

How to lift a box that is too large to fit between the knees

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Many studies compared lifting techniques such as stoop and squat lifting. Results thus far show that when lifting a wide load, high back loads result, irrespective of the lifting technique applied. This study compared four lifting techniques in 11 male subjects lifting wide loads. One of these techniques, denoted as the weight lifters' technique (WLT), is characterised by a wide foot placement, moderate knee flexion and a straight but not upright trunk. Net moments were calculated with a 3-D linked segment model and spinal forces with an electromyographic-driven trunk model. When lifting the wide box at handles that allow a high grip position, the WLT resulted in over 20% lower compression forces than the free, squat and stoop lifting technique, mainly due to a smaller horizontal distance between the L5/S1 joint and the load. When lifting the wide box at the bottom, none of the lifting techniques was clearly superior to the others.

Statement of Relevance: Lifting low-lying and large objects results in high back loads and may therefore result in a high risk of developing low back pain. This study compares the utility of a WLT, in terms of back load and lumbar flexion, to more familiar techniques in these high-risk lifting tasks.

Keywords: biomechanics; compression; lifting technique; low-back load; spine

Introduction

Manual lifting is associated with the risk of developing low-back pain (Norman *et al.* 1998, Hoogendoorn *et al.* 2000). The magnitude of spinal loads associated with manual lifting (e.g. Marras and Davis 1998, Arjmand *et al.* 2009, Lavender *et al.* 2009) has been shown to be sufficiently large to cause tissue damage *in vitro* (NIOSH 1997, Brinckmann *et al.* 1989). This suggests that spine load reduction through improvement of lifting technique could help to reduce the risk of developing low-back pain. Therefore, primary and secondary prevention of low-back pain usually includes instructions on lifting technique. However, such instructions can only be effective if they indeed result in reduced spine loading. A long-held and still influential belief is that bending the knees (squat lifting) reduces spine loading as compared with bending the back (stoop lifting). The question is whether this is indeed the case. Many investigators have attempted to answer this question (e.g. Leskinen *et al.* 1983, Anderson and Chaffin 1986, Toussaint *et al.* 1992, Dolan *et al.* 1994, Kumar 1996, Bazrgari *et al.* 2007). Reviews focusing on squat vs. stoop lifting concluded that the evidence regarding the best technique (i.e. the technique resulting in the lowest loading of the low back) is

inconclusive (van Dieën *et al.* 1999a, Burgess-Limerick 2003, Straker 2003).

In recent studies it was shown that the inconsistency in the literature can be explained by the fact that effects of lifting technique strongly interact with initial lifting height and box size (Kingma *et al.* 2004, 2006). Squat lifting indeed resulted in lower spine compression than stoop lifting when lifting a small crate at its handles between the knees. However, when lifting a wide load that could not be lifted between the knees, the difference between squat and stoop lifting disappeared when lifting at the handles and even reversed when lifting the crate at its bottom (Kingma *et al.* 2006).

The reason for this interaction is that in squat lifting, while reduced trunk inclination tends to reduce spine loading, an increased horizontal distance between pelvis and load when the knees are 'in the way', tends to increase spine load. Some studies investigated alternative lifting techniques, mainly focusing on prevention of the problem of the knees being 'in the way'. These alternatives include the modified squat, i.e. a squat lift with outward rotation of the knees (Kingma *et al.* 2004), a straddle technique, where one leg is placed beside the load (de Looze *et al.*

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1998, Kingma *et al.* 2006) and a kneeling technique, where one leg is placed beside the load and the participant kneels on the knee of the other leg (Kingma *et al.* 2006). Overall, when lifting wide loads, these techniques did indeed reduce spine loading compared with squat lifting but not down to levels below spine loading in stoop lifting (de Looze *et al.* 1998, Kingma *et al.* 2004, 2006). However, stoop lifting causes full flexion of the lumbar spine. While the evidence for flexion as a primary factor causing injury or as a factor reducing the injury threshold is not very strong (Adams and Hutton 1986), avoiding full lumbar flexion is widely believed, and in some studies indeed shown (Long *et al.* 2004), to be beneficial for low-back pain patients. While squat lifting reduces lumbar flexion relative to stoop lifting (Dolan *et al.* 1994, Hwang *et al.* 2009), the difference between stoop and squat reduces to only about 10° when lifting a wide load from floor level (Kingma *et al.* 2006). The reason is probably the large hip flexion, which tends to rotate the pelvis backwards, thereby flexing the lumbar spine.

The present study investigated another alternative lifting technique, which will be denoted as the weight lifters' technique (WLT). This technique is characterised by a very wide foot placement, straight but not upright back and moderate knee flexion. This paper will specifically focus on lifting wide loads, as no lifting technique has yet been reported to result in substantially lower back loading than other techniques for this type of lifting task. One obvious advantage of the WLT over the squat technique is reduced knee flexion, which may reduce knee joint loading and metabolic energy consumption compared with squat lifting. The question is, however, whether lumbar flexion and lumbar compression forces are also different between the WLT and the (modified) squat technique. As it is anticipated that the WLT allows bringing the pelvis closer to the load, it is hypothesised that the WLT results in lower spine loads than both stoop and squat lifting. Furthermore, it is hypothesised that lumbar flexion in the WLT is not larger than in squat lifting.

Methods

After signing an informed consent, 11 healthy young males (age 25.3 years, SD 6.6 years; weight 71.8 kg, SD 8.8 kg; height 1.76 m, SD 0.07 m) participated in the experiment. None of the participants had a history of low-back pain. The experiment was approved by the faculty's ethical committee.

Experimental design and procedure

During the experiment, participants lifted a large 15 kg box (height 0.38 m, depth 0.38 m, width 0.57 m) from

a shelf, suspended 50 mm above the surface of the force plate on which participants were standing.

Participants performed 16 lifts, two repetitions with four lifting techniques and two initial hand locations. The order of lifting technique and hand location was systematically varied over subjects. Only the last lift of each pair of lifts was taken for further analysis. Hand locations were box handle (height 0.34 m above the force plate) and bottom of the box (height 0.07 m above the force plate). The lifting techniques were: (1) a free lifting technique, i.e. the only instruction was to walk to the box and lift it in a symmetrical way; (2) a stoop technique, i.e. lifting by bending the back and keeping the knees extended; (3) a squat technique, lifting by bending the knees and rotating the knees outward and holding the trunk as upright as possible; (4) a WLT. For the latter technique, participants were instructed to spread the legs so that the outer edges of the feet were apart for a distance of about 60% body height, to bend the knees until the front edge of the knees was over the tips of the toes and to flex the hips while keeping the lumbar spine extended (Figure 1).

Each lift ended with standing upright while holding the box with the hands at about hip level. The lifting techniques are illustrated in Figure 1.

For all lifting techniques, verbal instruction was provided by a professional involved in lifting instructions to low-back pain patients on a daily basis and experienced in teaching participants how to perform the WLT. Prior to attachment of measurement equipment to the participants' bodies, they practised each lifting technique until both the participant and the professional were satisfied. Participants were, for all techniques, during both the practice sessions and the experiment, instructed to walk close to the box and lift the box to hip height using one of the instructed techniques. Participants were free to select their preferred lifting speed.

Dynamic 3-D linked segment model

A dynamic 3-D linked segment model was used to estimate net moments at the L5/S1 intervertebral disc. This model has been described in detail previously (Kingma *et al.* 1996) and has been internally validated by comparing a top-down to a bottom-up calculation of net moments. In addition, model results have been compared with independent net moment estimations by an electromyographic (EMG)-based model and a neural network-based model (Kingma *et al.* 2001). The current model uses anthropometrical data according to Zatsiorsky (2002). Furthermore, the anterior-posterior position of the centre of mass (COM) of the pelvis was

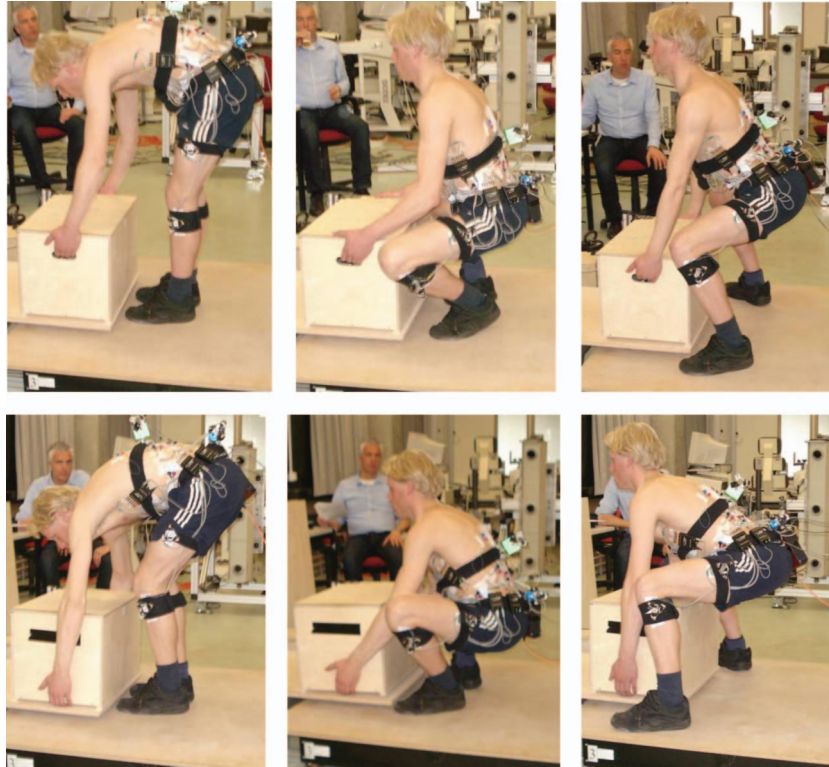


Figure 1. Photographs showing the stoop, squat and weight lifters technique for lifting the wide box at the handles and at the bottom.

estimated based on anatomical data reported by Plagenhoef *et al.* (1983) and the L5/S1 joint position was estimated based on anatomical data reported by Reynolds (1982). Anthropometric data were combined with force-plate data (measured at 200 Hz using a custom-made 1.0 × 1.0 m force plate) and kinematics from LED markers on the box and on cuffs attached to body segments (feet with lower legs, upper legs, pelvis and trunk) during movement. To optimise visibility, markers on the cuffs were attached to small metal plates, mounted on the cuffs with a double hinge joint. Trajectories of the cuff markers were recorded at 50 Hz and synchronised with force-plate signals, using an automated 3-D movement registration system (Optotrak, system accuracy: SD < 0.05 mm; Northern Digital Inc., Waterloo, Ontario, Canada), with three arrays of three cameras. Prior to the measurements, for each participant, the force plate and Optotrak system were calibrated and cuff markers were related to anatomical landmarks by making a short recording while a pointer containing six markers was placed at each landmark consecutively (Cappozzo *et al.* 1995). Marker data and force plate data were low-pass filtered using a bi-directional second order Butterworth filter at a cut-off frequency of 5 Hz. A global equation of motion (rather than a segment-by-

segment calculation) was used, as described by Hof (1992):

$$\begin{aligned} \mathbf{M}_{L5S1} = & -\mathbf{M}_g - (\mathbf{r}_g - \mathbf{r}_{L5S1}) \\ & \times \mathbf{F}_g - \sum_{i=1}^q [\mathbf{r}_i - \mathbf{r}_{L5S1}] \times m_i \mathbf{g} + \\ & \sum_{i=1}^q [(\mathbf{r}_i - \mathbf{r}_{L5S1}) \times m_i \mathbf{a}_i] + \sum_{i=1}^q d(\mathbf{I}_i \boldsymbol{\omega}_i) / dt \end{aligned} \quad (1)$$

where \mathbf{M}_{L5S1} is the net moment at the L5S1 joint, \mathbf{r}_g is the vector to the point of application of the ground reaction force, \mathbf{F}_g is the ground reaction force vector, \mathbf{r}_{L5S1} is the vector to the L5S1 joint, \mathbf{r}_i is the vector to the COM of segment i , m_i is the mass of segment i , q is the number of segments of the lower body up to L5S1, \mathbf{I}_i = the inertia tensor of segment i and $\boldsymbol{\omega}_i$ is the angular velocity vector of segment i . \mathbf{M}_g is the ground reaction moment measured by the force platform. This moment is non-zero around the vertical axis only. The L5S1 joint was chosen as the level of analysis because it is the intervertebral joint that is expected to undergo the largest loads. The global equation of motion allowed the use of one instead of two force plates. Anatomical axes of the trunk and pelvis were defined in upright standing posture as follows: positive X-axis

(lateral flexion) forward; positive Y-axis (flexion–extension) to the left; positive Z-axis (twisting) upward. Net moments were expressed in the pelvic axes system. The trunk movement relative to the pelvis was decomposed in the order Y–X–Z.

3-D Electromyographic-driven trunk model

Altogether 14 pairs of surface EMG electrodes were attached to the skin after abrasion and cleaning with alcohol (Ag/AgCl electrodes, inter-electrode distance 20 mm). Electrodes were bilaterally attached ventrally over the rectus abdominis (at the level of the umbilicus), the internal oblique (just superior to the inguinal ligament) and the anterior (approximately 15 cm cranial of the anterior superior iliac spine) and lateral (mid-axillary line, halfway between the iliac crest and the lowest edge of the ribcage) parts of the external oblique. Dorsally, electrodes were attached over the iliocostalis lumborum (6 cm lateral to L2) and over the longissimus thoracis pars lumborum (3 cm lateral to L1) and pars thoracis (4 cm lateral to T9). Prior to the actual experiment, participants performed three times seven attempted maximum isometric contractions of the trunk muscles as described by McGill (1991). EMG data were amplified (Porti-17TM; TMS, Enschede, The Netherlands; input impedance $>10^{12} \Omega$, common mode rejection ratio >90 dB), band-pass filtered (10–400 Hz) and A–D converted (22 bits at 1000 Hz) and stored synchronised to Optotrak and force plate data. Off-line, EMG signals were full-wave rectified and low-pass filtered at 2.5 Hz (Potvin *et al.* 1996). EMG data were normalised to maximum voluntary contractions and used as input to an EMG-driven trunk muscle model. The model has been described in more detail previously (van Dieën 1997, van Dieën and Kingma 2005) and consisted of a compilation of anatomical data described by Stokes and Gardner-Morse (1995) for the back muscles and by McGill (1996) for the abdominal muscles.

The model consisted of 90 muscle slips crossing the L5S1 joint. For muscle slips crossing the L4 and T12 level, nodes were used as points about which these long muscles were wrapped. In this way, the muscles follow the lumbar curvature during motion.

After assigning each of the 90 muscle slips to one of the 14 EMG signals, muscle forces were estimated as the product of the assumed muscle maximum stress, normalised EMG amplitude and correction factors for the instantaneous muscle length (Woittiez *et al.* 1984) and contraction velocity (van Zandwijk 1998). For each participant, a best fit between net moments and muscle moments was obtained by optimising over all lifts performed by a participant, three values for each participant: the gain, i.e. a scaling factor between

EMG amplitude and muscle stress, the position of the passive length–tension curve relative to the muscle optimum length and a scaling factor for the passive length–tension curve. Note that ‘all lifts’ included several other lifting tasks, not described in this paper.

Finally, to obtain compression and shear forces at the L5S1 intervertebral joint, muscle forces and net reaction forces were summed after projecting them on the axis system connected to the L5S1 disc, i.e. the plane that separates the disc in equal upper and lower parts. For convenience, shear forces pushing the upper vertebra (L5) forward were indicated as positive. The body COM location was calculated from the COM of the individual body segments, with the COM of each arm assumed to be on a line between the handle and the shoulder.

Statistics

Primary outcome variables were peak values of the extension moment, absolute peak values of the lateral flexion and torsion moments and peak values of lumbar flexion, i.e. the flexion between the thorax and the pelvis. Furthermore, time series of the forces at the L5S1 joint, calculated by the EMG-assisted trunk model, were used to calculate peak compression forces and peak forward shear forces. Secondary outcome variables were the knee flexion, minimum height of the body COM horizontal distance from the L5S1 joint to the load, the trunk inclination and the total net reaction force at the L5S1 joint, all at the instant of peak extension moment. For the values described above, repeated measures ANOVA were applied (one ANOVA for each dependent variable) with lifting technique (four levels: stoop; free; squat; WLT) and grip height (high/low) as independent variables. A significance level of $p < 0.05$ was used. Subsequently, follow-up ANOVA per handle condition and Bonferroni *post-hoc* tests were performed in case of significant main effects of, or interactions with, lifting technique.

Results

ANOVA results

As might be expected because of the symmetrical characteristics of all lifting techniques, asymmetrical moment components were small. Absolute lateral flexion moments ranged from 14 (SD 15) Nm to 25 (SD 24) Nm over techniques and handle conditions, with no significant effects of condition or lifting technique. While torsion moments significantly varied over conditions and techniques, they ranged from only 7.4 (SD 9.3) Nm to 13.6 (SD 7.6) Nm. Asymmetric moment components are not presented in tables or

figures. All other dependent variables showed a highly significant effect of lifting technique and the extension moment, compression force and lumbar flexion also showed effects of grip height and interactions between grip height and lifting technique (Table 1).

Differences between lifting techniques for lifting the box at the handles

When the box was grabbed at the handles, lifting with the WLT and squat techniques resulted in 17–23% lower net extension moments than lifting with the stoop and the free techniques (Figure 2). Compression forces (Figure 2) showed a somewhat different pattern, with only the WLT resulting in significantly lower compression forces (ranging from 20–26%) than each of the other lifting techniques.

Forward shear forces (Figure 2) were not different between techniques. Not surprisingly, lumbar flexion (Figure 2) was smaller in WLT and squat lifts than in stoop lifting. No significant difference in lumbar flexion was found between the WLT and the squat lift.

Differences between lifting techniques for lifting the box at the bottom

When grabbing the box at the bottom, the WLT resulted in a net extension moment in between the other techniques and did not differ significantly from any technique (Figure 2). However, the squat technique resulted in 9 and 11% smaller net extension moments than the stoop and free techniques, respectively. Compression forces showed no significant differences between any of the lifting techniques. Forward shear forces were higher in the WLT than in stoop and squat lifting. In contrast, lumbar flexion

was smaller in the WLT than in any other lifting technique.

Secondary outcome variables

As might be expected, knee flexion was smallest and body COM minimum height was highest in stoop lifting (Figure 3). Furthermore, as anticipated, peak knee flexion was smaller and the minimum COM height was higher in the WLT than in squat lifting.

The horizontal distance between the L5S1 joint and the box, an important determinant of back loading in lifting, was smaller in the WLT than in all other techniques, both for lifting at the handles and for lifting at the bottom of the box. With the exception of the stoop vs. free lift in lifting at the bottom of the box, the stoop, free and squat lifting techniques did not differ from each other in horizontal L5S1 to load distance.

Trunk inclination, another determinant of back loading in lifting, was smaller in the WLT than in stoop lifting and smaller in squat lifting than in the WLT. Note, however, that in lifting at the bottom of the box, the squat lift resulted in 59° of trunk inclination, so that the moment arm of the trunk COM was substantial for squat lifting as well. The total net reaction forces at the L5S1 joint, which is due to a constant gravitational force plus the overall acceleration of the upper body plus box, were affected by lifting technique (Table 1). *Post-hoc* tests showed only a slightly smaller acceleration in the WLT than in squat lifting when lifting at the handles but not when lifting at the bottom of the box.

Discussion

For all lifting techniques used in the present study, compression forces were higher when boxes were grabbed at the bottom than when boxes were grabbed at the handles. The magnitude of this effect of handle use was consistent with findings in depalletising tasks (Davis *et al.* 1998, Marras *et al.* 1999) and in accordance with subject preference on grip location (Jung and Jung 2010). This is most likely mainly due to the effect of handle use on grip height, which strongly affects back loads (Ferguson *et al.* 2002, Lavender *et al.* 2003, Hoozemans *et al.* 2008).

Weight lifters technique

In the present study, it was hypothesised that, when lifting a large box that does not fit between the knees, the WLT results in lower spine loads than both the stoop and squat lifts and in lumbar flexion that is not larger than in squat lifting. Consistent with previous

Table 1. Results of repeated measures ANOVA for effects of grip height and lifting technique on back load and postural variables for lifting a wide load.

ANOVA	Grip height	Technique	Grip height * Technique
Mextension	0.001	< 0.001	0.001
Lumbar flexion	< 0.001	< 0.001	0.035
Compression	0.009	< 0.001	0.022
Shear	0.070	< 0.001	0.122
Knee flexion	0.001	< 0.001	0.092
COM minimum	< 0.001	< 0.001	0.029
Horizontal distance	0.185	< 0.001	0.002
Trunk inclination	< 0.001	< 0.001	0.037
Total net reaction force	0.393	< 0.001	0.388

COM = centre of mass.

Values shown in bold indicate significant effects.

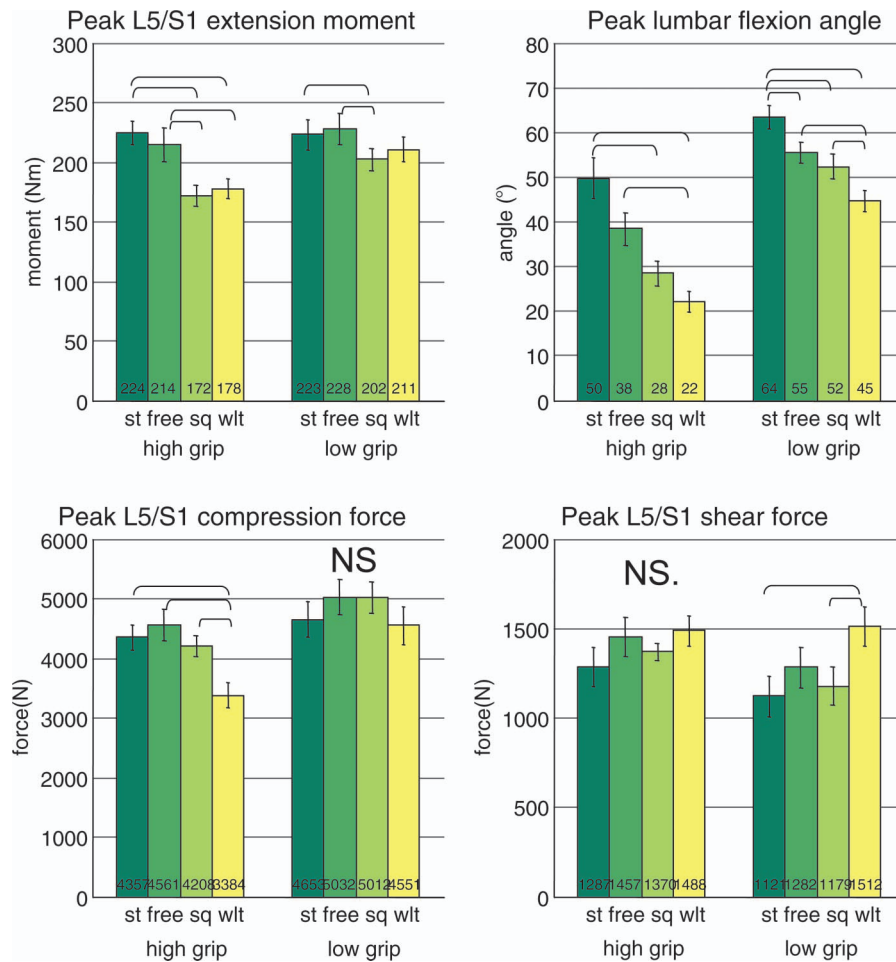


Figure 2. Peak extension moment, lumbar flexion and compression and shear force for lifting a wide box with the handles (high grip) and at the bottom (low grip), using a stoop (st), free, squat (sq) and weight lifters' (wlt) technique. Significant differences between individual lifting techniques are indicated by parentheses. Error bars indicate 1 SD. The numbers indicate the value represented by the bar. NS = the follow-up ANOVA for the handle condition did not indicate a significant effect of lifting technique.

work (Kingma *et al.* 2004, 2006), the results did depend on whether the box was grabbed at the handles or at the bottom. Those conditions will be discussed separately.

Weight lifters' technique vs. other techniques when a large box is lifted at the handles

When the large box was grabbed at the handles, i.e. at a height of 0.34 m, the WLT resulted in lower extension moments than stoop and free lifting. Compared with stoop lifting, this may in part be due to the fact that the trunk inclination was substantially more advantageous in the WLT. More importantly, the horizontal distance between the L5/S1 joint and the load was more than 10 cm smaller in the WLT than in the other three lifting techniques. The horizontal distance of the load relative to the body has been shown

to have substantial effects on low-back loading (Potvin *et al.* 1992, Schipplein *et al.* 1995, Lavender *et al.* 1999, Ferguson *et al.* 2002), except when participants are allowed to pull the load towards them prior to lifting it (Faber *et al.* 2007). Compared with squat lifting, the WLT also resulted in a horizontal distance that was about 10 cm smaller. In addition, the upper body plus box acceleration was slightly smaller than in squat lifting. However, at the same time, trunk inclination was, on average, 27° larger, so that resulting net moments did not differ between WLT and squat lifting. In spite of this, L5/S1 compression forces in WLT lifts were not only lower than in free and stoop lifting, but also substantially (about 20%) lower than in squat lifting. About half of this difference could be traced back to more abdominal co-contraction and to a larger compressive net reaction force in squat lifting, the latter being due to larger upward accelerations and a

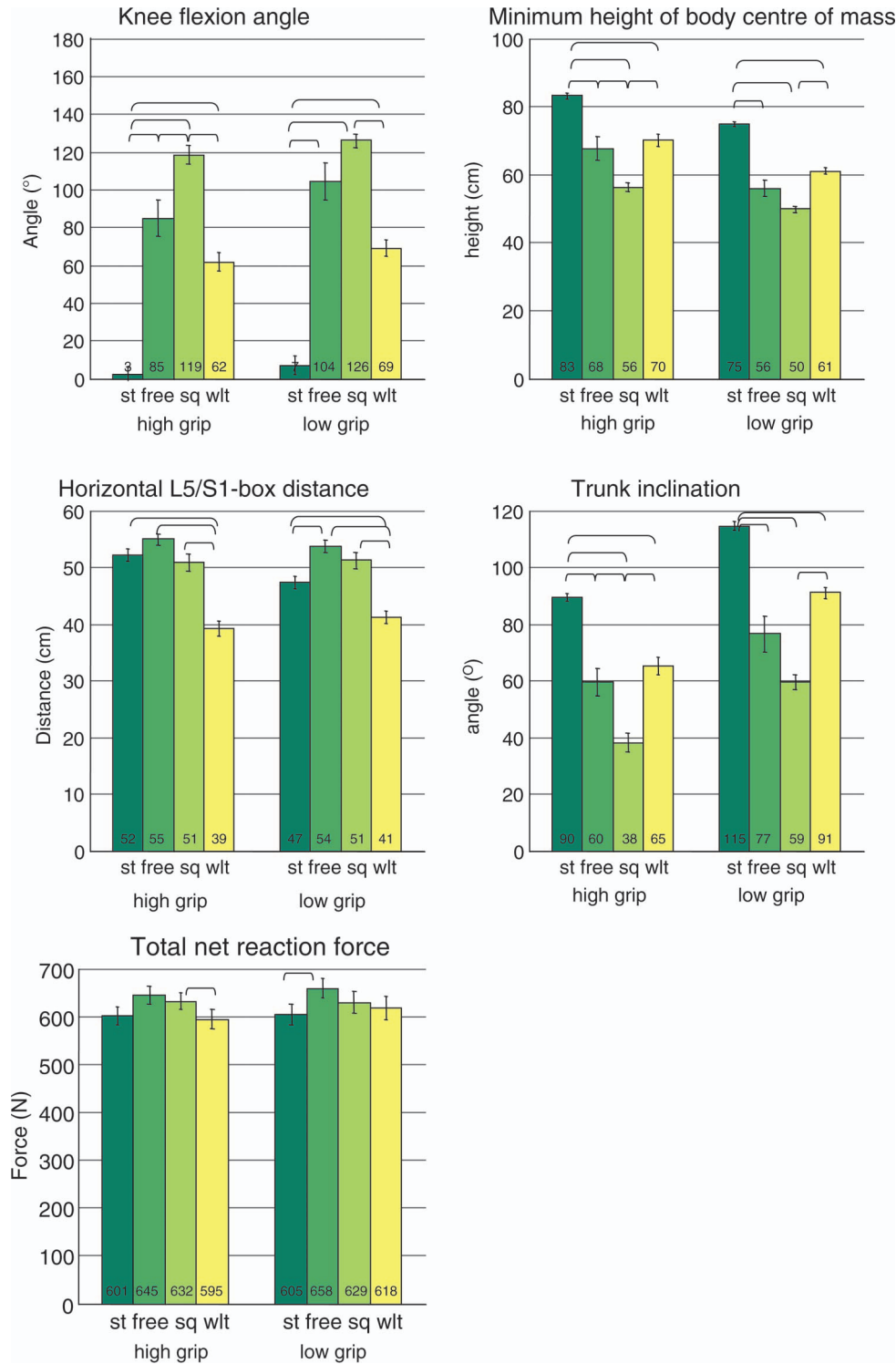


Figure 3. Knee flexion angle, minimum height of the body centre of mass, horizontal L5-S1-box distance and trunk inclination for lifting a wide box with the handles (high grip) and at the bottom (low grip), using a stoop (st), free, squat (sq) and weight lifters' (wlt) technique. Significant differences between individual lifting techniques are indicated by parentheses. Error bars indicate 1 SD. The numbers indicate the value represented by the bar.

more upright pelvis. The other half was due to a systematic difference between the squat lift and the WLT in the fit between net moment and the moment

calculated by the EMG-driven model. This difference may well be due to differences in muscle recruitment between the two lifting techniques that are not

sufficiently accurately represented in the model. For instance, Claus *et al.* (2009) showed that the activation of the deep multifidus muscles, which is probably under-represented in the EMG signals, increases with lumbar lordosis. As the WLT resulted in the least amount of lumbar flexion, this could have resulted in some underestimation of compression forces in the WLT.

In spite of an increased trunk inclination when lifting with the WLT, lumbar flexion was not larger in the WLT than in squat lifting. In fact, although not significant ($p = 0.11$), lumbar flexion even tended to be smaller in WLT lifts. Apparently, reduced knee flexion in the WLT allowed participants to bend forward by flexing the hips instead of the lumbar spine more than in squat lifting. Finally, while vertical body COM displacement was larger than in stoop lifting, it was smaller than in squat lifting and comparable with a self-selected free lifting technique. This indicates that energy consumption may be comparable to self-selected techniques and lower than in squat lifting, probably enhancing the compliance in using the WLT. It is concluded that when lifting a large box at handles that allow a high grip, the WLT can be recommended as it has advantages relative to all other techniques tested here, while no disadvantage could be detected.

Weight lifters' technique vs. other techniques when a large box is lifted at the bottom

For a low grip position, i.e. when lifting the box at the bottom, the WLT did not, in spite of a smaller distance from L5S1 to the box, differ from any of the other techniques in terms of either net moments or compression forces. The reason is that the trunk inclination in the WLT was 90° (Figure 3) so that the moment arm of the trunk was at its maximum and both reduction of trunk inclination (squat lift) and increase of trunk inclination (stoop lift) acted to reduce the moment arm of the trunk. From *in vitro* research, it is clear that the compressive forces for lifting the box at the bottom, which ranged between 4500 and 5000 N over lifting techniques, could potentially cause an endplate fracture (Brinckmann *et al.* 1989). Whereas lumbar flexion was reduced in the WLT compared with all other techniques, shear forces at the L5S1 joint were higher compared with the stoop and squat techniques. This high shear force in the WLT was caused by the combination of a large pelvic inclination, causing relatively large shear forces due to the net reaction force, combined with a limited lumbar flexion, which, relative to the L5S1 joint, slightly increases the muscular component of the shear force relative to other techniques (Kingma *et al.* 2004). For shear forces, the values found in the present study are in the

range of values that have been reported to cause bony failure *in vitro* (Lamy *et al.* 1975, Cyron *et al.* 1976). However, whereas compression-related damage, i.e. healed endplate fractures, are commonly found *in vitro* (Vernon-Roberts and Pirie 1973), and may well be a cause of low-back pain (van Dieën *et al.* 1999b), spondylolysis, a type of damage that may be associated with shear force failure, is much less common and poorly associated with low-back pain (van Tulder *et al.* 1997). It is therefore unclear whether, for lifting the large box at the bottom, the increased shear force in the WLT would increase the risk of developing low-back pain.

At this point, it is unclear which of the techniques is to be preferred for lifting a large box at the bottom. While hyperflexed spines have been shown to have a reduced compressive strength (Adams *et al.* 1994), such levels of flexion are not likely to occur *in vivo* (Adams and Hutton 1986), especially not in the techniques that do not result in the largest amount of lumbar flexion, i.e. the free, squat and WLT. Nevertheless, when lumbar flexion is to be avoided, which has been shown to be beneficial for many acute low-back pain patients (Long *et al.* 2004), the WLT might be preferred over other techniques.

Over all, there does not seem to be a convincing argument, for healthy subjects, to prefer one lifting technique over another when a large box needs to be lifted at the bottom. Rather, especially when considering the high compression forces involved in all lifting techniques for this condition, this lifting condition should be avoided. One way would be to provide handles close to the top side of the box, for each and every box. Another way might be to tilt boxes without handles prior to lifting them (Gagnon *et al.* 1993).

Stoop vs. squat lifting compared to previous studies

It has previously been shown that the answer to the question whether low-back loading is higher in stoop lifting or in squat lifting depends on task characteristics, such as initial lifting height and load size (Kingma *et al.* 2006). When lifting a small load with a hand grip position substantially above floor level, squat lifting either resulted in comparable (Kjellberg *et al.* 1998, Hwang *et al.* 2009) or in smaller (Shin and Mirka 2004, Bazrgari *et al.* 2007) extension moments and compression forces than stoop lifting. In contrast, squat lifting was found to result in higher back loads than stoop lifting when lifting small loads from floor level (Dolan *et al.* 1994) or a large box at the bottom (Kingma *et al.* 2006). Taking into account that rotating the knees outward reduces back loading compared with more traditional squatting with the knees forward (Kingma *et al.* 2004), the present

pattern of moment and compression force differences between stoop and squat lifting is consistent with previously reported patterns for lifts using a wide load (Kingma *et al.* 2006).

A specific comparison with previous lifts with a 'modified squat' (Kingma *et al.* 2004) shows less consistency. Whereas that study reported 13% higher moments in (modified) squat lifting compared with stoop lifting, 10% lower moments were found in the present study. This could be due to subtle differences in the task as well as in participant population and in the method. With regard to the task, the size of the box was slightly different between studies. Furthermore, the load was 15 kg in the present study against 10.5 kg in the previous study. Finally, in the present study, lifting conditions may have been more consistent with occupational practice, as the participants were asked to walk several metres forward and then stop and lift the box. The previous study did not involve forward walking prior to lifting but used instructed foot placement. With regard to participant characteristics, some factors such as flexibility of the hips and lumbar spine could play a role, but were not quantified in either of the studies. With regard to the method, participants were instructed through video in the previous work, whereas instruction by a professional and supervised practice was used in the present study. Furthermore, the method of calculating net moments was different, in that the previous analysis was 2-D, whereas a full body 3-D inverse dynamics model was applied in the present study. Especially for the modified squat, where knees are rotated outward, the 3-D model may have resulted in more accurate estimates of leg COM and L5/S1 locations. The net moments calculated in the present study were checked by applying a top-down vs. bottom-up comparison of net moments (de Looze *et al.* 1992, Kingma *et al.* 1996, Plamondon *et al.* 1996). Differences between top-down and bottom-up calculated net moments were, averaged over participants, below 6% when lifting at the handles in all lifting techniques, and even below 3% when lifting at the bottom of the box in all lifting techniques. More importantly, the pattern of differences between lifting techniques was the same in the top-down and bottom-up calculated net moments. This suggests that the present net moments are accurate.

Limitations

One limitation of the present study is that only loads of 15 kg were used. With these loads, the contribution of trunk posture and acceleration to back load is larger than the contribution of the box. As the WLT consistently reduced the horizontal distance between the low back and the box, it might be anticipated that,

for lifting heavier loads, more pronounced reductions of back load will be found with the WLT.

Another limitation is that all lifting tasks were of a symmetrical nature, which represents only about 50% of industrial lifting tasks (Dempsey 2003). Furthermore, because the trunk muscle model in the present study represents male anthropometry, only male participants were included. It has been shown that gender may interact with lifting technique (Lindbeck and Kjellberg 2001, Marras *et al.* 2003). Finally, only healthy young participants were studied. Low-back pain patients may show altered lifting behaviour (Lariviere *et al.* 2000, Marras *et al.* 2004, Wrigley *et al.* 2005). However, especially for those patients in whom flexion provokes pain (Long *et al.* 2004), a technique such as the WLT, which minimises lumbar flexion without increasing compression forces, may be advisable.

Conclusion

In conclusion, when lifting a large box at handles that are located at the upper part of the box, the WLT is to be preferred over the squat, stoop and free lifting technique, because it reduces low-back loading relative to all techniques, reduces lumbar flexion relative to stoop and free lifting and reduces knee flexion relative to squat lifting. Lifting a large box of only 15 kg at the bottom results in high back loads irrespective of lifting technique and should thus be avoided.

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