Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713701117

Trunk muscle activation and low back loading in lifting in the absence of load knowledge

M. P. De Looze[a]; M. C. Boeken-Kruger[a]; S. Steenhuizen[b]; C. T. M. Baten[c]; I. Kingma[b]; J. H. Van Dieën[b]
[a] *Human Movement Sciences*, Vrije Universiteit and TNO Work and Employment, PO Box 718, 2130 AS Hoofddorp, The Netherlands, [b] *Human Movement Sciences*, Vrije Universiteit, Amsterdam, The Netherlands, [c] Roessingh Research and Development, Enschede, The Netherlands,

Online publication date: 10 November 2010

To cite this Article De Looze, M. P. , Boeken-Kruger, M. C. , Steenhuizen, S. , Baten, C. T. M. , Kingma, I. and Van Dieën, J. H.(2000) 'Trunk muscle activation and low back loading in lifting in the absence of load knowledge', Ergonomics, 43: 3, 333 — 344

To link to this Article: DOI: 10.1080/001401300184440

URL: http://dx.doi.org/10.1080/001401300184440

ERGONOMICS, 2000, VOL. 43, NO. 3, 333–344

Trunk muscle activation and low back loading in lifting in the absence of load knowledge

M. P. DE LOOZE†*, M. C. BOEKEN-KRUGER†, S. STEENHUIZEN‡, C. T. M. BATEN§, I. KINGMA‡ and J. H. VAN DIEËN‡

†*Human Movement Sciences*, Vrije Universiteit and TNO Work and Employment, PO Box 718, 2130 AS Hoofddorp, The Netherlands

‡*Human Movement Sciences*, Vrije Universiteit, Amsterdam, The Netherlands

§Roessingh Research and Development, Enschede, The Netherlands

Keywords: Lifting; Load knowledge; Muscle activation; Spinal load; Movement control.

People who know the actual mass of an object to be lifted normally prepare themselves before attempting a lift to control the movement and to minimize low back loading. In this study, the trunk muscular reactions and low back torque were investigated in the situation in which the individual did not know the actual mass but only had some idea of the range within which the mass lay. Nine males lifted boxes weighing 6.5 or 16.5 kg under the condition in which they knew the actual mass before attempting a lift (the 'known' condition) and the condition in which they only had the information that the mass would be within the range of 6.5 – 16.5 kg (the 'unknown' condition). The ground reaction forces and body movements were measured in the trials and, from these, the L5/S1 torques were calculated. The activation of back and abdominal muscles was also measured. For the 6.5 kg weight, a higher (16%) back muscle activation in grasping the box and a higher (10%) peak L5/S1 torque in actual lifting were observed in the 'unknown' compared with the 'known' weight condition. For the 16.5 kg weight, the back muscle activation was lower (10%) during grasping, and higher (10%) during lifting in the 'unknown' compared with the 'known' weight condition. Knowledge of the load had no effect on the activation of the abdominal muscles. It was concluded that in the so-called 'unknown' conditions, the risks of low back injury were increased in comparison with the conditions where the actual weight was known in advance.

1. Introduction

The act of lifting is believed to be related to the development of low back pain (Frank *et al*. 1996). Certainly, lifting puts high mechanical loads on musculoskeletal structures in the lower back. The trunk musculature, having several functions in lifting, plays a crucial role. The large superficial back muscles are activated to extend the trunk. The abdominal muscles, in cooperation with the deep intersegmental back muscles, are involved in stabilizing the spine (Tesh *et al*. 1987, Panjabi *et al*. 1989). As a negative effect, the back and abdominal muscles largely determine the load on spinal motion segments (de Looze *et al*. 1999). This yields a neuromuscular challenge

*Author for correspondence. e-mail: m.dlooze@arbeid.tno.nl

Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online © 2000 Taylor & Francis Ltd
http://www.tandf.co.uk/journals/tf/00140139.html

to control the lifting movement such that musculoskeletal loads are kept within safe margins.

To control a lift appropriately, people prepare themselves before the actual lift. These anticipatory preparations concern increased levels of trunk muscle activation and postural adjustments such as shifting the centre of mass backwards (Toussaint *et al*. 1997, van Dieën and de Looze 1999). A prerequisite for a proper preparation is knowledge about the actual mass of the load before the attempt to lift. In a situation where people were misled by a sudden change of a mass to 6 kg after a long series of 16-kg lifts, an inadequate preparation was evoked, leading to a higher L5/S1 torque and a higher risk of falling, as compared with lifting 6 kg with appropriate preparation (Commissaris and Toussaint 1997).

The daily situation of workers like refuse collectors, luggage dispatchers and movers is fundamentally different from the situation in which an unsuitable preparation is achieved by giving false expectations. They are not misled about the load mass, but instead, before lifting the load, have some idea about the range wherein its mass lies, although they do not know the actual mass. From a practical point of view it is interesting to know how people would react to these 'uncertain' conditions and whether they are exposed to higher spinal loading than people who are fully aware of the actual load mass.

Experimental studies comparing conditions where people either know the actual mass or do not, except for possibly having some idea of the range of weights to be lifted, are not conclusive. Butler *et al*. (1993) estimated the peak L5/S1 torque for lifting loads of 0, 15, 25 and 30 kg. Only at 0 kg was the peak torque 30% higher in the condition of not knowing the actual mass as compared with the known condition. At the other masses, no such difference was found. Patterson *et al*. (1987) studied the peak L4/L5 torque in lifting 6.8, 10.2 and 13.8 kg. They observed a general tendency towards higher peak torques in the condition of not knowing the actual mass. While these studies show some discrepancy in results with respect to the effect of load knowledge on low back torques, it should also be stressed that the low back torque in itself might remain unaffected if both back and abdominal muscle activations change in the same direction (thereby affecting the spinal loading forces).

The aim of the present study was to find out whether the condition of only knowing the range of masses to be lifted (in the following referred to as the 'unknown' condition) would yield different reactions of the back and abdominal muscles and low back torques in comparison with the condition of knowing the actual load mass (referred to as the 'known' condition).

Since the optimal preparation in the unknown condition might be hampered, the muscular reactions and torques were expected to be different from those in the known condition. Specifically, for masses at the lower end of the range, a higher initial effort, probably perceptible in the low back torque and back muscle activation, was expected in the unknown condition as compared with the known condition. The opposite was expected for masses at the higher end of the range. Second, as a safety measure to guarantee spinal stability, higher levels of activation of the abdominal muscles were expected in the unknown than in the known condition. It should be noted that the second expectation might conflict with the first to some extent, since an increase in abdominal activation might lead to an increase in back muscle activation to off-set the abdominally created trunk flexion torque.

2. Methods

2.1. *Subjects and tasks*

Nine healthy male subjects (mean age 24.6 years, SD 2.8; mean stature 1.78 m, SD 0.04; mean total body mass 74.2 kg, SD 9.1) participated in the experiments. They were informed about the protocol in advance and they had given their written informed consent.

The Faculty's ethical committee approved the protocol of lifting movements. The movements started from an erect posture and consisted of lowering the body (without a load in the hands) by flexing the knees and the trunk, grasping a box and symmetrically lifting the box by extending the knees and trunk to knuckle height in the erect standing position (which was the end position of the movement). The subjects were not allowed to make a distinct stop in between the lowering of the body and the lifting phase, but were instructed to grasp the box in one fluid pattern of motion.

The box to be grasped (width•depth•height = 0.44•0.36•0.24 m) was placed on a platform 0.065 m above the floor and 0.45 m in front of the subject's heels. In that position, the two handgrips of the box were 0.27 m above the ground. The same box was used in all the trials. It weighed either 6.5 or 16.5 kg depending on its content, which was not visible to the subjects. The onset of the movement was marked by a verbal signal. The duration of the movement was imposed by a metronome: audible signals indicated the instants of time of the onset of the movement, the distinct stop in between the lowering and lifting phase, and the end of the lifting phase. The total movement of lowering the body, grasping the box and lifting lasted 1.8 s.

Before the experiment, the subjects were allowed to practise with loads of known weights at the upper and lower limits of the range of possible masses that would be used, namely 6.5 and 16.5 kg. Actually, these were the only two masses used in the study, but the subjects were not made aware of this. The subjects were also ignorant of the total number of trials.

In total six pairs of two trials were performed. In the first trial of each pair the subjects had no further information than the indicated range of possible masses (unknown condition). This was followed by the second trial wherein the same box mass was used but the subject was told the mass of the load (known condition). Thus, both boxes in each pair always had the same weight, and the subject had knowledge in each second trial of both the numeric mass value (verbally informed) and a perceptual value (experienced in the first trial). The order of the six pairs of trials, three with 6.5 kg and three with 16.5 kg, was systematically varied across subjects.

2.2. *Measurements and biomechanical model*

To estimate the L5/S1 torques, a 3-D model (Kingma *et al*. 1996) representing two feet, two lower legs, two upper legs and one pelvis segment was applied. This model requires input of ground reaction forces, segment anthropometry and kinematic data.

Ground reaction forces for both feet were recorded simultaneously by means of two force-plates (Kistler type 9281B, Winterthur, Switzerland) and stored at 60 Hz after low-pass filtering at 30 Hz. The segment masses, the positions of the centres of mass and the inertia tensors were estimated on the basis of anthropometric measures, regression equations (McConville *et al*. 1980) and body segment densities (Dempster and Gaughran 1967).

To gather the kinematic data, a thermoplastic brace was tightly moulded to each body segment. Attached to these braces were five thin rods of different lengths, all having a reflective marker (diameter 10 mm) at their extremity. The 3-D positions of these markers were recorded (at 60 Hz) by use of four video-cameras of a VICON (Oxford Metrics, UK) motion-analysis system. The joint centre positions, the centre of mass positions and the inertia tensors (which are the required input for the biomechanical model) were determined from the recorded movement of the brace markers in the 3-D global axis system by a procedure described in detail by Kingma *et al.* (1996). The joint centre and centre of mass positions were filtered at an effective cut-off frequency of 5 Hz, using a fourth-order Butterworth filter with zero-phase lag. Segment linear and angular accelerations were obtained by double differentiation of the segment centre of mass positions and segment angles. At each instant in time the basic equations of motion were applied to the feet, lower legs, upper legs and pelvis respectively to obtain the joint torque at the L5/S1 joint. This (total) L5/S1 torque was projected onto the anatomical axis systems yielding the component of interest, namely the trunk flexing-extending torque at L5/S1.

2.3. *Muscle activation*

The electro-myographic activation (EMG) of 10 muscles was recorded bilaterally by means of 10 pairs of bipolar disposable silver–silver chloride electrodes (Medi-Trace). The electrode sites were: for the lumbar erector spinae, 10 mm medial to the diagonal line between the spina iliaca posterior superior and the lateral end of the 12th rib at L3 height; for the thoracic erector spinae, 30 mm lateral to the 10th thoracic spinous process; for the rectus abdominis, on the most pronounced part of the muscle at umbilicus height; for the external obliques, lateral to the umbilicus and ~50 mm above the spina iliaca anterior superior; for the internal obliques, half-way between the spina iliaca anterior superior and symphysis pubica, just superior to the inguinal ligament. The EMG signals were recorded by telemetry, rectified, filtered (bandwidth 10 – 200 Hz) and stored (600 Hz). For normalization of the signals, subjects performed maximum voluntary contractions (MVC) in separate trials for the muscles. These included attempted trunk flexion and extension in supine and prone positions.

2.4. *Data analysis*

The movement of the body throughout the experimental task was divided into three consecutive phases: a downward movement phase, a grasping phase and a lifting phase. The grasping phase was determined by the time span between the first hand contact with the box (indicated by the onset of motion of a marker attached to the box by a flexible strip) and the instant of lift-off (indicated by an electrical pulse from a switch at the bottom of the box). Only the second half of the entire lowering movement until box contact was defined as the 'downward movement phase'. Similarly, the first half of the upward movement starting from the instant of lift-off was defined as the 'lifting phase'. A repeated measures multivariate analysis of variance (MANOVA) was applied to test the significance of the overall effects of load knowledge, load mass and movement phase. Univariate F-tests and Tukey–HSD comparisons (significance level $p < 0.05$) were applied to interpret the separate effects on mean and peak values of the L5/S1 torque and the muscle activation.

3. Results

Figure 1 shows the time curves for the L5/S1 torque and muscle activation for one subject lifting 6 kg. The vertical lines indicate the beginning and end of the grasping

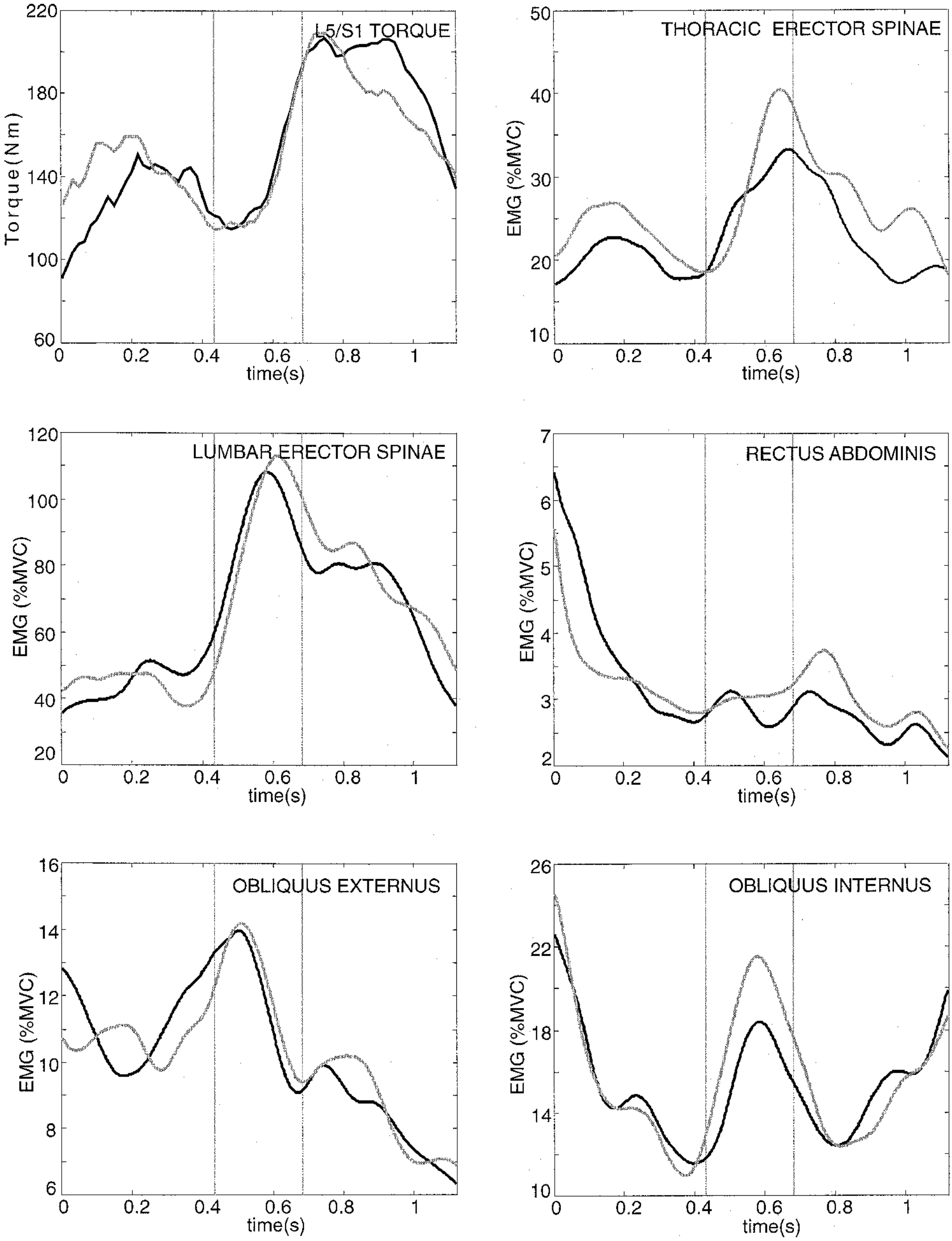

Figure 1. Time curves of the L5/S1 torque and levels of muscle activation in the downward phase (defined as the second half of the total movement of lowering the body), the grasping phase and the upward phase (defined as the first half of the total lifting phase), all separated by the vertical lines, for one of the subjects lifting 6.5 kg. The grey curve represents the unknown condition; the black curve the known condition.

phase. The curves representing the unknown and known condition seem to be similar. In both conditions the L5/S1 torque shows a steep rise during grasping as the pulling force on the box increases. A peak value is reached in the lifting phase when the maximal vertical acceleration coincides with a (still) flexed trunk position. The similarity between the time curves of the L5/S1 torque and of the back muscle activation indicates the involvement of these muscles in generating the torque. The pattern of activation precedes the torque pattern, which can be explained by the electro-mechanical delay of ~130 ms for the back muscles (van Dieën *et al*. 1991). The abdominal muscles show lower activation levels than the back muscles, while their patterns were more variable across subjects.

The next figures show the group's averages and standard deviations for the grasping and lifting phases. The downward movement phase was omitted here because load knowledge did not show any significant effect before box contact. Figure 2 shows the mean and peak L5/S1 torque. There was no significant main effect for load knowledge. However, the interaction between load knowledge, mass and movement phase did show a significant effect ($p = 0.011$, df = 2), namely, at 6.5 kg, the peak L5/S1 torque during lifting was significantly higher (on average by 9.7%) in the unknown as compared with the known condition. A main effect of movement phase was also found, namely finding higher peak and mean torques in lifting than in grasping ($p < 0.001$, df = 2).

Figures 3 and 4 show the activation levels of the back and abdominal muscles respectively. Since there were no left-right differences, only the means over the right and left muscles are presented. With respect to the back muscles, significant interaction effects were found at the thoracic level. At 6.5 kg, the peak and mean activation in the grasping phase were higher (on average by 16.3 and 34.8% respectively) in the unknown condition than in the known condition ($p < 0.001$, df = 2); at 16.5 kg, the mean activation was lower (11.0%) during grasping and higher (10.4%) during lifting, in the unknown compared with the known condition ($p < 0.001$, df = 2). At the lumbar level, the same tendencies were observed, but these were not statistically significant.

No significant differences in abdominal muscle activations were found between the unknown and known conditions (figure 4). Significant main effects of mass and phase were found, indicating a higher activation of the abdominal obliques at 16 kg than at 6.5 kg ($p = 0.002$, df = 1) and a lower activation of the rectus abdominis in the downward phase than in grasping or lifting ($p = 0.045$, df = 2).

Finally, when considering the unknown conditions only, it was found that differences in torque and muscle activation between the 6.5 and 16.5 kg conditions occurred in the lifting phase, but did not generally occur in the grasping phase. (In contrast, the differences between known and unknown conditions [at similar weights] had already occurred before lift-off.) From this observation it seems that in the unknown condition the grasping phase is used to learn about the weight, leading to differences between weight conditions only after lift-off. This is in line with the finding that the grasping phase in the unknown condition lasted somewhat longer than in the known condition (on average, 0.37 as compared with 0.32 s).

4. Discussion

4.1. *Back muscle activation and low back torque*

Adequate preparatory postural and muscular actions in lifting require information about the load mass before the attempt and are of importance, since inadequate

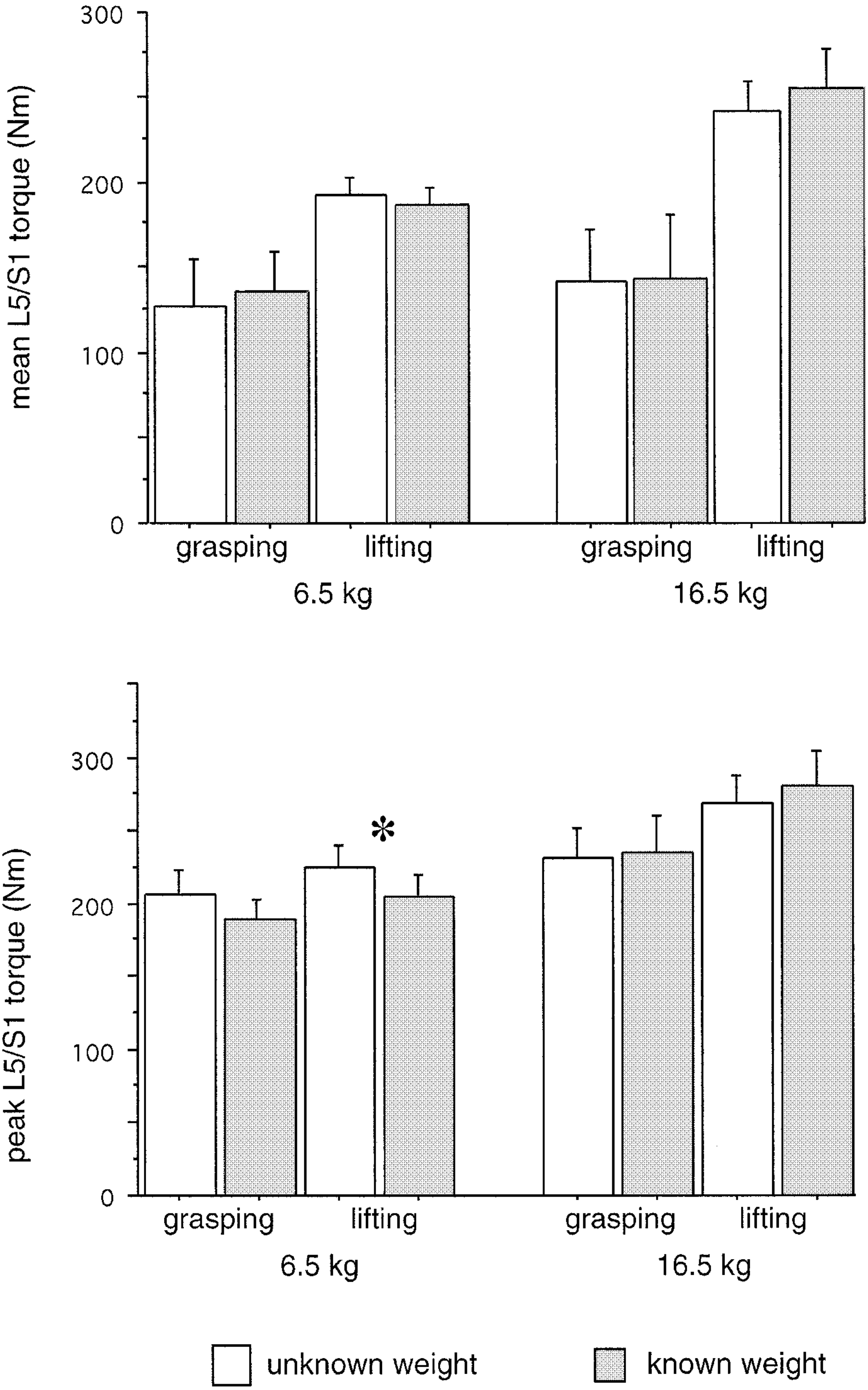

Figure 2. Group averages and SD of the mean and peak L5/S1 torque level in the grasping and lifting phases, for the 6.5 and 16.5 kg lifts and in the known and unknown conditions. *Significant difference (at $p < 0.05$) between the unknown and the known condition.

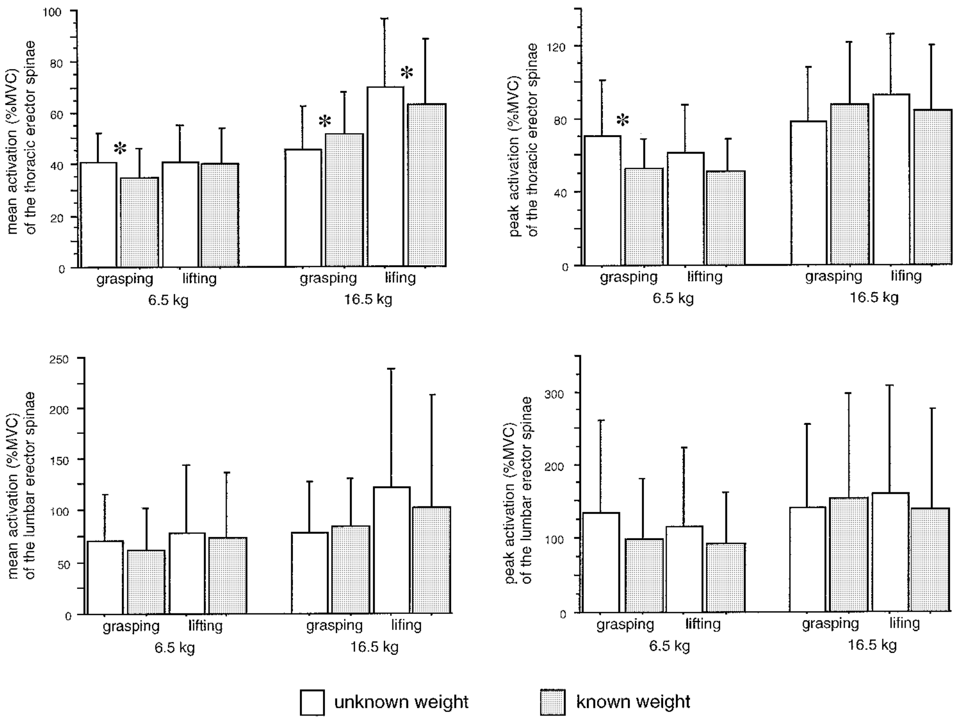

Figure 3. Group averages and SD of the mean and peak level of activation of the erector spinae at the lumbar and thoracic levels in the grasping and lifting phases, for the 6.5 and 16.5 kg lifts and in the known and unknown conditions. *Significant difference (at $p < 0.05$) between the unknown and the known condition.

preparation increases the low back load and the risk of falling (Commissaris and Toussaint 1997). When people only know the range within which a load mass lies, but not the actual mass, the preparation for a lift may not be optimal. In the present study it was investigated whether this would lead to muscular reactions and low back torques in situations other than those in which people know the actual mass.

When lifting a mass at the lower end of the range, the back muscles, particularly at thoracic level, were activated during grasping more in the unknown than in the known condition. As a result, a higher peak L5/S1 torque is reached shortly after lift-off. This higher initial effort was expected and seems the result of subjects aiming at lifting a mass higher than the actual one. When lifting a mass at the high end of the range, the results seem to indicate the opposite. Initially, during grasping, the mean activation of the thoracic back muscles was lower in the unknown than the known condition. In the lifting phase, however, the thoracic muscles were activated more in the unknown than in the known condition, which indicates that the initial low activation before lift-off is compensated after lift-off. At this high mass, the differences in muscle activation did not result in any significant differences in the L5/S1 torque. It is possible that, because of the electro-mechanical delay, the effect on the torque of the lower muscle activity before lift-off could be neutralized by the higher activity after lift-off. Another explanation might be the observed (although not significant) tendency towards a lower abdominal muscle activation in grasping

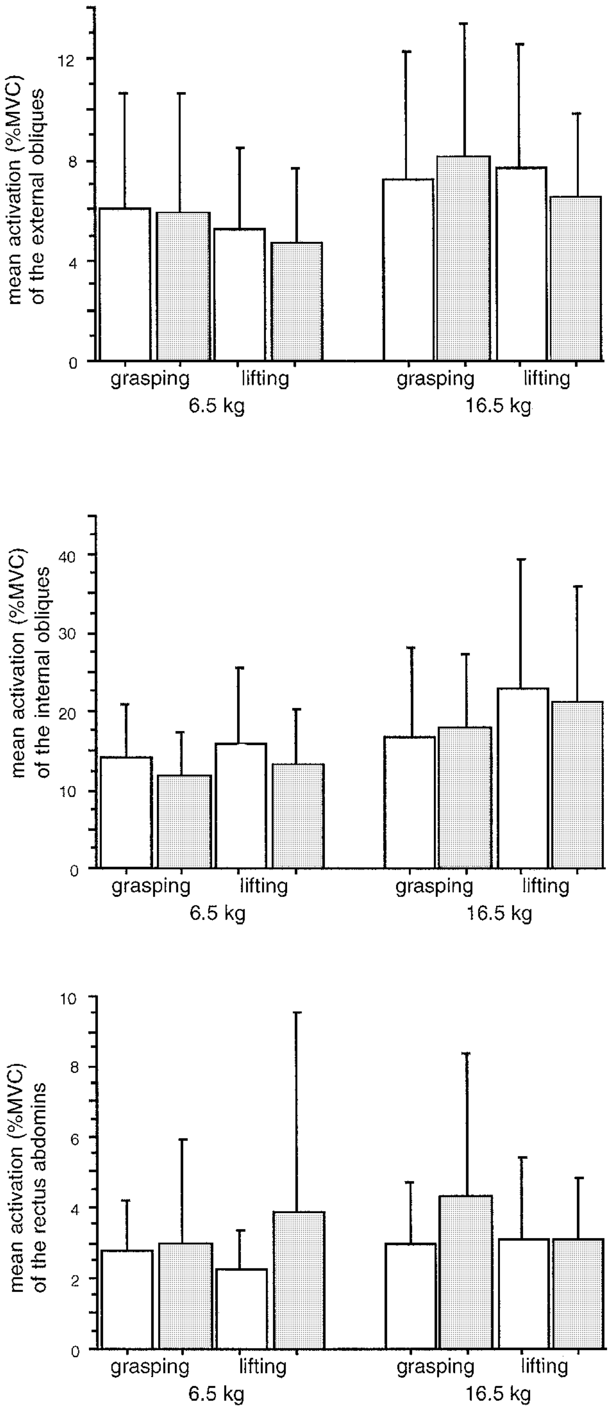

Figure 4. Group averages and SD of the mean level of activation of the abdominal muscles in the grasping and lifting phases, for the 6.5 and 16.5 kg lifts and in the known and unknown conditions.

and an increased abdominal muscle activation in lifting when knowledge of the load is absent. The results from the lumbar back muscles showed the same tendencies as those from the thoracic muscles (although they were not significant).

The results of Butler *et al.*'s (1993) study concerning the L5/S1 torques agree with our findings. Using masses from 0 to 30 kg, they found significantly higher peak torques at 0 kg in the unknown condition than in the known condition, but at 30 kg no differences in torque were found. In contrast with Butler *et al.*'s and with the present study, Patterson *et al.* (1987) found a tendency, irrespective of mass, towards higher peak torques in the unknown conditions. Possibly, their subjects were aiming at lifting a mass that was even higher than the highest mass used, for they may not have known the upper limit of the range of masses.

Finally, in the present study, a slightly longer grasping phase was found in the unknown condition, which indicates that subjects were more careful in starting their attempt to lift. Clearly, this was not sufficient to cancel all the effects on muscle activation and torque as described above.

4.2. *Abdominal muscle activation*

Most authors suggest that, in lifting and other activities that require the generation of a torque to extend the trunk, the abdominal muscles are activated to stabilize and protect the spine from large intervertebral motions and structural deformations (Tesh *et al.* 1987). This suggestion is in line with the results from studies where the trunk was loaded by the act of catching objects in front of the body (Marras *et al.* 1987, Lavender *et al.* 1989, 1993). These studies showed that limitation of the view of the falling object, which decreases the state of knowledge about the instant at which loading will occur, results in a higher level of abdominal muscle activation.

In line with this it was expected in the present study that the abdominal muscle activation would increase to guarantee stability when the state of knowledge about the actual load mass was unknown. The results do not confirm this expectation, since no differences in abdominal activation were observed between known and unknown conditions. Either the expectation of a higher abdominal muscular activity was unjustified or another abdominal muscle, the transversus abominis (which was not recorded), was activated more intensively in the absence of load knowledge. This muscle has been found previously to be critically involved in spinal stabilization without creating much additional loading on the spine (Cresswell *et al.* 1994). The present study, however, was limited to the abdominal muscles that had the potential to contribute significantly to the spinal load.

4.3. *Low back loading*

What do the above-mentioned effects of the absence of load knowledge mean with respect to the musculoskeletal loading on the low back region? For a load mass of 6.5 kg, a 9.7% higher L5/S1 torque was found when knowledge about the load mass was absent. The L5/S1 torque can be seen as a global measure of the load on the lower back. It determines the minimum trunk extensor force required from the back muscles, which largely determines the compression on spinal motion segments. The musculoskeletal loading in the low back region could be increased further by increased co-activation. This did not result from the absence of knowledge of the load. Therefore, estimating the additional load on the low back due to the absence of load knowledge at $\sim$10% seems reasonable. However, it should be noted that all this concerns the low mass, 6.5 kg, condition. At such a mass, any increased risk related to a momentary loss of balance or uncontrolled segmental rotation (Commissaris and Toussaint 1997) might be more important than the 10% rise in magnitude of spinal load.

In the 16.5 kg condition, there was no effect of load knowledge on the L5/S1 torque. Thus, on that basis, any additional risk of the absence of load knowledge could not be quantified. Nevertheless, the findings on back muscle activation point towards an increased risk in the grasping phase. In that phase, a 10% lower back muscle activation was found in the unknown condition, which was compensated by a 10% increase in activation after lift-off. The activation of too few muscle fibres while pulling at the handles in the grasping phase (where the low back load is already close to its peak value), is likely to lead to greater trunk flexion. This would stretch the activated back muscle fibres. It is known from the literature that such eccentric muscle actions at high intensity are accompanied by high risks of damage to the muscle fibres or to the connective tissue in series with the muscle fibres (Armstrong 1984). In addition, the significant deviations in back muscle activation, both in grasping and in lifting, indicate less optimal muscular control in the unknown condition than in the known condition. It might be that this leads locally instantaneously to increased mechanical loads. The fact that the low back load at the higher masses is relatively high *per se*, irrespective of the state of load knowledge, stresses the importance of these suggestions of increased hazards for lifting unknown loads.

In conclusion, the observed differences in L5/S1 torques and back muscle activation patterns between the known and unknown conditions indicate a higher low back load when the mass to be lifted is not known in advance of the lift attempt, at least for masses at the lower and higher ends of the range. This, together with an increased risk of loss of balance, points towards an additional hazard for the workers who do not know the actual load mass but only the possible mass range. Therefore, it is recommended that the lifting of unknown masses should be prevented as far as possible. Reorganization of the work process to avoid the handling of loads with highly variable masses or the labelling of objects with their weights might be helpful. Working environments where this cannot be achieved need special care. The present results provide arguments for the need for more conservative lifting criteria (i.e. lower maximum limits) than normally applied, for work situations where the load mass is variable and not known before each lift attempt.

References

Armstrong, R. B. 1984, Mechanisms of exercise-induced delayed onset muscular soreness: a brief review, *Medicine and Science in Sports and Exercise*, **16,** 529–538.

Butler, D., Andersson, G. B. J., Trafimow, J., Schipplein, O. D. and Andriacchi, T. P. 1993, The influence of load knowledge on lifting technique, *Ergonomics*, **36,** 1489–1493.

Commissaris, D. A. C. M. and Toussaint, H. M. 1997, Load knowledge affects low back loading and control of balance in lifting tasks, *Ergonomics*, **40,** 559–575.

Cresswell, A. G., Oddsson, L. and Thorstensson, A. 1994, The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research*, **98,** 336–341.

Dempster, W. T. and Gaughran, R. L. 1967, Properties of the body segments based on size and weight, *American Journal of Anatomy*, **120,** 33–54.

van Dieën, J. H. and de Looze, M. P. 1999, Anticipatory activity of trunk muscles in a lifting task is directional. *Experimental Brain Research* (in press).

van Dieën, J. H., Thissen, C. E. A. M., Ven, A. J. G. M.van der and Toussaint, H. M. 1991, The electro-mechanical delay of the erector spinae muscle: influence of force development, fatigue and electrode location, *European Journal of Applied Physiology*, **63,** 216 – 222.

Frank, J. W., Kerr, M. S., Brooker, A., DeMaio, S. E., Maetzel, A., Shannon, H. S., Sullivan, T. J., Norman, R. W. and Wells, R. P. 1996, Disability resulting from occupational low back pain. *Spine*, **21,** 2908 – 2917.

Kingma, I., de Looze, M. P., Toussaint, H. M., Klijnsma H. G. and Bruijnen, T. B. M., 1996, Validation of a full body 3-D dynamic linked segment model. *Human Movement Science*, **15,** 833 – 860.

Lavender, S. A., Marras, W. S. and Miller, R. A. 1993, The development of response strategies in preparation for sudden loading to the torso, *Spine*, **18,** 2097 – 2105.

Lavender, S. A., Mirka, G. A., Schoenmarklin, R. W., Sommerich, C. M., Sudhakar, L. R. and Marras, W. S. 1989, The effects of preview and task symmetry on trunk muscle response to sudden loading, *Human Factors*, **31,** 101 – 115.

de Looze, M. P., Horemans, H., Groen, H., Kingma, I. and van Dieën, J. H. 1999, Abdominal muscles contribute in a minor way to peak spinal compression in lifting, *Journal of Biomechanics*, **37,** 655 – 662.

Marras, W. S., Rangarajulu, S. L. and Lavender, S. A.,1987, Trunk loading and expectation, *Ergonomics*, **30,** 551 – 562.

McConville, J. T., Churchill, T. D., Kaleps, I., Clauser, C. E. and Cuzzi, J. 1980, *Anthropometric Relationships of Body and Body Segment Moments of Inertia*. AFAMRL-TR-80-119 (OH: Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base).

Panjabi, M., Abumi, K., Duranceau, J. and Oxland, M. 1989, Spinal stability and intersegmental muscle forces, *Spine*, **14,** 194 – 200.

Patterson, P., Congleton, J., Koppa, R. and Huchinson, R. D. 1987, The effects of load knowledge on the stresses at the lower back during lifting, *Ergonomics*, **30,** 539 – 549.

Tesh, K. M., Shaw Dunn, J. and Evans, J. H. 1987, The abdominal muscles and vertebral stability, *Spine*, **12,** 501 – 508.

Toussaint, H. M., Commissaris, D. A. C. M., Hoozemans, M. J. M., Ober, M. J. and Beek, P. J. 1997, Anticipatory postural adjustments before load pickup in a bimanual whole body lifting task, *Medicine and Science in Sports and Exercise*, **29,** 1208 – 1215.