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Underestimation of object mass in lifting does not increase the load on the low back

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Abstract

Sudden, unexpected loading on the low back is associated with a high incidence of low back pain. Experiments in which sudden loading was applied during standing revealed increased compression forces on the spine and increased trunk angle, which may cause injury to the spine and hence explain this association. During a more dynamic daily activity, i.e. lifting, this could not be demonstrated, which may be due to experimental constraints. We therefore reinvestigated the loading of the low back when subjects were lifting an unexpectedly heavy object. Ten males lifted boxes, weighing 1.6 or 6.6 kg, at a self-selected lifting velocity. In some trials the mass of these boxes was unexpectedly increased by 10 kg. The ground reaction forces, body movements and trunk muscle activity were measured and from these, the L5/S1 torques and compression forces were estimated. Underestimation of the mass did not lead to an increase in low back loading. This finding was independent of the mass the subjects were expecting to lift. In conclusion, no evidence was found to support inference regarding causality of the association between sudden loading and low back pain during whole body lifting movements. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Lifting; Low back; Load; Underestimation

1. Introduction

Mechanical loading is suggested to be an important factor in the development of low back pain (van Dieën et al., 1999b; Pope and Novotny, 1993). From epidemiological data, it can be concluded that especially sudden, unexpected loading on the low back is related to a high incidence of low back pain (Manning et al., 1984; Magora, 1973). Experimental evidence to explain this association has been derived from studies in which a perturbation was applied while subjects were standing (Lavender et al., 1993; Marras et al., 1987; Cholewicki and McGill, 1996; Cresswell et al., 1994; Thomas et al., 1998; Mannion et al., 2000). Higher muscle activity, causing higher forces on the spine, were found when a load was unexpectedly applied than when the same load was applied expectedly (Mannion et al., 2000; Thomas et al., 1998). In addition, the trunk angle was increased, which may cause sudden stretch of the posterior structures of the spine (Krajcarski et al., 1999).

A presumably more common source of unexpected loading is an incorrect estimation of the mass of an object to be lifted. Such loading may occur for example when nursing staff handles patients (Ljungberg et al., 1989) or when drivers unload trucks. However, only one study (van der Burg et al., 2000) has been published in which subjects lifted an object of which the mass was underestimated. Surprisingly, when lifting an object from the ground that was underestimated by 10 kg, no increase in net torque or lumbar angle was found. It is conceivable that the disturbance caused by the unexpected increase in mass was not sufficient to really perturb the lifting movement, since in this experiment subjects were asked to lift as fast as possible. Consequently, the extensor muscles can be expected to be maximally activated already. The extending torque produced would be sufficient to lift the heavier mass at a reduced speed. Possibly different results will be found when the lifting velocity is less and the muscle activity is scaled with respect to the expected object mass (Looze et al., 2000). In addition, forces acting on the spine were

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not quantified in the previous study. However, a peak in abdominal muscle activity was found (van der Burg et al., 2000), which may increase the compression force at the spine. This peak was not reflected in the net torque, which was used to describe low back load. In the present study the compression forces on the spine will be estimated with an EMG driven distribution model.

This study was designed to investigate in more depth whether the underestimation of a mass in a whole body, bimanual lifting task increases low back loading. High pre-load levels of the trunk reduced trunk rotations and co-activation in response to a perturbation during stance (Krajcarski et al., 1999). This will attenuate the increase in spinal compression force. Therefore, expected load mass was assumed to mediate the effects of underestimation. We studied the effect of an unexpected addition of 10 kg to two expected masses of 1.6 and 6.6 kg. All lifts were performed at a self-selected lifting velocity. Low back load was studied by analysing the torque at the L5–S1 joint, the maximum lumbar angle and the compression force at the L5–S1 joint.

2. Materials and methods

Ten male subjects (age 21.9 years (SD 2.4), height 1.82 m (SD 0.07), body mass 72.2 kg (SD 10.2)), none of whom had a history of back pain, participated in the experiment. All subjects provided written consent prior to the experiment. The subjects were asked to lift a plastic box, weighting between 1.6 and 16.6 kg in a self-selected, symmetrical lifting movement. The box was placed 0.20 m in front of their toes and 0.10 m above floor-level. In this position, the handgrips of the box were 0.27 m above the ground. The protocol had been approved by the local ethics committee.

The experiment consisted of four series of lifting movements, of which the sequence was varied between the subjects. In all series, the same box was used, in which different weights were placed to vary the box mass. To study the unperturbed lifting movements, the subjects performed at least ten lifting movements with constant box masses of 1.6, 6.6, 11.6 or 16.6 kg. The 1.6 and 6.6 kg lifting series are named the expected low mass conditions; the 11.6 and 16.6 kg lifting series are called the expected heavy mass conditions. At the end of the two expected low mass series (1.6 and 6.6 kg), a mass of 10 kg was unexpectedly placed in the box (unexpected loading conditions; respectively 11.6 (1.6) kg condition and 16.6 (6.6) kg condition). To prevent the subjects from being able to predict when changes in mass would occur, the number of lifting movements varied between the series. Between the lifting movements the subjects were asked to put on headphones with loud music and wear non-transparent glasses, so that it was possible to change the masses in the box without the subjects noticing.

The lifting movement was recorded at 100 Hz using an automated video-based recording system (Optotrak™, Nothern Digital Inc., Canada). Ten LED's were placed on the skin on the right side of the body to indicate the location of the following joints: the fifth metatarsophalangeal joint, the ankle joint (the distal part of the lateral malleolus), the knee joint (epicondylus lateralis), the hip joint, the lumbo-sacral joint (as in Looze, 1992), the spinous processes of the first thoracic vertebra, the caput mandibula (the head), the lateral border of the acromion, the elbow joint (epicondylus lateralis) and the wrist joint (ulnar styloid). Three markers were attached to the box to be able to infer the sagittal plane location of the box centre of mass. The lumbar angle was defined as the angle between the line through the hip joint and lumbo-sacral joint (L5–S1) and the line through L5–S1 and the spinous process of the first thoracic vertebra. During upright stance the lumbar angle was defined zero, with flexion the lumbar angle increases. Anthropometric data (body mass, length of segments, standing height) were measured. Ground reaction forces were recorded simultaneously with the movement registration by means of a force platform (Kristler, 9218B). To calculate the onset of the upward lift force exerted on the box, the box was placed on a force platform equipped with strain gauges. All analogue force signals were amplified, filtered (10 Hz, fourth order Butterworth filter), sampled (100 Hz) and stored. The torque at the lumbo-sacral (L5–S1) joint was calculated with the use of a dynamic two-dimensional linked segment model (Looze et al., 1992).

Electromyography (EMG) data were obtained by surface-EMG recordings of the prime back and abdominal muscles. Prior to the experiment disposable EMG-electrodes (Ag/AgCl) were attached after cleaning and gentle abrasion of the skin. The centre-to-centre electrode distance was 2.5 cm. The EMG-signals were recorded from the left erector spinae muscles: m. longissimus at the level of L1, the m. iliocostalis at the level of L2 and the multifidii at the level of L5. The abdominal muscles that were measured were the rectus abdominus muscle and the external and internal oblique muscles. The oblique muscles were subdivided into two functional sections, a lateral and an anterior part (McGill, 1996). The electrodes of the lateral part of the internal obliques were placed at the lumbar triangle, whereas the electrodes of the anterior part were placed cranial to the inguinal ligament. The lateral part of the external obliques was recorded midway between the iliac crest and the rib cage in the mid-axillary line, while the anterior part was recorded at the umbilical level and above the ventral iliac. The rectus abdominus was recorded 2 cm lateral to the midline at the level of the anterior superior iliac spine. The EMG signals were amplified 20 times (Porti-17, Twente Medical Systems), band-pass filtered (10–400 Hz) and stored on a disk at a sample frequency of 1600 Hz with a 22 bit resolution. The EMG signals were high-pass filtered (digital finite impulse response filter, 30 Hz) to reduce the influence of possible movement artefacts and *electrocardiographic signals* (Redfern et al., 1993), rectified and low-pass filtered (second order Butterworth filter, 2.5 Hz, (Potvin et al., 1996)). All digital filtering was bi-directional to avoid phase shifts of the signals. For normalisation of the signals, the subjects performed maximum voluntary isometric contractions as described by McGill (1991). The maximum value of the three attempts was used for normalisation.

To estimate spinal compression, an EMG driven model as described in van Dieën et al. (2000) and van Dieën and Kingma (1999) was used, comprising 90 muscles crossing the L5–S1 joint. Muscle forces were estimated as the product of the maximum muscle stress, normalised and time shifted (120 ms) EMG amplitude and correction factors for the instantaneous muscle length and contraction velocity. These correction factors are based on dynamical properties of human and animal muscles as described by van Zandwijk (1998) and passive length tension properties as described by Woittiez et al. (1984). Maximum muscle stress was iteratively adjusted to obtain maximum agreement (least squares) between the time series of the muscle moments and net external moments.

The last two lifting movements of each of the four constant box mass conditions were recorded. Of course, the lifting movements in which the mass of the box was unexpectedly increased were also recorded. The start of the upward, actual lifting movement was defined as the instant an upward lift force was exerted on the box. A total of 1.30 s (300 ms before and 1 s after the start of the upward lift force) were analysed, according to the lifting movement that was performed most quickly.

For both mass conditions (11.6 and 16.6 kg) an analysis of variance with repeated measures (ANOVA) was used to test the effects of condition (expected low mass, expected heavy mass, and unexpected loading) on the maximum values of the torque at the L5–S1 joint, the lumbar angle and the spinal compression. Significant effects were examined with paired t-tests with Bonferroni-correction (two-sided) to test, which conditions significantly differed from each other. In view of the intra-individual variance this was not done for the muscle activity data. Effects were considered to be significant at $p<0.05$, implying a p-value with the Bonferroni correction of less than 0.0167.

3. Results

When the subjects were lifting the unexpectedly 10 kg heavier box, they appeared to be expecting the light box. In both unexpected loading conditions, the net torque at the L5–S1 joint and the lumbar angle were similar to the expected low mass conditions before the upward lifting movement had started (Figs. 1 and 2). However, muscle activity data did show some discrepancy between the unexpected loading and the expected low mass conditions before this time (Fig. 3). In the 16.6 (6.6) kg condition the activity of the m. erector spinae at the level of L1 resembled more the 16.6 kg condition than the 6.6 kg condition before the start of the actual lifting movement.

After the box had been grasped, i.e. when the upward lifting movement had started, the variables deviated from the planned, expected low mass condition. The muscle activity increased to the activity level of the expected heavy mass condition or higher (Fig. 3). In consequence, the peak in back muscle activity occurred later in time compared with the expected heavy mass conditions (Fig. 3). Approximately, 200 m after the

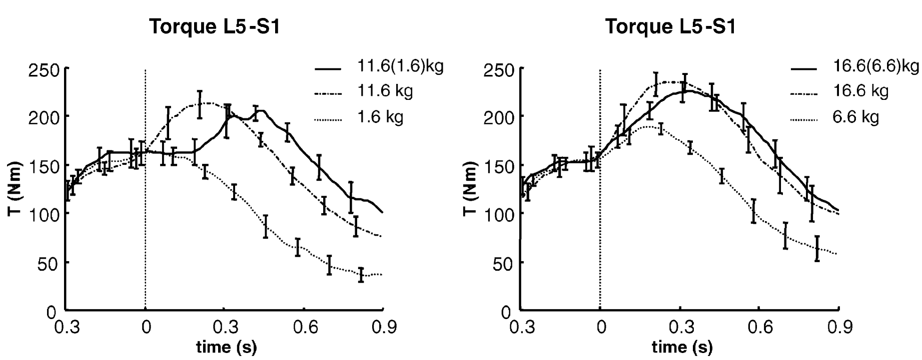

Fig. 1. Time series of the net torque at the L5–S1 joint for the 11.6 (1.6) kg condition (left) and the 16.6 (6.6) kg condition (right). The maximal torques in both unexpected conditions were similar to the heavy mass conditions. Each trial was synchronised in time to onset of upward lift force. The solid line represents the unexpected heavy mass condition. The dotted line represents the expected low mass condition and the dashed line the expected heavy mass condition. The bars indicated one standard error of the mean. The dotted vertical line represents the start of the actual lifting movement.

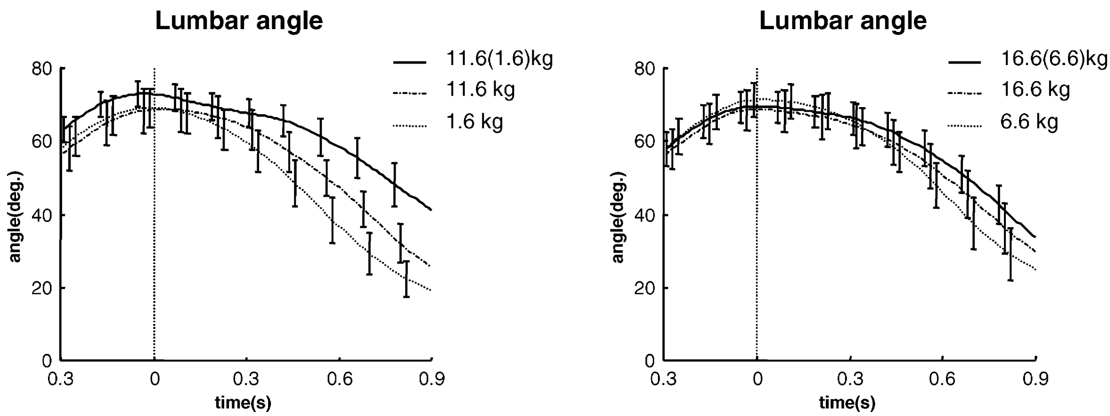

Fig. 2. Time series of the lumbar angle for the 11.6 (1.6) kg condition (left) and the 16.6 (6.6) kg condition (right). In both unexpected conditions, the maximal angle in the unexpected condition was not increased compared to the heavy mass condition. Each trial was synchronised in time to the onset of upward lift force. The solid line represents the unexpected heavy mass condition. The dotted line represents the expected low mass condition and the dashed line the expected heavy mass condition. The bars indicated one standard error of the mean. The dotted vertical line represents the start of the actual lifting movement.

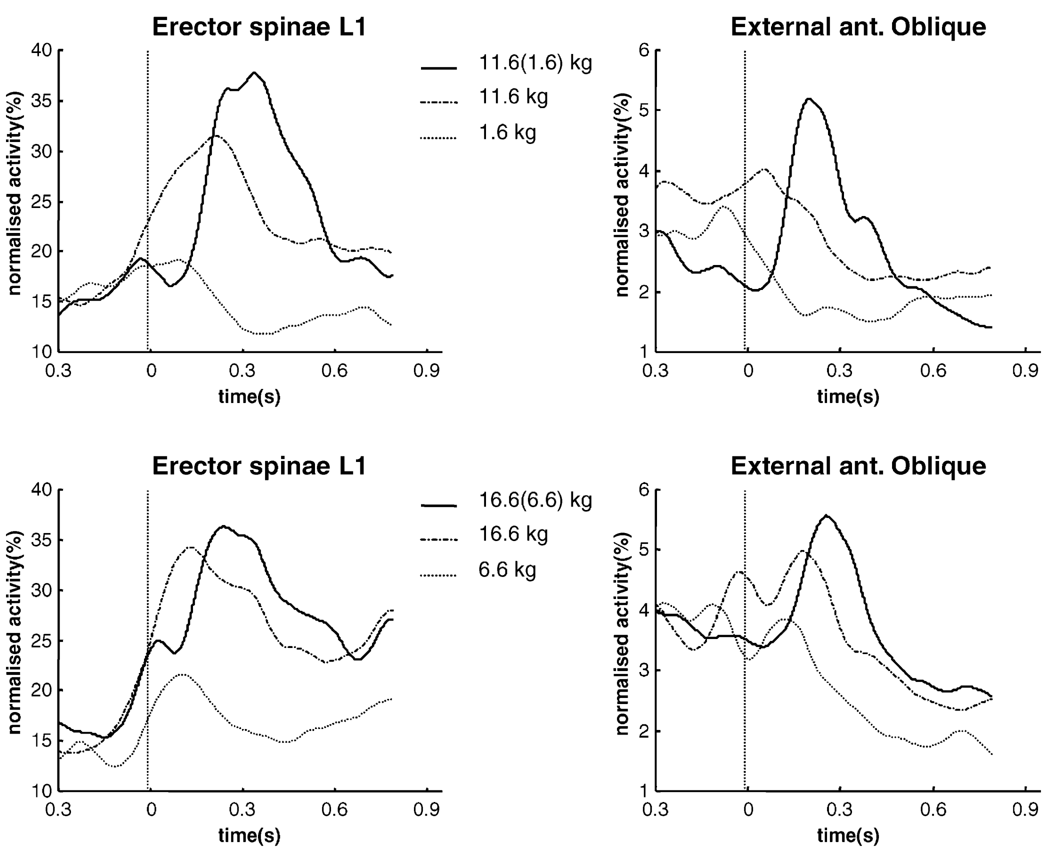

Fig. 3. Time series of the muscle activity for both 10 kg mass increase conditions. Only the most representative muscles are shown, i.e. the erector spinae at the level of L1 and the external anterior oblique muscle. After the start of the lifting movement, the muscle activity in the unexpected conditions, increased to the level of the expected heavy mass or higher. Each trial was synchronised in time to onset of upward lift force. The upper panels showed the 11.6 (1.6) kg condition, and the lower panels the 16.6 (6.6) kg condition. The solid line represents the unexpected heavy mass condition. The dotted line represents the expected low mass condition and the dashed line the expected heavy mass condition. The dotted vertical line represents the start of the actual lifting movement.

onset of the upward box force, the torque at the L5–S1 joint was increased to the level of the expected heavy mass condition (Fig. 1). In line with this, the trunk was extended more slowly than in the expected heavy mass conditions (Fig. 2). The excursions from the expected heavy mass condition appeared to be different for both unexpected loading conditions. The curve of the lumbar angle diverged more from the expected heavy mass

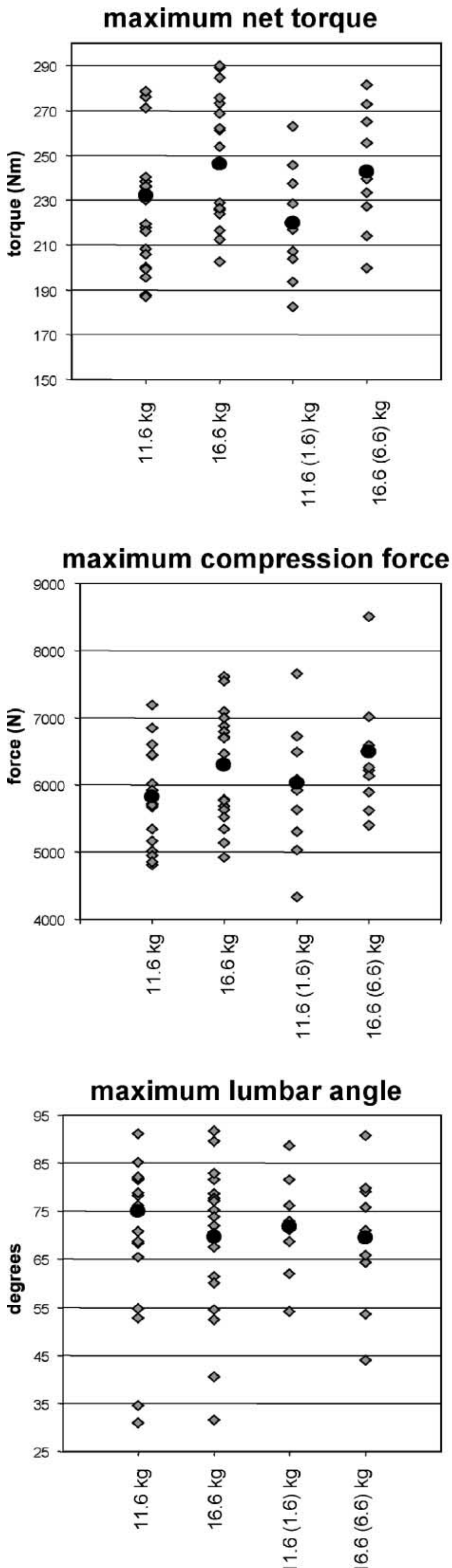

Fig. 4. Scatter plots of the maximum net torque (upper panel), maximum compression force (middle panel) and the maximum lumbar angle (lower panel). The variation in peak values was not increased in the unexpected loading conditions compared to the expected loading conditions. The large circles indicate the mean values. The diamonds represent the maximum values of all individual subjects.

condition in the 11.6 (1.6) kg condition than in the 16.6 (6.6) kg condition. The same was seen for curve of the net torque at the L5–S1 joint, which also differed more from the expected heavy mass condition curve in the 11.6 (1.6) kg condition than in the 16.6 (6.6) kg condition.

Underestimation of the mass to be lifted did not cause an increase in low back loading. Although the abdominal muscle activity showed a small peak just after the start of the lifting movement, the maximum compression forces in both unexpected loading conditions were similar to the heavy mass conditions (Fig. 4, 11.6 (1.6) kg: 5826–6023 N, $p = 0.40$; 16.6 (6.6) kg; 6300–6496 N, $p = 1.00$). Besides, the variation in maximum net torque and maximum compression force did not increase in the unexpected loading conditions (Fig. 4). As an indication of the quality of the model predictions, the correlation between the net torques and the estimated muscle torques was calculated. All muscle torque estimates were strongly correlated to the net torque (78% above $r = 0.80$). The maximum net torque at the L5–S1 joint in 11.6 (1.6) and the 16.6 (6.6) kg conditions were not significantly different from the corresponding expected heavy mass conditions (Figs. 1 and 4; 220–232 Nm, $p = 0.925$; 243–246 Nm, $p = 1.00$ respectively). Finally, in neither of the two unexpected loading conditions an increase in lumbar angle was seen. The maximum lumbar angle in the 16.6 (6.6) kg condition was not significantly different from the 6.6 and 16.6 kg conditions ($p = 0.31$, Figs. 2 and 4). In the 11.6 (1.6) kg condition, the maximum lumbar angle was significantly smaller than in the 11.6 kg condition (75.0° compared to 71.8°, $p = 0.005$). However, the differences in lumbar angle between these conditions appeared to be very small (Figs. 2 and 4).

Expected load mass did not mediate the increase in spinal compression in the unexpected conditions. In both unexpected conditions, the compression forces and net torque were similar to the expected heavy mass conditions (Figs. 1 and 4). However, according to our expectations, the movement pattern was more disturbed in the low mass condition than in the heavy mass condition (Fig. 2).

4. Discussion

This study was designed to investigate the effects of underestimation of a mass to be lifted on low-back loading. Subjects lifted, in a self selected lifting velocity, a box, of which the mass was unexpectedly increased by 10 kg. Independent of the expected high or low mass, the maximum net torque, the maximum compression force and the maximum lumbar angle were not increased compared to the expected lifting of the same mass. However, the movement execution appeared to be less disturbed when the subjects expected to lift a heavier mass.

The subjects did not expect the mass of the box to be heavier in the unexpected load conditions. Before the onset of the lift force most parameters of the unexpected load conditions were similar to the low mass condition. Although the muscle activity of the erector spinae muscle at the L1 level would suggest that the subjects adapted their activity to the increased mass, all muscles showed large variations in muscle activity before the start of the lifting force. Furthermore, the muscle activity after the start of the lifting movement was different from the heavy mass condition. In addition, a more global parameter, the net torque, showed no difference between the low mass conditions and the unexpected conditions before the onset of lift force.

The compression forces found in this study are comparable to the compression forces that are usually described in literature (van Dieën et al., 1999a). Although there may be some experimental errors due to the model used, the error will be systematic, in other words the comparison between the different conditions will be valid. Furthermore, we have additional indicators of low back load (i.e. net torque, muscle activity), of which the results converge to the same conclusion.

When subjects underestimated the mass to be lifted, the maximum loading on the low back resembled the maximum loading of the expected lifting movements. The small peak of abdominal muscle activity did not increase the compression forces on the spine. When subjects underestimate the mass, the trunk flexion did not increase, which indicates that no sudden stretch on the posterior structures of the back occurred. With similar mean back loads, an increased injury risk may be present due to increased variation in back loads and thus an increased probability of peak forces that exceed the injury threshold. However, in this experiment the variations in back load parameters were similar in expected and unexpected loading conditions. So, these data indicate that subjects are able to adequately correct the lifting movement to the heavy mass when they lift an underestimated mass at a self-selected, low velocity. Consequently, no excessive loading will occur. However, it cannot be excluded that unexpected loading will occasionally be the cause of injury due to corrective responses, which did not occur in the limited number of perturbed trials recorded in the present experiment. Also larger discrepancies between the expected mass and the actual mass than studied here might lead to other effects.

In previous studies (van der Burg et al., 2000; Commissaris and Toussaint, 1997), the low back load when lifting an incorrectly estimated mass was equal to the load when lifting the expected mass. In contrast, in the present study the load was equal to the load during lifting the same and correctly estimated mass. Hence, not the expectation, but the actual mass determined low back load. This disparity may be due to the fact that in both previous studies the subjects had to lift at maximum speed. This will entail a short duration of the lifting movement, which does not allow large corrections of the muscle activity while the subject is still in a bending position. In the present results such corrections were observed and hence a higher peak load is expected to occur.

These results are in contrast with the results of experiments on unexpected loading during standing. When a load was suddenly applied during standing, the loading on the low back was higher than, instead of similar to, when the load was expectedly applied. In the erect posture trunk muscle activity is necessary to remain stability of the spine (Cholewicki et al., 1997), especially during unexpected loading conditions. As a consequence, perturbations require immediate, active muscular corrections. In flexed postures, less extra muscle activity is necessary to maintain stability of the spine (Cholewicki et al., 1996). Another factor that may explain the different results in the standing and lifting studies may be the nature of the perturbation. In the lifting experiments, the subjects induce the perturbation themselves, while in the standing experiments the perturbation is timed by the experimenter. Lower compression forces were found when the timing of the perturbation was determined by the subjects (sliding a box off the edge of the table), than when a mass was unexpectedly dropped in a box held in the subjects' hands (Mannion et al., 2000). When the timing of the perturbation is known, subjects are able to anticipate a possible perturbation. Less muscle activity will be necessary to maintain balance and stability of the spine.

The maximum low back loading appeared to be independent of the subjects' expectation on the mass to be lifted. In contrast with van der Burg et al. (2000) and Krajcarski et al. (1999), the abdominal muscle activity did not depend on mass expectation or back load at the instant of perturbation (= pre-load). This may indicate that in the 11.6 (1.6) kg condition the threat to the stability of the spine was less than in the previous studies. Possibly the self-selected lifting velocity, and in consequence, the low rate of applying the perturbation, was responsible for this. However, underestimation of the mass to be lifted disturbed the movement pattern more when the subjects were expecting to lift a low box mass. This finding is corroborated by previous studies (van der Burg et al., 2000; Krajcarski et al., 1999). At the instant of perturbation, the difference in extending torque with the expected heavy mass condition was less in the 16.6 (6.6) kg condition compared to the 11.6 (1.6) kg condition, which may explain the more disturbed movement in the low mass expectation condition.

Underestimation by as much as 10 kg of the mass in lifting does not increase the loading of the low back to levels above the level of expected lifting of the same heavy mass. Subjects were able to correct their lifting movement to the increased mass, such that no sudden or excessive loading occurred. This was independent of the mass of the object the subjects were expecting to lift. In this experiment, no evidence is found to support inference regarding causality for the association between sudden loading and low back pain during whole body lifting.

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