arm of $\mathbf{F}_{ver}$ relative to CoM. The effect on $\mathbf{M}_{ext}$ (Figure 3, left panel) in condition C is that the lifting phase is started with a larger $\mathbf{M}_{ext}$ (compared with A and the 16-kg box) inducing a significantly larger counter-clockwise (rearward)-directed $\mathbf{L}$ (Fig. 4, left panel). An amplified corrective response can be observed in CoP (Fig. 3, right panel) and the fore-aft CoP speed (Fig. 5, right panel). The time traces clearly indicate a pronounced posterior shift, thereby reducing the positive moment arm of $\mathbf{F}_{ver}$, consequently limiting the much larger $\mathbf{M}_{ext}$ that would have occurred had the CoP followed the path observed in the 16-kg trials. The corrective backward CoP shift started 177 ms (SD 28) after box lift-off in C, 192 ms (SD 15) in B, and 206 ms (SD 72) in A. No statistically significant difference in the start of the backward CoP shift was observed.

The average peak rate of change of CoP was significantly different in the three conditions (Wilks lambda 0.28, $P = 0.022$). The peak CoP speed was -0.90 ms^{-1} (SD 0.26) in A, while the CoP speeds in B and C were both significantly higher -1.23 ms^{-1} (SD 0.29) in B and -1.52 ms^{-1} (SD 0.34) in C. The differential CoP speed-response suggests a difference in corrective responses depending on the difference between expected and actual perturbation due to the pick-up of the box.

Corrective responses in the lifting phase: backward stepping

Trials in which subjects exhibited a corrective backward stepping response in series C were selected. Apparently, the anticipatory postural adjustments were scaled for a 16-kg box and, consequently, the actual braking effect of picking up the 6-kg box was too small. Also, the corrective responses following box pick-up were apparently deemed insufficient by the system and a corrective stepping response was performed to prevent further disturbance of equilibrium, consistent with previous observations of (Horak and Nashner 1986) Horak and Nashner (1986). Three subjects stepped with their right foot, five with their left foot. In Fig. 5 (left panel) the medio-lateral CoP time history is plotted for condition C. The three curves of the medio-lateral CoP excursion of subjects stepping with their right foot were inverted to enable averaging with the curves of subjects stepping with their left foot. The average stepping response latency (SRL, time from box lift-off to 0.25 cm deflection of the medio-lateral CoP curve: see Fig. 5, left panel) was 235 ms (SD 41). The onset immediately followed the peak in backward CoP speed. This suggests that the stepping responses were sequenced, or appended, to the preceding "automatic" or corrective response (McIlroy and Maki 1993). The observed stepping response latencies were similar to those observed in movable platform tests, in which reaction time trials ("execute step immediately after detecting any platform motion") yielded latencies of 228–242 ms

(McIlroy and Maki 1993). For the three steps with the right foot the average time between the CoP deflection and foot-off was 83 ms (SD 17), suggesting that the preparatory phase preceding the swing phase was rather short. The short delay between response initiation and foot-off is most probably related to the sharp reduction in $\mathbf{F}_{ver}$ occurring simultaneously. Therefore, the preparatory phase (lateral weight transfer to unload the swing leg) normally observed in stepping responses following platform perturbations could be omitted.

Discussion

Effect of predictability of postural disturbance on anticipatory postural adjustments

Anticipatory control of motor output is important because anticipatory postural adjustments counteracting predicted perturbations can be initiated before the availability of sensory information characterising the full nature of the postural disturbance (Johansson and Westling 1988; Gordon et al. 1991). This type of control enables movements to be executed fast and fluently. However, it leads to errors when the postural disturbance unexpectedly changes (Greene 1972). It was demonstrated previously that apart from anticipatory postural adjustments, subjects relied on corrective responses after load pick-up to neutralise the postural disturbance (Toussaint et al. 1997b). Therefore, it was hypothesised that the CNS would assemble a counteractive strategy scaling the magnitude of the anticipatory postural adjustments with the assessed level of predictability of the postural disturbance. Consistent with this hypothesis, it was observed that the number of stepping responses varied with the number of 16-kg trials that formed the prior experience when the final 6-kg trial of the experimental series A, B and C was presented.

The follow-up question was whether control relied more on anticipation in the stepping trials, compared with trials in which such gross signs of imbalance were absent. In this study it was shown that subjects when stepping (i) exhibited differential anticipatory postural adjustments in comparison with 6-kg trials in which expectation was not shaped by preceding 16-kg trials, and (ii) scaled the anticipatory postural adjustments similar to those of the 16-kg trial preceding it. These findings emphasise the programmed nature of the anticipatory postural adjustments and the ability of the CNS to selectively tune the anticipatory postural adjustments to stored information gained during the previous lift(s).

The metrics of the anticipatory postural adjustments in condition C exhibited especially scaling of $\mathbf{L}$ (reaching phase) and $\mathbf{p}_{hor}$ (grasping phase), whereby differences in $\mathbf{F}_{hor}$, CoM and $\mathbf{M}_{ext}$ subserved this scaling. This suggests that in the programming of the anticipatory postural adjustments, the direction and amplitude of the impulse associated with box lift-off are incorporated and that internal representations of the moving body (Lestienne and Gurfinkel 1988) are used to tune the adjustments to this disturbance (Hirschfeld and Forssberg 1991). This is consistent with studies that show that internal representations of the limb's mechanical properties and its behaviour during the intended action are used for anticipatory scaling of motor commands during reaching and catching tasks (Ghez et al. 1991; Lacquaniti et al. 1992).

Corrective responses in trials with unexpectedly reduced mass of the box

In condition C the anticipatory postural adjustments were apparently scaled for a 16-kg box and, consequently, the actual braking effect of picking up the 6-kg box was too small to match the rearward-directed translational and angular momentum. Nevertheless, none of the subjects fell and apparently the following corrective responses were such that the overshoot in $\mathbf{p}_{hor}$ and $\mathbf{L}$ was equilibrated adequately, while the lifting movement could be performed successfully. This suggests that the corrective response is adequately tuned to the voluntary activity (Hirschfeld and Forssberg 1991).

The corrective response that occurred manifested itself as a sharp rearward shift of the CoP. The position of the CoP is to a large extent dependent on the ankle torque (Oddsson 1990; Toussaint et al. 1992; Winter 1992), and thus the rearward shift of the CoP is indicative of a difference in activation of the muscles spanning the ankle joint. The accommodation of the CoP in response to an (unexpected) perturbation has previously been described as (a part of) one of the primary postural reactions (e.g. Nashner 1976). The observed average latency of the CoP shift (in A, B and C) was 192 ms. If a phase lag of 90 ms between the change in the electromyogram and the change in mechanical output (electromechanical delay) is taken into account (Cavanagh and Komi 1979; Olney and Winter 1985), the data could support the suggestion that an "automatic" response is operative comparable to responses observed in platform perturbation tasks in which the platform is displaced backwards (Horak and Nashner 1986). However, given a similar rearward CoP shift, although not as pronounced and rapid, in condition A and B as in the 16-kg trial, it can be conjectured that the rearward shift is part and parcel of the mechanics of the lifting movement and not a *direct* response to the disturbance of box pick-up. And indeed, in a study on the control of an unperturbed repetitive lifting task in which the load is held during the whole lifting cycle, a rapid rearward shift of the CoP is still observed (Toussaint et al. 1995). This can, of course, not be related to load pick-up. The CoP shift in the continuous lifting study was deemed instrumental in tuning $\mathbf{M}_{ext}$ to $\mathbf{F}_{g}$. As intimated in the Results, the sharp rearward CoP shift reduces the moment arm of $\mathbf{F}_{ver}$, thereby constraining $\mathbf{M}_{ext}$. Depending on the magnitude of the anticipatory adjustment, especially in $\mathbf{L}$ and $\mathbf{p}_{hor}$, a more pronounced and more rapid compensatory response is required and consistent with this explanation the average peak rate of change of the

CoP was significantly different in the three conditions. Thus not the rearward CoP shift *per se*, but the speed and magnitude should be considered as the corrective response. The modulation of this response could be a reflection of centrally mediated changes in gain occurring prior to the onset of the perturbation, similar to the scaling of "automatic" responses observed after platform perturbations (McIlroy and Maki 1993). With this strategy the corrective responses are intimately tied to the normally evolving mechanics of the lifting movement.

The disturbance to equilibrium in C manifested itself especially as an overshoot in rearward horizontal momentum. It is therefore rather surprising that in the early lifting phase (0–600 ms, Fig. 2), the peak amplitude of the forward-directed $\mathbf{F}_{hor}$ did not increase. The peak in $\mathbf{F}_{hor}$ in condition C occurred on average 277 ms after lift-off, leaving sufficient time to program such a response (Fig. 2). Only when the lift (and stepping response, $t \pm 750$ ms, Fig. 1) is almost completed and a new static equilibrium must be established, is $\mathbf{F}_{hor}$ in C significantly more positive compared with the trial under A. This suggests that the overshoot in horizontal linear momentum is accommodated after completion of the step. From a mechanical standpoint, an early reduction of $\mathbf{p}_{hor}$ could be undesirable since the required forward-directed $\mathbf{F}_{hor}$ is in fact a friction force, the magnitude of which is limited by the normal force ($\mathbf{F}_{ver}$) and the friction coefficient. Given the rapidly declining $\mathbf{F}_{ver}$, an increased $\mathbf{F}_{hor}$ could induce a slip (Grieve 1983). Furthermore, increasing a forward-directed $\mathbf{F}_{hor}$ would increase $\mathbf{M}_{ext}$ (Fig. 1), resulting in an amplification of the undesired rearward rotation. From a motor control perspective, the invariancy of the $\mathbf{F}_g$ amplitude in the early lifting phase suggests that this is a critical feature for optimal performance and thus one of the important controlled variables of the lifting task, as was suggested previously by Toussaint et al. (1995). It could be an economic approach of the CNS to control the final force output regardless of which muscles are activated (Keshner 1994). Macpherson (1988a, b), for example, tested the biomechanical strategies of cats maintaining stance during platform translations in different horizontal directions. It appeared that a directionally invariant external force vector was produced, while modulated amplitudes of EMG to correct for different directions of the platform were observed. Because the force vector was invariant, it was concluded that the force vectors were programmed at some higher level and that the choice of muscle activation was subordinate to it. Apparently, the compensatory response to the unexpectedly lighter load in condition C was such that the original parameter settings related to force amplitude of the lifting task remained unaffected. By using the strong shift in CoP the peak amplitudes of $\mathbf{F}_g$ and $\mathbf{M}_{ext}$ could remain unaffected in the early lifting phase, while still the undesired rearward angular momentum was equilibrated rather quickly. These observations suggest that the processes organising equilibrium and movement are closely related. It ensures that the parametric changes necessary to maintain dynamic balance in response to unforeseen changes in the environment are established quickly while the locomotor motions of the body can be executed relatively unaffected (Nashner 1980).

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